METEOROLOGICAL CONDITIONS AFFECTING THE DISPERSION OF LANDFILL ODOR COMPLAINTS

by

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ABSTRACT

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One of the factors recognized as affecting the dispersion of landfill odors off-site are complex meteorological conditions. A major issue is lack of consistent means to identify the odors and their intensity. The aim of this research was to investigate the influence of meteorological parameters (temperature, humidity, pressure, wind direction, wind speed, precipitation accumulation and weather conditions) on the frequency of odor complaints from nearby neighborhoods. Methods involved collection of ten years of data on odor complaints and weather conditions to determine if there were commonalities. Sophisticated statistical analyses employed did not reveal any relationships between odor complaints and weather alone. Need for substantial improvement of detailed information is recognized. To help identify the factors that influence odor complaints- a revised odor complaint form, along with operational adjustments, were recommended. An "Odor Threat

Assessment Level" is proposed to assist landfill site personnel in managing daily operations, based on weather conditions.

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1 INTRODUCTION

Controlling odors at landfills is one of the most critical challenges facing the solid waste management industry (Dincer et al. 2006; Che et al. 2013). Of great importance is to find a way how to minimize odors at waste disposal facilities since waste disposal is a crucial service for society (McKendry et al. 2002), yet offsite odors can create ongoing concerns with residents and businesses (Ko et al. 2015). Many odor causing compounds with very low odor thresholds can be found in solid waste operations. Even though concentrations may be very low, the perception is that if odors can be detected, then they must be harmful to human health (Ranzato et al.2012). The most complex issue related to nuisance odors is the subjective nature of detection related to its quantification. Of concern is that perceptible odors may not even originate from landfill activities but may have been reported merely because of the presence of a solid waste facility nearby. There are situations where odor complaints are filed about odors that were actually associated with more mundane activities such as mowing grass (Personal communication with site personnel).

The fugitive nature of odors makes them very difficult to intercept and manage because odors can be transported considerable distances in just a matter of minutes, depending on many different factors such as source strength, weather patterns, wind speed, and direction (Brozozowski, 2017). Complex atmospheric conditions and local winds have the potential to affect the strength of odors perceived in the field (Zeiss et al. 1993; Sarkar et al. 2003; Larro et al. 2004; Wenjing et al. 2015). Some meteorological conditions increase the strength of odors, while others tend to facilitate odor dispersal away from landfill sites (McKendry et al. 2002). With all of that being said, nothing can be done at solid waste facilities to modify the climate or microclimate. As a result, solid waste managers must give attention to operating their facilities in a manner that would reduce any potential impact to nearby neighborhoods. Therefore, a useful tool could be installing a weather station (SCS Engineers, 2009) to collect site-specific data on key meteorological conditions such as temperature, wind direction, wind speed, pressure, humidity, and other climatic data in real time. Operating solid waste facilities in relation to meteorological conditions can assist in identifying what weather conditions dominated at the time an odor complaint was filed (McKendry et al. 2002). By monitoring meteorological conditions, certain solid waste operations could be scheduled and planned for more favorable weather conditions. As an example, if the wind direction is known, workers should try to avoid working on the upwind side of the landfill site that could potentially produce odors and disperse them downwind. Another example where monitoring meteorological data can be very useful is to demonstrate to regulators that on the day the odor complaint was logged, the wind was actually blowing in the opposite direction so there is no relation between the site and odor complaints. Hence, by looking into the data information with wind directions at the time of the complaint, it could be concluded that the wind was not in fact blowing in the direction of that particular community.

The frequency of odor complaints can help to document the magnitude of odor impacts. Patterns or trends can help in verifying odors and identifying sources. Citizen odor complaints should be treated seriously and seen in a positive light, since by identifying unfavorable conditions and being notified about those events, operators can investigate the source and implement proper measures to deal with the issue (McKendry et al. 2002, SCS Engineers, 2009; Air Quality Management District, 2009; Golder Associates Inc., 2010).

1.1 Background

One of the major environmental problems and important challenges facing solid waste management industry are nuisance odor emissions (Dincer et al. 2006; Che et al. 2013). The fact is that a landfill site that manages solid waste is prone to decay that will produce offensive smells (Clark, 2009). In the past, solid waste facilities were not forced to operate in such close proximity to residential areas as they have to today. Increased population density has resulted in pressures to expand previously undeveloped areas around landfills such that they are being transformed into urban neighborhoods. Residential areas in proximity to solid waste facilities and enhanced awareness have resulted in increasing number of odor complaints facing landfill managers (Southamton, 2013). As a result, solid waste facilities need to find better ways to operate the landfill site while they apply the best available odor mitigation strategies to prevent, minimize or better manage odors in order to be a good neighbor to nearby residents.

Citizen odor complaints can seem at first to be an inconvenience for solid waste facilities, but actually they can be a useful tool in identifying the real sources of odors and improving day-to-day operations at the landfill. Also, odor complaint data logs, if collected properly with important information on meteorological conditions, odor characteristics, and location at the time of occurrence, may help with correlating odors to key meteorological parameters to determine the conditions that influence the strength and dispersion of odors downwind to communities (McKendry et al. 2002).

Meteorological parameters such as temperature, humidity and pressure are known to influence the emissions of odors (Che et al.2013; Capanema et al. 2014), while wind speed and wind direction are responsible for dispersion of odors downwind to residential areas (Air Quality Management District, 2009; Ying et al. 2012). Odor causing compounds can be dispersed for a distance of a mile or more from sources within the landfill site (Qdais, 2007; Che et al. 2013). Establishing appropriate odor complaints procedures while including vital information on the weather conditions at the time, can be used to correlate citizen odor complaints, meteorological parameters, solid waste operations and other activities that generate odors such that landfill operations can be delayed to times when weather conditions are less probable to generate off-site odors (Air Quality Management District, 2009).

1.2 Odors Generated at Solid Waste Facility

The most common and the most economical method for solid waste disposal in many parts of the world is landfilling. Accordingly, landfills will continue to be the most suitable disposal path for solid waste (El-Fadel et al. 1997). Sanitary landfills are designed with a purpose to bury the waste while preventing further human contact and preventing groundwater contamination (Freudenrich, 2017). A typical landfill design is presented in Figure 1.

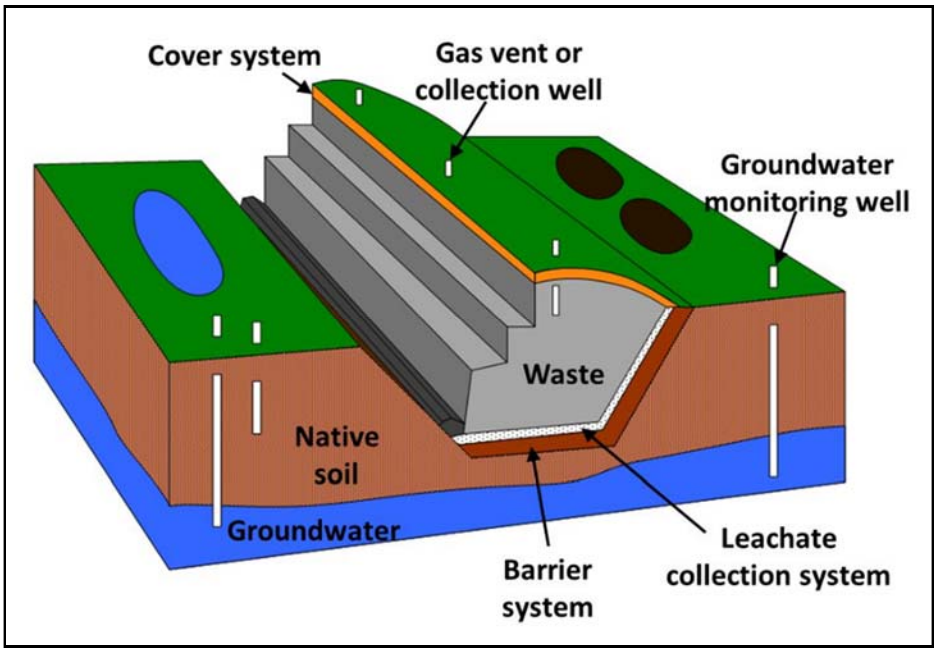


Figure 1. A Typical Landfill Design (Benson, 2017)

The main sources that generate odors at landfills are landfill gas (LFG), municipal solid waste (MSW) or biosolids at the active working face or open tipping floor, as well as leachate. Landfill gas is produced due to: 1) anaerobic decomposition of waste to produce hydrogen sulfide and other odorants (El-Fadel et al.1997), 2) volatilization of chemical constituents that occurs when wastes transform from a liquid or solid to a vapor (ATSDR, 2001; MassDEP, 2007) ; and 3) chemical reactions that arise when the waste is mixed together in disposal operations (MassDEP, 2007). If not managed properly, MSW disposed at the active face of the landfill can be responsible for production of nuisance odors while diffusing gas emissions to the atmosphere (Chemel et al. 2012).

Some solid waste operational activities also contribute to odor impacts at landfills. Drilling in the waste mass to construct landfill gas collectors can result in fugitive emissions escaping through the borehole while open to the atmosphere (EPA, 2000; Personal communication with site personnel). A similar scenario occurs when excavating tranches, where odors also can escape the landfill body while exposed to atmosphere (EPA, 2000; McKendry et al. 2002; Personal communication with site personnel). Insufficient vacuum (ACUA, 2017) on the landfill while extracting landfill gas could also contribute escape of odors. Type and thickness of cover (Anunsen, 2007; Santonastaso et al. 2014) is of great importance since adequate cover (daily or intermediate) ensures that gases (and odors) do not escape. Waste receiving and processing activities are another potential source of odors, since work at the landfill active area may cause odor emissions until the waste is spread, compacted and covered (McKendry et al. 2002; Clark, 2009; Personal communication with site personnel). Overly odorous loads, such as household garbage or wastewater treatment biosolids, papermill sludge, and other waste products are all potential contributors to nuisance odors (Personal communication with site personnel). Leachate seeps may also be an odor source (NSWMA, 2008; Golder Associates Inc., 2010; Palmiotto el al. 2014; Personal communication with site personnel). If there is too much water in the landfill, it will clog collectors while reducing the ability to remove LFG, which results in higher odors. In general, odors produced by leachate are formed when water from precipitation flows through the MSW in a landfill cell and transports odors from the waste itself. If the leachate collection system is not operating appropriately, odors can escape through manholes or be carried to the atmosphere by venting, and then migrate offsite (NSWMA, 2008). Odors generated within the landfill itself can escape through the cover, through cracks, through LFG wells, and through lateral migration (Yazdani, 2015). A summary of some of the solid waste operational activities that could contribute to odor is presented in Table 1. These examples were obtained from interviewing landfill managers from facilities participating in this study.

Table 1. Examples of Operational Activities that Typically Contribute to Odors

Operational Activities	**Contribution to Odor**
Drilling in the waste mass to construct landfill gas collectors	Odors escape through the borehole while open the atmosphere
Excavating trenches in waste to install horizontal gas collectors	Odors escape while trench is open to atmosphere
Insufficient vacuum on the landfill to extract gas	Odors escape as fugitive emissions
Inadequate cover (daily or intermediate), cover type and thickness	Odors escape from higher pressure inside the landfill to lower atmospheric pressure through cracks or weaknesses in the cover
Leachate seeps	Odors escape with the leaking of fluids out of the waste along the slopes
Collector clogging caused by too much water in the landfill	Odors escape with gas well condensates or build up in areas that are clogged and find a different way to the surface or release to the atmosphere
Waste receiving and processing activities	Waste has odor when delivered to the landfill active area and may cause odors until the waste is spread, compacted and covered
Overly odorous loads	Waste has odors associated with household garbage, biosolids, sludges, RSMs, etc.

Figure 2 illustrates how gaseous emissions escape from a landfill.

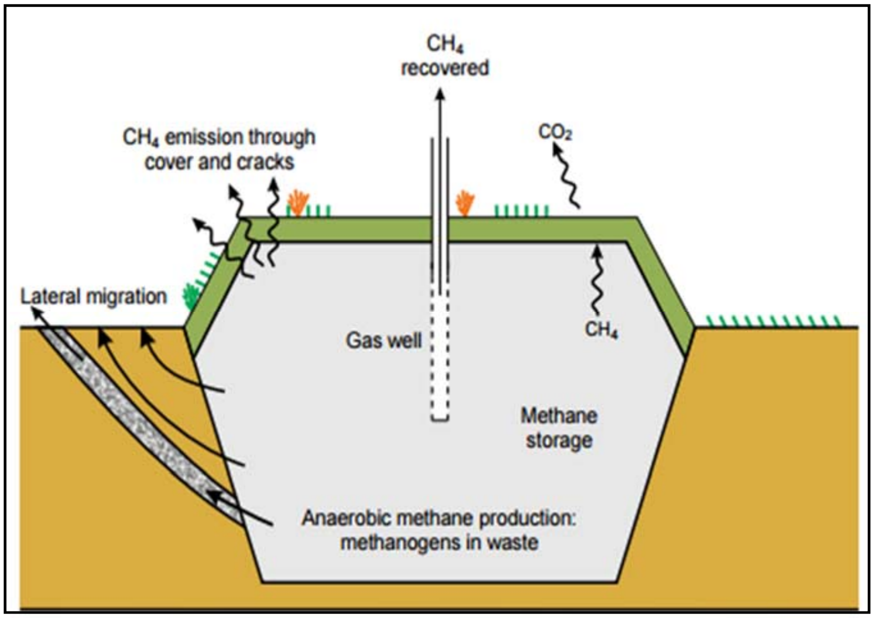


Figure 2. Gas Production, Transport, and Emission from a Landfill (Yazdani, 2015)

The majority of landfill gas is produced when organic waste, yard waste, paper products, and other biodegradables are decomposed anaerobically by bacteria (MassDEP, 2007). Generation of gas is also greatly affected by the age and type of waste the landfill is receiving, as well as the environmental conditions inside the landfill, such as temperature, moisture content, pH, alkalinity, composition of daily cover, and the physical compression density of the waste (Yazdani, 2015). Generally, the more organics and moisture content available in the landfill, the greater the microbial decomposition and gas production (ATSDR, 2001).Table 2 summarizes the composition of a typical landfill gas. Methane and carbon dioxide are two main components of landfill gas which typically account for 90% of the total gas produced (El-Fadel et al. 1997; Tchobanoglous & Kreith, 2002; Dincer et al. 2006; Golder Associates Inc., 2010), and both are odorless so neither contributes to landfill odor complaints. Nitrogen and oxygen are usually present in small amounts in

LFG, mainly as a result of air being trapped within the waste, and both are also odorless (El-Fadel et al. 1997). Thus, the odor originates from the trace compounds and minor constituents.

Table 2. Landfill Gas Composition (El-Fadel et al. 1997)

Component	**Concentration Range** *Percent Dry Volume Basis*
Methane	40 – 70
Carbon Dioxide	30 – 60
Nitrogen	3 – 5
Carbon Monoxide	0 – 3
Oxygen	0 – 3
Hydrogen	0 – 5
Hydrogen Sulfide	0 – 2
Trace Compounds	0 – 1

Trace compounds and hydrocarbons present at a very low percentage may be comprised of many different chemicals as presented in Table 3.

Table 3. Trace Compounds in Landfill Gas (El-Fadel et al. 1997)

Component	**Concentration Range** *mg/m^3*
Alcohols	2 – 2500
Organosulphur Compounds	3 – 240
Halogenated Hydrocarbons	1 – 2900
Aromatic Hydrocarbons	30 – 1900
Aldehydes	0 – 200
Ketones	0 – 50
Hydrocarbons • Alkanes • Cycloalkanes • Alkenes • Others	 • 20 – 4500 • 1 – 1000 • 6 – 1100 • 8 – 600
Esters	0 – 1300
Ethers	0 – 250

Nuisance odors are mostly the result of the existence of small concentrations of odor causing compounds (esters, hydrogen sulfide, organosulfurs, alkylbenzenes, limonene, and other hydrocarbons) in landfill gas released to the ambient air (El-Fadel et al. 1997). A large variety of odor causing compounds (more than 300) have been recognized in landfill gas (McKendry et al. 2002; Anunsen, 2007; Ko et al. 2015). Nuisance odors are most often related to sulfur-containing compounds, essentially mercaptans and sulfides- especially hydrogen sulfide (McKendry et al. 2002). Also, ammonia is often identified as responsible for causing odors in landfill gas (Henry & Gehr, 1980; Kim et al. 2005; Romain et al. 2005; Ko et al. 2015). Ammonia is a characteristic product of protein degradation. It is a colorless gas with a pungent odor (Romain et al. 2008; Ko et al. 2015). It does not linger in the atmosphere for a very long time since it breaks down readily in water and evaporates quickly (Chen et al. 2003). Hydrogen sulfide is generated when sulfate is biologically reduced, producing a strong, "rotten egg" smell. It is toxic and poses a threat to landfill gas-to-energy equipment because it is corrosive (Fairweather & Barlaz, 1998). Hydrogen sulfide is often associated with construction and demolition debris (C&D), as well as with recovered screen material (RSM) from screening mixed C&D, since biodegradation of gypsum drywall, a primary component of C&D debris, is identified as a major cause of hydrogen sulfide production (Yang et al. 2006).

A study by Cooper et al. (2011) measured concentrations of hydrogen sulfide in the ambient air at several locations around a C&D landfill located in Central Florida. Measured concentrations were used to estimate hydrogen sulfide emission rates that were used to model H_2S odor buffer distances (marked as "red", "yellow" and "green" zones). The model used in the study was the American Meteorological Society/Environmental

Protection Agency Model (AERMOD). Model inputs require relevant meteorological conditions such as: wind direction, wind speed and stability class. To be relevant to hydrogen sulfide odor issues at other landfill facilities, local meteorological patterns, at least a one-year of hourly meteorological data, and multiple visits to measure in-situ H_2S emission rates are necessary (Cooper et al. 2011).

The level at which odors are first detected by the human nose is called the odor detection threshold (ODT), and it varies from person to person. A selection of trace odorants commonly detected in LFG is presented in Table 4. Hydrogen sulfide odors can be detected at relatively low levels in the air (0.00075-0.0015 mg/m^3), well below the limit that would pose a threat to human health of 30 mg/m^3 by the Occupational Safety and Health Administration (OSHA) and 15 mg/m^3 by the National Institute for Occupational Safety and Health (NIOSH) (ATSDR, 2017). Odor thresholds for hydrogen sulfide and ammonia, as well as different odor character categories typically observed around landfills, are also presented in Tables 4 and 5.

Table 4. Odor Detection Threshold of Selected LFG Odor Causing Compounds (McKendry et al. 2002)

Odor Compound	**Reported Concentration in LFG *(mg/m³)***	**Reported OTD Range *(mg/m³)***
Butanoic Acid	0.1 – 210	0.0000029 – 9
Butyl Mercaptan	0.01 – 16.1	0.006 – 12
Diethly Disulfide	0.1 – 1.0	0.0003 – 0.02
Dimethly Disulfide	0.02 – 40	0.00023 – 12
Dimethyl Sulfide	0.02 – 135	0.00033 – 0.6
Ethyl Mercaptan	0.1 – 120	0.00025 – 0.001
Methyl Mercaptan	0.005 – 430	0.0000003 – 0.02
Ethyl Butanoate	0.1 – 350	0.00003 – 0.28
Hydrogen Sulfide	0.0005 – 97,152	0.0001 – 2.8
Methyl Butanoate	0.2 – 125	0.0019 – 0.077
Propyl Mercaptan	0.05 – 2.1	0.0000025 – 0.00014
Xylene	0.0015 – 1100	0.0002 – 100

Table 5. Some of the Common Odor Causing Compounds in Landfill Gas (ATSDR, 2016)

Component	**Odor Description**	**Odor Threshold *(mg/m³)***
Hydrogen Sulfide	Strong rotten egg	0.00075 – 0.0015
Ammonia	Pungent acidic or suffocating	0.75- – 3.75
Benzene	Paint thinner-like	2.89
Dichloroethylene	Sweet, ether-like, slightly acrid	0.363
Dichloromethane	Sweet, chloroform-like	766.7 – 1148.18
Ethylbenzene	Aromatic, benzene-like	420.3 – 2802
Toluene	Aromatic, benzene-like	40.6 – 60.9
Tricholoroethylene	Sweet, chloroform-like	123.6
Tetrachloroethylene	Sweet, ether-like or chloroform-like	365
Vinyl chloride	Faintly sweet	27.5 – 55

Table 6 lists the common odor categories used in describing landfill odors. Category "Trash" is a mixture of smells, since it cannot be described with only one type of smell (sweet, sour, etc.) and be placed to any of the given character categories.

Table 6. Odor Character Categories (Curren, 2012)

Odor Character Category	**Common Descriptors**
Non-descriptive	Trash
Sulfur/Cabbage/Garlic	Rotten egg, natural gas, skunk
Rancid	Sour, dirty diaper, sweet-sour
Fecal/Sewery	Feces, manure, sewage
Fragrant/Fruity	Perfume
Solvent/Hydrocarbon	Chemical
Burnt	Burnt rubber, exhaust, burnt trash
Putrid/Dead Animal	Dead animal
Earthy/Musty/Grassy	Musty, decaying vegetation
Sweet	Sweet trash
Fishy/Ammonia	Ammonia

Another useful tool in helping personnel to categorize odors is an odor wheel (Curren, 2012). The main idea of an odor wheel is to describe more specific odors, and not just broad categories, such as “putrid” or “sweet.” Once categorized by the description of the smell, odors can be further categorized by the strength of odor, on a scale from 0-5 or “undetectable to unbearable,” or recognize if there is a presence of multiple odors at the site (Mendrey, 2014). One example of modified odor wheel for landfills is presented in Figure 3.

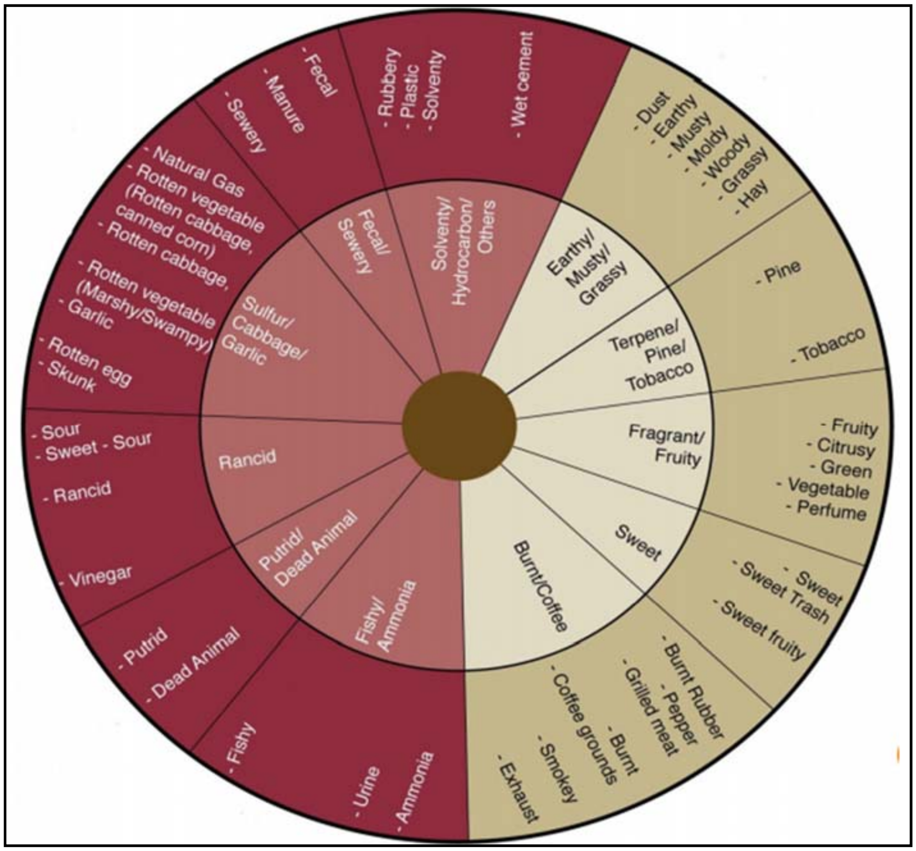


Figure 3. Example of a Landfill Odor Wheel (Curren, 2012)

Odors generated at solid waste facilities do not necessarily pose a risk for human health, but they create a nuisance for people living or working near a facility, which could lead to odor complaints (ATSDR, 2016) and troubled relationships between the public and landfill management.

1.3 Meteorological Factors Affecting the Odor Emissions

One of the main factors influencing the dispersion of odors off-site, while increasing their potential of becoming an odor annoyance to people living and working near the landfill site, are the meteorological conditions which have highly localized variability. Even if solid waste managers are doing everything in their power to operate in the best manner to reduce the odor emissions, they cannot control the weather and its impact.

A relation between some types of meteorological conditions and odor complaints at solid waste facilities has been noticed (Blumberg et al., 2001; Capelli et al., 2008; Epstein, 2011). Odor complaints tend to occur with no or very weak wind, high humidity, cloudy skies, and in situations where thermal inversions occur (Epstein, 2011). Inversions tend to trap odors and keep them closer to the ground (Epstein, 2011). These conditions mostly appear early in the morning since there is a higher possibility for stable atmospheric conditions, when there is less mixing of the atmosphere (Energy and Environmental Affairs, 2017). During unstable weather conditions, such as windy days, clear skies and high solar radiation, the atmosphere mixes more, and odor complaint frequency tends to be lower (Epstein, 2011; Energy and Environmental Affairs, 2017). With an increase in temperature, particularly early in the morning, odors are more likely to migrate off-site, since higher temperature stimulates faster molecular movement and hence odor diffusion (Epstein, 2011). Even though high temperatures in summer months stimulate increasing strength of nuisance odors, odor emissions have a tendency to disperse more quickly due to successive events of unstable weather conditions. In contrast, during winter months, odor emissions are less due to low temperatures as well as lower odor dispersion that is affected by more frequent stable atmospheric conditions (Sattler & Devanathan, 2007).

High humidity, like high temperature, also influences the strength of odors (Che et al. 2013) because humid air is able to trap odors, which allows them to linger longer. Also, with higher humidity, our sense of smell becomes more enhanced since the humid air brings aqueous odor molecules directly to our nose receptors (Kuehn et al. 2008). Similarly, pressure seems to have a noticeable effect as well. Low pressure days are associated with rain and cloudy skies (Thompson, 2016)). When the vapor pressure inside the landfill body is higher than in the ambient air, more landfill gas will escape. The reason for that is that vapors attempt to equilibrate with atmospheric pressure by migrating from regions of high pressure to low pressure (Wenjing et al. 2015). Precipitation also has a strong impact on both the strength of odors and also how quickly they dissipate. The rate of decomposition of the waste is affected by the amount of moisture available, which results in higher gas production rates (ATSDR, 2017). Rainfall and moisture that collects in the pore spaces in the landfill body force gases to migrate out of the landfill to the ambient air. Conversely, surface soil or cover material that is wet can inhibit the escape of odor gases from the landfill body (ATSDR, 2001). A summary of meteorological conditions and their impact on odors is presented in Table 7.

Table 7. Meteorological Conditions and Expected Impact on Odors

Factor	**Conditions**	**Impact**	**Reference**
Wind speed and direction	• Weak wind, stable conditions • Clear, strong wind, low variability in wind direction	• Highest odor detection • Significantly lower odor detection	(Capelli et al., 2008; Air Quality Management District, 2009; SCS Engineers, 2009; Baltrėnas et al. 2012)
Temperature	High	• Higher odor detection • Unstable conditions	(USEPA 2000; Sattler, 2007; Golder Associates Inc., 2010)
Precipitation	High	• Wet soil prevents LFG migration • Rain seepage into the pore spaces pushes out gases into the atmosphere	(Sadowska- Rociek et al. 2009; Golder Associates Inc., 2010; ATSDR, 2017)
Humidity	High or foggy	• Higher odor detection • Warm humid air enhances human sense of smell • Traps smells so they linger longer	(Berglund, 1998; Kuehn et al. 2008; Golder Associates Inc., 2010; Che et al. 2013)
Weather conditions	• Clear sky, sunny and windy • Overcast, no wind, high humidity/fog, thermal inversions	• Complaints rarely received • Complaints are more common	(MassDEP, 2007; Air Quality Management District, 2009; Golder Associates Inc., 2010; Epstein, 2011)
Thermal inversions	Season changes (Fall → Winter, Winter→Spring)	During the period of the year in which inversions are more common, odors are held more closely to the ground and are more likely to be detected	(NSWMA, 2008; SCS Engineers, 2009; Golder Associates Inc., 2010; Epstein, 2011; Energy and Environmental Affairs, 2016;)
Pressure	Low	More LFG seeps into the air	(USEPA, 2000; Golder Associates Inc., 2010; Thompson, 2016)

In terms of meteorological factors, investigators have most frequently attempted to correlate wind speed and direction directly to the dispersion of odor emissions and to the locations where citizen odor complaints are received from (Gallego et al. 2008; Sadowska-Rociek et al. 2009; Sakawi et al.2011; Baltrėnas et al. 2012). Baltrėnas et al. (2012) took samples downwind, upwind, and crosswind, from different distances to the site in Lithuania, where the prevailing winds were south and northwest. Odor concentration is expressed in European odor units per cubic meter of air (OUE/m^3). It represents the number of dilutions necessary to make the sample concentration equivalent to the concentration of smell (Baltrėnas et al. 2012). Results showed that wind direction and wind speed were major factors influencing the dispersion of odors and the increase in the detection concentrations. Higher odor concentrations were noticed when there was a favorable wind direction (SW), compared to lower odor concentrations when not downwind (NE). When winds were 9 m/s from the southwest, the measured odor concentrations were 51 and 61 OUE/m^3 (sampling points 1 and 2), while when the winds were recorded out of the northwest at 2 m/s, the highest measured concentration was nearly 9 times lower at 7 OUE/m^3 (sampling point 4). In France and Poland (Sadowska-Rociek et al. 2009), an odor survey attempted to correlate the following meteorological conditions to odorant concentrations: air temperature, wind speed, wind direction, atmospheric pressure, precipitation and humidity. However, the results obtained from the landfill site in France did not show a significant correlation between odorant concentrations and atmospheric conditions due to the small amount of data collected. To test the exterior factors that impact the increase in odor concentrations, a longer study period was performed. It was observed that concentrations of tested odorants were highly influenced by the wind speed and pressure. On days where the wind speed was strong (>25 mph), odor concentrations had a tendency to decrease, while pressure drop caused an increase in the concentrations. With higher pressure (>980 hPa), the concentrations were very low (<100 μg/m^3), as shown in Figure 4. Also, the impact of precipitation was observed on the VOC concentrations in the atmosphere. Events corresponding to precipitation or high humidity frequently resulted in a decrease in VOC concentrations. Generally, concentrations of odor causing compounds decreased on rainy days with strong winds (Sadowska-Rociek et al. 2009).

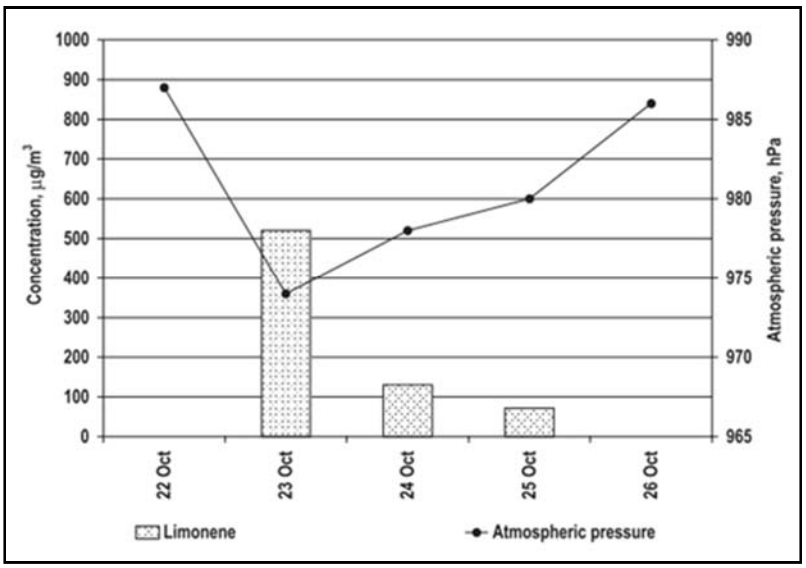


Figure 4. Concentration of Limonene Affected by Atmospheric Pressure (Sadowska-Rociek et al. 2009)

1.4 Odor Complaints

Citizen odor complaints are more frequent in urban areas where people are living and working in close vicinity to solid waste facilities (Southamton, 2013; EPA, 2017). Due to zoning, there are usually other industrial facilities operating close to each other, such that it can be difficult to accurately identify the origin of odors and the responsible party for generating the odor complaints off-site (Sarkar et al. 2003). Solid waste facilities use odor complaint logs to evaluate their operational performance with regard to nuisance odor emissions. However, odor complaints by themselves cannot be used as a measure to prevent odor emissions since they do not provide true objective, quantitative data on how to minimize the odors nor do they provide any insight on odor migration mechanisms or possible causes. The reason for that is because odor complaint logs often lack valuable information that could potentially lead to better understanding of site-specific characteristics (McKendry et al. 2002; Air Quality Management District, 2009; SCS Engineers, 2009; Golder Associates Inc., 2010). They can be vague, uncertain and inconsistent with the information given. As an example, there is a difference between the exact time when the odor was observed compared to the time when the complaint was filed. Not knowing the exact time of the odor occurrence limits the possibility of cross-comparison with meteorological conditions and site activities to accurately identify the source of odor (McKendry et al. 2002).

Feedback from people living close to a landfill site about the landfill operations, including odors, should be managed effectively, since that is a crucial part of successful management of waste operations (McKendry et al. 2002). Standard ways that citizens submit odor complaints are to the local authorities, regulatory agencies, or directly to the facility. Procedures for odor complaints at a site usually consist of a 24 hour per day open phone line that goes to an answering service that takes basic information, such as the nature of the event, contact information, when the event started, the time of the call, etc. The call is then forwarded to the responsible site personnel for a follow-up call the next day and courtesy visit to check on the validity of the odor complaint. During the courtesy visit, the trained representative performs an odor survey to verify the odor complaint and suggest corrective action, if warranted. However, what to sample for remains elusive.

When correlating information obtained from complaint logs with the actual observations made by solid waste management personnel from the site, at the time of the odor complaint, odor mitigation strategies can be developed to reduce nuisance odor emissions (McKendry et al. 2002; Golder Associates Inc., 2010). Furthermore, a weather station can be installed at the landfill site, which provides real-time information on local meteorological conditions (SCS Engineers, 2009). Correlation of meteorological conditions with respect to locations from which odor annoyances are occurring could help in identifying odor sources at the site. Once the source of odor is known, proper monitoring and management of solid waste operations can be implemented with the aim of reducing dispersion to residential areas. For example, by knowing the wind direction, waste can be disposed to an alternate working face, since an odor event will impact residential areas only if favorable wind conditions exist. If the direction of the wind is not towards the working face, or if the wind speed is too strong or too weak, there will be no impact and thus no change needed to landfill operations (McKendry et al. 2002).

Sakawi et al. (2011) used information on odor perception from 190 surveys collected within a 2 km (1.24 miles) radius of a landfill fence in Malaysia. The results showed that 55% of those surveyed have made at least one official complaint to landfill personnel regarding nuisance odors. Those that did not complain, either did not know where to make the complaint, did not care about the odors, or thought that somebody else would file the complaint such that they did not have to. Based on the time of day, the highest detection of odors was at night with 31%, followed by 28.4% which stated that they could detect the odors throughout the whole day. When taking the weather conditions (such as wind direction, wind speed, temperature and humidity) into consideration, 92.6% of respondents stated that they believed that the nuisance odors close to their homes were associated with the weather. Factors such as wind, rainfall and high temperature were identified by 40.6% of respondents as being likely responsible for higher nuisance and odor detection. The most important influence was recognized as wind direction with 30.5%, followed by rainfall with 22.6% and hot/dry weather with 6.3% (Figure 5).

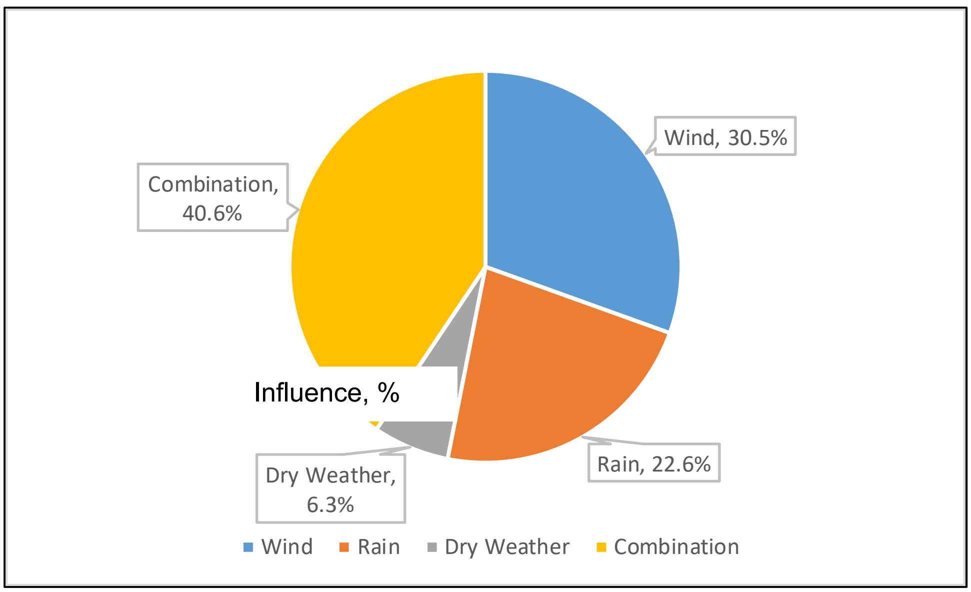


Figure 5. Weather Conditions Influence on Odor Detection for a Landfill in Malaysia (Sakawi et al. 2011)

Also, the location of where the odors were initially detected was also asked as part of the survey. The choices were: 1) inside of the house, 2) just outside of the house, and 3) outdoors (such as park, roads, etc.). The worst odors were detected just outside of the house with 50.5%. Based on the odor intensity (range from 1-4, where 4 is a strong odor and 1 is barely detectable), 74.2% detected strong odor, presented in Figure 6 (Sakawi et al. 2011).

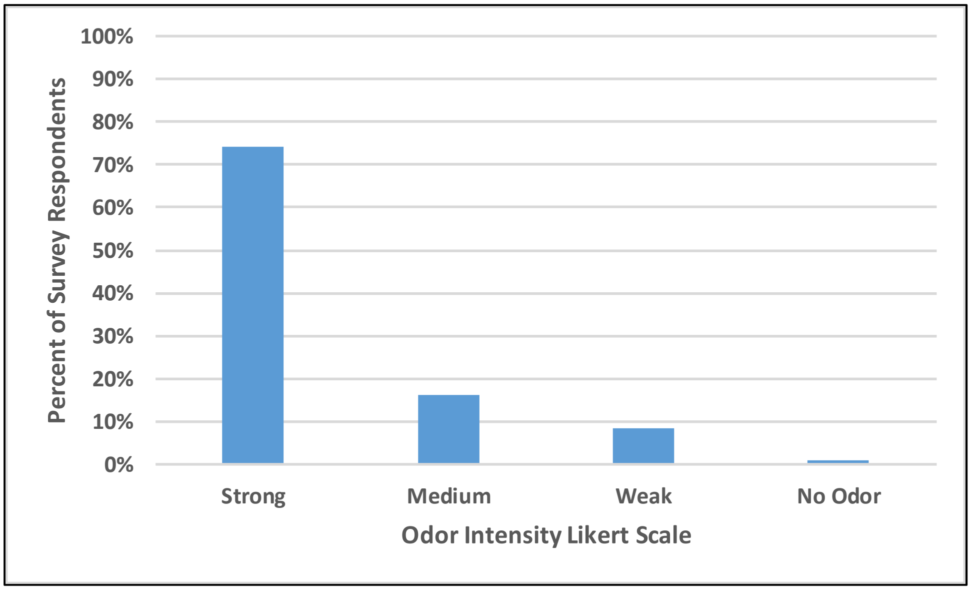


Figure 6. Odor Intensity Recognized by the Respondents Near a Landfill in Malaysia (Sakawi et al. 2011)

Chemel et al. (2011), in France, used odor complaints data coupled with meteorological conditions to identify which weather conditions can be expected to correlate with nuisance odors. The ARW (Advanced Research Core of the Weather Research and Forecasting (WRF) model meteorological model was used, for both winter and summer season variations, to forecast the scenarios that could cause an increase in the number of odor complaints by the communities located in close proximity to the landfill. Meteorological data (for the period from 2002-2004) on pressure, temperature, humidity, wind speed, wind direction and precipitation was collected from the weather station located at the landfill site. For the same time period, odor complaint data (which included the date, location and duration of the odor nuisance) was acquired (n = 71) from within a 5 km (3.10 miles) radius around the landfill site. The results showed that two types of weather conditions, moderately stable and unstable, triggered the majority of odor complaints, with more than 15 complaints per 100 days, while other conditions generated less than 7 complaints per 100 days. Wind speed and precipitation were the most descriptive meteorological parameters since precipitation rinses the atmosphere thereby reducing odor concentrations, while wind speed dictates the direction in which odors will be dispersed (Table 8). With little or no wind, odors tend to be retained longer resulting in higher localized concentrations. The study determined that clear skies and unstable weather conditions contribute the most to odor annoyances; however, the complexity of local terrain should also be considered, since it can affect the meteorological conditions (Chemel et al. 2012).

Table 8. Description of Weather Classes Related to Number of Odor Complaints for a Study Conducted in France (Chemel et al. 2012)

Regional Atmospheric Stability	Risk of Precipitation	Wind Speed/ Direction		Number of Days	Number of Complaints (*)	Complaints per 100 Days
		>1500 hPa	<1500 hPa			
Moderately stable	Very low	Very low /NA	Very low /NA	121	19 (2)	15.7
Unstable	Very low	Very low /NA	Very low /NA	89	14 (1)	15.7
Neutral	Low	Very low /NA	Very low /NA	182	12 (7)	6.6
Very stable	Low	Very low /NA	Very low /NA	113	7 (2)	6.2
Very stable	Moderate	Moderate /N	Moderate /S	105	5 (0)	4.8
Moderately stable	Moderate	Moderate /E	Moderate /NW	77	3 (2)	3.9
Moderately stable	High	Strong /N	Low /NA	104	4 (2)	3.8
Moderately stable	High	Moderate /S-SE	Moderate /N-NW	82	3 (1)	3.7
Moderately stable	Moderate	Moderate /S	Low /NA	72	2 (0)	2.8
Moderately stable	Moderate	Strong /E	Low /NA	81	2 (0)	2.5
Very stable	Moderate	Low /N	Low /NA	44	0 (0)	0.0

(*) The number of complaints that were identified as being related to waste operations (e.g. opening of a new cell) is indicated in parenthesis.

Che et al. (2013), in China, conducted an analysis of meteorological conditions at different distances from a landfill site with the aim of identifying scenarios that lead to more odor complaints from nearby neighborhoods. Meteorological data was collected for the calendar year of 2011, and the surrounding population was surveyed (n = 845 responses). The results showed that 87.4% of respondents that made odor complaints, claimed that the strongest odors tend to occur mostly during summer, while other seasons had substantially lower percentages (spring 5.96%, autumn 4.04%, and winter 2.55%). The average number of odor annoyances in the summer period was 11. Summer peak complaints were attributed to impacts of high temperature, humidity and pressure. In the study area, high temperatures, for summer month of July, were in the range from 31°C to 37°C (88°F-99°F), and humidity was in the range of 60-75% due to subtropical high pressure. Generally, those meteorological conditions with low pressure and high temperature and humidity, tend to coincide with an increase in odor emissions (Capelli et al. 2008). Also, it was observed that the winds from the east and southeast were directly correlated to the highest incidence rate of odor complaints. Correlation between the distance from the landfill and the number of odor complaints showed that as the distance from the landfill site increases, the odor complaints decrease since odors cannot be detected in the same concentrations as in close proximity to the landfill (P=100% of respondents living within 1.86 miles from the landfill noticed nuisance odors), as presented in Figure 7.

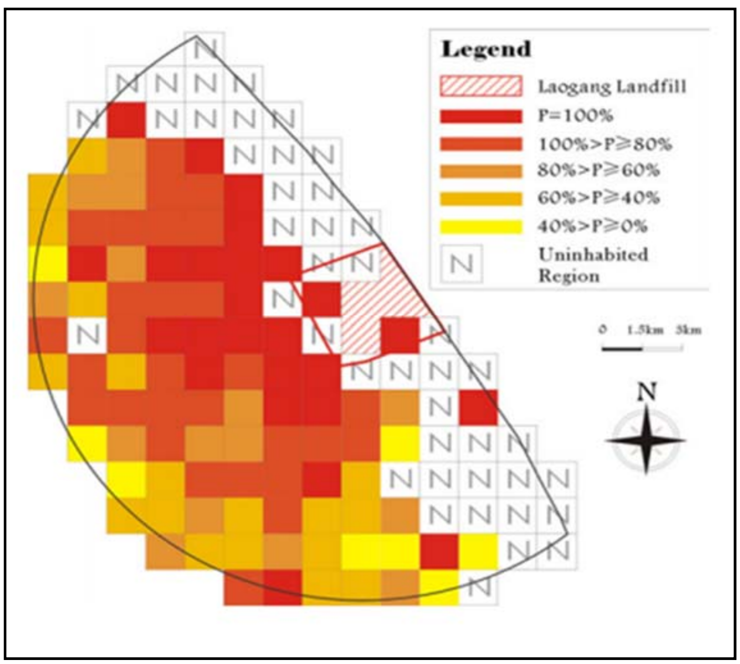


Figure 7. Proximity to the Laogang Landfill Site, in China, Related to Higher Frequency of Odor Events (Che et al. 2013)

Figure 8 shows that the majority of odor complaints was received from the communities surrounding the landfill that were directly downwind in the northwest quadrant (Che et al. 2013).

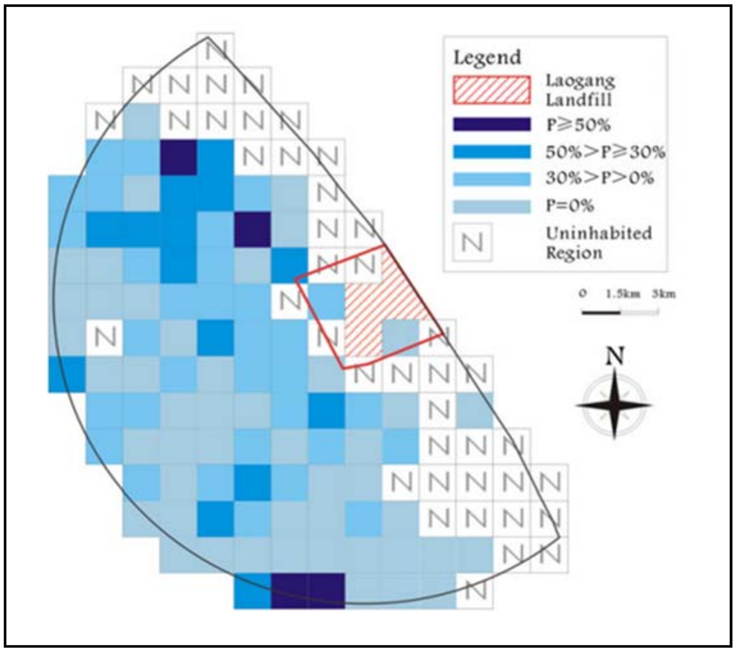


Figure 8. Spatial Distribution of Clusters of Odor Complaints from the Laogang Landfill Site, in China (Che et al. 2013)

1.5 Odor Detection Techniques

Proper characterization and measurement of odors are crucial components of detection. Some of the challenges in odor detection are related to the chemical complexity of odorous gas emissions and the subjective character of human sense of smell in odor perception (Lebrereo et al. 2011). The most common techniques for odor detection are: 1) dynamic dilution olfactometry, 2) chemical analyses, and 3) electronic nose technology (Capelli et al. 2013).

Odor detection techniques are mainly focused on sensory analysis where the human olfactory sense has the ability to detect the existence of some odor causing compounds in the ambient air. The reason for that lies in the fact that many of the chemical detectors are not as responsive for the odor causing compounds when compared to the human nose (Van Ruth, 2001). Odors recognized by a human's sense of smell can serve as an early warning signal of gas emissions from a landfill site. The most common approach for measuring odor concentrations is dynamic dilution olfactometry based on the human perception of smell. In this method, a trained panel of odor experts is exposed to a sample of odorous air in different dilutions to determine the threshold of the odorous emissions (St. Croix Sensory, 2005). In the beginning, the degree of dilution is very high, such that most of the trained panelists will not observe the odor. Then, the sample is diluted less and less, and this process continues until all the panelists perceive the odor and confirm that they smell it (Baltrėnas et al. 2012). Since human responses to odor can be subjective and vary among individuals, multiple panelists with tested sensitivities within a controlled range are required to reduce the uncertainties. In practice, a team of panelists is reduced to just two, and sometimes to only one (Nicolas et al. 2006).

Chemical analyses, on the contrary, are more objective, precise and repeatable in quantifying specific odorants (Lebrero et al. 2011). Techniques such as gas chromatography coupled with various detectors or mass spectrometry (GC/MS), are used for the characterization of the chemical composition of odorous gas samples (Smet et al. 1999). As an analytical measurement, GC/MS allows detection of odor causing compounds with low odor thresholds that can be categorized as a source of nuisance odors. Even though results can show a wide range of compounds present in a sample, analytical methods for every single odorant are not developed as yet, and the method cannot provide information on how certain odorants are actually perceived by the human sense of smell. Also, it cannot be directly correlated with an odor characterization (Göpel, 1998).

Dincer et al. (2006), in Turkey, investigated the composition of odorous gasses generated at a landfill site using GC/MS. Detected VOCs were sulfur/nitrogen compounds, monoaromatics, aldehydes, esters, halogenated compounds, ketones, and volatile fatty acids. The highest concentrations identified were monoaromatics (47.4 μg/m^3) and halogenated compounds (62.9 μg/m^3). Two sampling periods were selected, May and September, to represent the beginning and end of the hot and dry season (in Turkey), with five sampling points. In both periods, the total VOC concentrations were very similar except for sampling point five (Figure 9). The reason for that was ongoing waste burial in May, while the site was covered with soil during September.

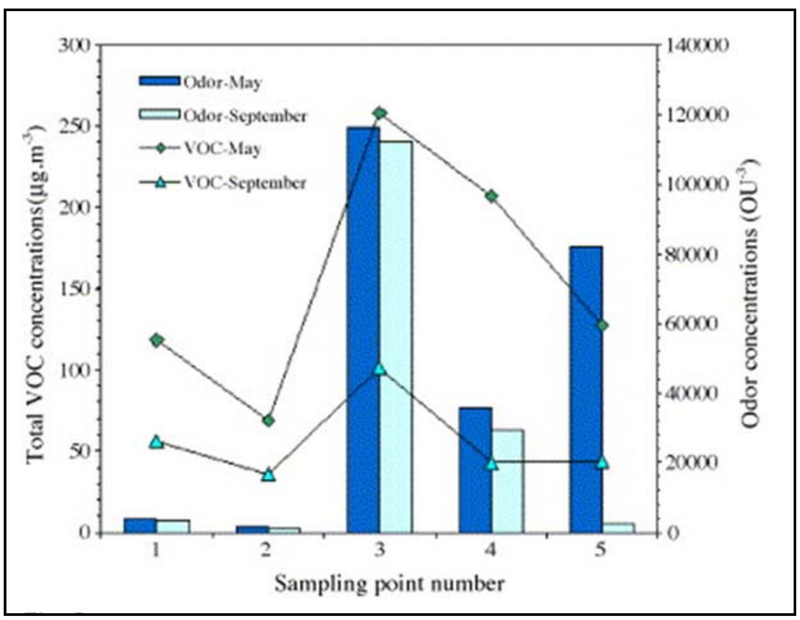


Figure 9. Relationship between Odors and Total VOCs Concentrations, in May and September, at Landfill Site in Turkey (Dincer et al. 2006)

Statistical analyses were performed to determine a correlation between chemical concentration and odors (Table 9), with the most correlated groups highlighted in bold. A step-wise multiple regression identified aldehydes, ketones and total VOCs, as the best estimators of variability in odor concentrations, with $r^2 = 0.96$ (n=10, P<0.01) (Dincer et al. 2006).

Table 9. Pearson Correlation Coefficients between the Different Compound Groups and Odor (n = 10), Study in Turkey (Dincer et al. 2006)

	Odor	**Total VOCs**	**Acids**	**Aldehydes**	**Esters**	**Halogenated compounds**	**Mono aromatics**	**Ketones**	**S and N compounds**
Odor	1	**0.64***	0.23	**0.91***	0.52	−0.10	0.55	**0.73***	0.41
Total VOCs		1	0.63	0.76*	0.87*	0.23	0.93*	0.88*	0.02
Acids			1	0.21	0.61	−0.18	0.69*	0.37	−0.33
Aldehydes				1	0.58	−0.04	0.66*	0.91*	0.53
Esters					1	0.02	0.94*	0.79*	−0.30
Halogenated compounds						1	−0.03	−0.02	−0.03
Mono aromatics							1	0.83*	−0.18
Ketones								1	0.29
S and N compounds									1

*Statistically Significant (P<0.05)

While measuring odors by using a trained panel followed by GC/MS is valuable, it also requires a lot of time and resources, which is why these types of measurements are rarely carried out in practice (Nagle et al. 1998). A more rapid way of monitoring odors, in the field over different time periods, is performed using an electronic nose, which is a sensor array capable of mimicking the behavior of the human olfactory system to identify and distinguish between different odor causing compounds, gases and vapors (Bhandare et al. 2013) The key components of an electronic nose are: 1) the observing system, which detects the odors, and 2) the pattern identification system, which uses a set of electronic elements to interpret the signal. The electronic nose can be used to identify odorants, determine their concentrations, and characterize the odor perception (Keller et al. 1995).

Using coffee for example, the human sense of smell detects the whole chemical composition as "coffee," while electronic noses detect the coffee as a mixture of multiple chemicals acting together to produce the odor of coffee (Blesson et al. 2013). Unfortunately, the system must be calibrated to laboratory olfactometry measurements, which are again limited by human subjectivity.

Capelli et al. (2008) considered the use of different odor detection techniques including chemical analysis, dynamic olfactometry and electronic noses, in estimating the odor emissions migrating off-site from a solid waste facility in Italy. Also, the techniques were compared to see if a correlation could be demonstrated. Four seasonal periods of monitoring were used: winter, spring, summer and fall. Examined pollutant compounds found at the waste grinder are linked to theoretical odor concentration values. Results showed that chemical analysis by GC/MS can be a useful tool for identifying chemical composition of odorous sample while there was no obvious correlation between the results obtained by chemical analysis and olfactometric analysis (Figure 10). The reason for that lies in the fact that the human sense of smell cannot distinguish all of the components present in the odorous sample and instead detects them as a whole, which results in a high level of inaccuracy.

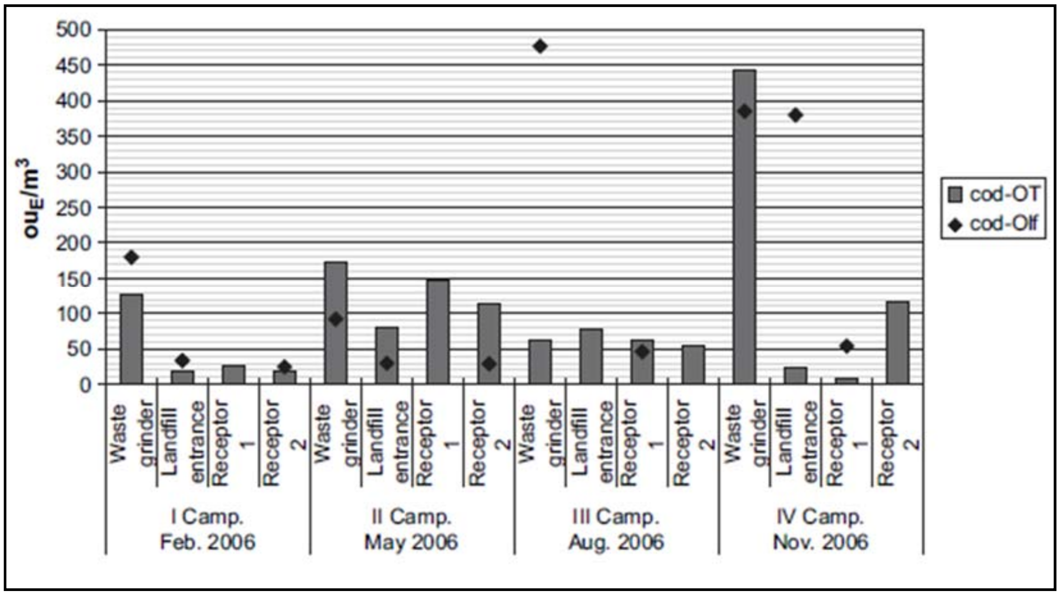


Figure 10. Comparison between c_{od} Values Measured by Olfactometry Analysis and Theoretical Odor Concentration Values, Landfill Site in Italy (Capelli et al. 2008)

Ambient air monitoring with the electronic nose showed the time percentages in which the instrument perceived presence of odors from the landfill (Figure 11). Analysis of meteorological conditions showed that higher odor detection was noticeable during unstable weather conditions, such as weak wind with unstable direction, while during the clear presence of a predominant wind direction, odor detection at the same locations was notably lower. Study revealed that even though three different types of techniques for odor identification do not necessary correlate, each of them have intrinsic value while also demonstrating the complexity of odor monitoring (Capelli et al. 2008).

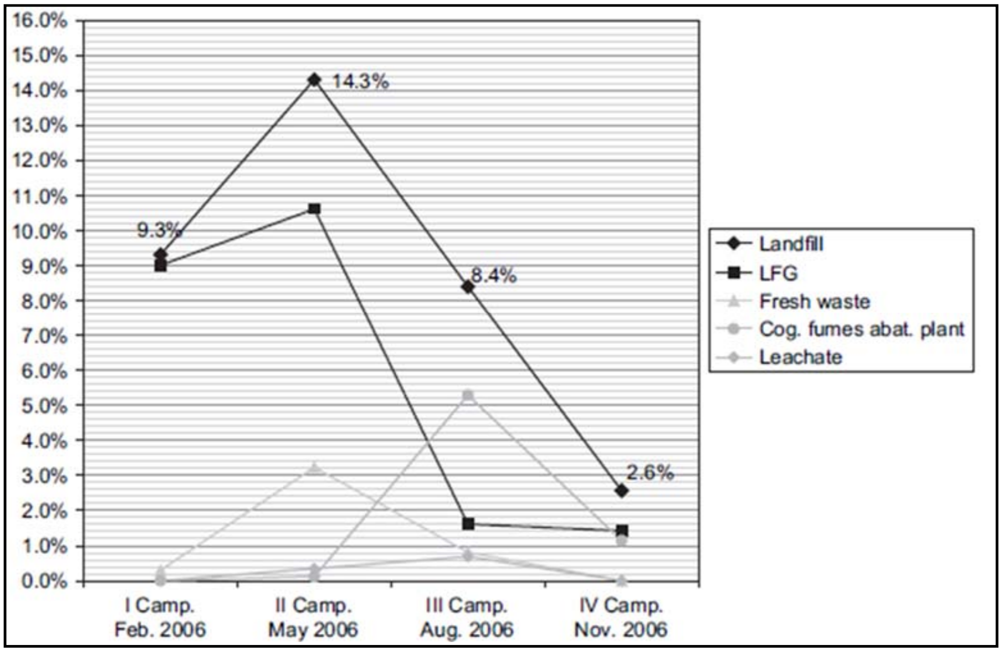


Figure 11. Recognition of Different Olfactory Classes by Electronic Nose at Receptor 1 (Capelli et al. 2008)

This study showed how monitoring of meteorological conditions can be a very useful tool to assess the odor gas emissions transmitted from the landfill site to the close by neighborhoods in order to propose potentially better operation practices. However, each of the techniques used for odor detection were implemented at the same site while obtaining vastly different results. A summary of advantages and disadvantages for each of the major odor detection techniques in presented in Table 10.

Table 10. Advantages and Disadvantages of Various Odor Detection Techniques

Technique	Type	Method	Advantages	Disadvantages	Reference
Chemical Analysis	Analytical	GC/MS	• Detection of pollutants with low odor detection • Useful to analyze odor composition • More objective, repeatable and accurate	• Difficulty in relating the chemical composition of an odor mixture to its olfactory properties • Little information about the odorant real impact on human receptors	• Capelli et al. 2008 • Bratolli et al. 2011 • Lebrero et al. 2011 • Capelli et al. 2013 • Capelli, et al. 2014
Dynamic Olfactometry	Sensorial	Human nose as a sensor	• Most common approach • Determine the odor concentrations	• Subjective • Expensive ($224-$336 per measurement) • Time consuming	• Capelli et al. 2008; • Lebrero et al. 2011 • Baltrėnas et al. 2012 • Gutiérrez et al. 2015 • Deshmukh et al. 2017
Electronic Noses	Senso-Instrumental	Artificial noses, which can distinguish between different odors Single odorants, such as H_2S and NH_3, have been commonly used as surrogate markers	• Make assumptions about the landfill odor impact on the points where instruments are installed; • Useful management tool (for both laboratory and on field purpose)	• Dependent upon operational choices • Only partial characterization of odor emissions • Problems with reliability and sensitivity, especially to temperature and humidity	• Capelli et al. 2008; • Lebrero et al. 2011; • Capelli et al. 2013; • Capelli et al. 2014 • Deshmukh et al. 2015 • Giungato et al. 2015 • Giungato et al. 2016 • Eusebio et al. 2016

1.6 Odor Control Technologies

Testing different sources at the site can provide information on concentrations and emission rates to determine the magnitude of an odor problem (Kehoe et al. 1996). This information could be useful for implementing proactive strategies to address migration of odors off-site. If, for example, forecasts of meteorological conditions conducive to odorant transport can be identified in advance, odor emissions can be minimized by altering landfill operations ahead of time (Strech et al. 2001). Once odorant and sources have been identified, the next step is implement an odor control strategy.

Some odor control technologies prevent odorant emissions from migrating outside of the landfill site and are key to good odor management and continued existence of a facility (Epstein, 2011). Some of the methods successful in minimizing landfill odors are: 1) cover management - placing a daily cover on recently unloaded waste while also reducing the odors from gases generated by bacterial decay; 2) flaring landfill gas - flaring thermally destroys odor causing compounds in the landfill gas; and 3) biofiltration - venting the landfill gas through a biological media filter, resulting in often less powerful and offensive odor causing compounds (ATSDR, 2001).

Process modification is another strategy that includes adjusting the solid waste operations in order to reduce the production of odorous compounds (Strech et al. 2001). Those can vary from simple changes in operations to extreme ones, such as (Strech et al. 2001; McKendry et al. 2002):

- use more than one working face accessible at any time depending on monitored meteorological conditions

- reduce the size of active working face
- increase the depth of cover material and/or replace the type of cover material on landfill surfaces
- avoid delivery of highly odorous wastes when the wind direction is unfavorable
- use route control to minimize the contact of waste handling vehicles with residential areas
- record all site activities on a daily basis for possible identification of specific activities that could lead to an odor annoyance

In cover management, soil cover is used daily to reduce the intensity of recently placed wastes (ATSDR, 2001). More substantial covers are implemented at landfill closure to minimize potential of moisture infiltrating the refuse, encouraging bacterial growth and further decomposition (ATSDR, 2001). A study by Anunsen (2007) tested three different types of landfill covers (red soil, wood mulch and compost) to reduce odors from LFG at smaller or older landfill sites. Results revealed that red soil could be successful in reducing concentrations of H_2S, with the capability to dilute H_2S at a LFG flow rate of 100 L per day per square meter with H_2S concentration of 40 ppm to 40 L per day per square meter with H_2S concentration of 10 ppm (Anunsen, 2007).

Flaring is a combustion technology used to destroy the compounds in landfill gas with a destruction efficiency greater than 98% (ATSDR, 2001; Caulton et al.2014). It is most efficient if the LFG is composed of at least 20% methane by volume to avoid supplemental fuel costs to operate the flares (ATSDR, 2001). In addition to producing methane and carbon dioxide, the anaerobic digestion process also generates H_2S and siloxanes. Siloxanes are large molecules that mainly consist of silicon and oxygen. Contaminants, as such, become a concern when they volatilize into the landfill gas and during flaring operations, microcrystalline silica can be created, which can damage gas engines, heat exchangers, etc. It is recommended to clean the LFG before combustion to avoid any operational, health and environmental issues (Ajhar et al. 2010). Efficiency of the process is greatly affected by operational conditions but also relies on other factors, such as: wind speed, gas heat content, and the absence of water or hydrocarbons in the gas flow (Cid-Vazquez et al. 2012).

Incineration is one of the most commonly used odor control technologies. Hydrocarbons are oxidized to carbon dioxide and water vapor while any noncombustible materials (glass, metals, etc.) remain as ash. In situations where odorants are flammable, this process efficiency has been reported as greater than 95% (Kehoe et al. 1996), potentially reducing the weight of waste up to 75% and volume up to 90%. However, there is also an environmental concern due to contaminant emissions released, such as dioxin and mercury (Dasgupta, 2015), which must be dealt with using additional air pollution control devices.

When the concentration of the odorants is raised and can potentially be recovered for reuse, adsorption such as activated carbon is a successful technology (Shareefdeen & Singh, 2005). The efficiency of the process is practically 100% for vapors with a high retentively value (Von Bergen, 2012). Also, the efficiency of the process decreases with time since the adsorbent binds more and more of the compound (Kehoe et al. 1996). For exhaust streams containing VOCs, biofiltration (Stanley & Muller, 2002) can be effective (>99.8%). This process includes the use of a bed of biologically activated material through which the exhaust stream is fed. The process has the ability to handle high (>200 ppm) concentrations of H_2S at lower velocities (12-54 fpm). There is low maintenance cost in media replacement since the lifetime is usually 3-5 years. Also, higher odor removal can be possible (efficiency in some of the cases can be >99.8%); however, it cannot remove all odor causing compounds (Stanley & Muller, 2002).

Odor masking introduces pleasant smelling compounds to counteract or cancel out the nuisance odor impact. Masking agents, such as organic compounds or derivatives from synthetic aromatic chemical manufacture (e.g. vanillin, methyl ionones, eugenols, benzyl acetate, phenylethyl, alcohol, heliotropin), are designed to imitate natural and pleasant odors that are not considered as offensive to the human sense of smell (Von Bergen, 2012). However, they do not lower the concentrations of odor causing compounds in landfill gas nor do they minimize the impact of odorants on human health. The process is greatly affected by geography and topography since the effectiveness of the technology decreases with distance of the complaint from the source of the odor (Kehoe et al. 1996). Application is simple and requires minimal capital investment; however, chemical replacement costs will add up. Masking agents should never be used to mask or cover up a toxic concentration of gas since it could be fatal to receptors who do not recognize the danger. Special care must be used when handling masking agents since spillage or contact on some part of the body can result in offensive odor concentrations and possible physical harm (Von Bergen, 2012). A summary of the available odor management technologies with advantages, disadvantages, removal efficiencies and costs are presented in Table 11.

Table 11. Summary of Characteristics of Common Odor Management Technologies (Sungthong et al. 2011; Bindra et al. 2015; Emam, 2015)

Technology	Advantages	Disadvantages	Efficiency (%)	Cost (Capital/ O&M)
Cover Management	• Best management practice • Helps reduce odors from newly deposited waste • Minimal O&M costs	• Not a removal process, only a barrier • Costs vary based on the type of material selected • Limited capacity	>99* 65** 30***	Low/ Low
Flaring	• Can be installed nearly anywhere even with poor LFG quality	• Generates noise and heat • Source of greenhouse gasses emissions • Fire/explosive hazard • Energy value of LFG is wasted	>98	High/ Moderate
Process Modification	• Decreases emissions of odor causing compounds at the source	• Limitations related to waste pick-up and drop-off handling due to traffic conditions • Unpredictable weather conditions • Insufficient land capacity • Increased management activities required	NA	Low/ Moderate
Biofiltration	• Simple technology • No chemicals required • Odor compounds transformed	• Large land area required • High energy demand • Water demand	>90%	Moderate/ Low
Incineration	• Excellent for VOCs • Good for concentrated air streams • Odor compounds are completely oxidized • Small footprint	• Requires air pollution control technologies for air toxics, SO_2 and NO_x emissions • High capital and O&M costs	>95%	Very High/ High

Technology	Advantages	Disadvantages	Efficiency (%)	Cost (Capital/ O&M)
Odor Masking	• Low capital costs • Efficient for intermittent or variable odor events • Small space requirements	• Odor is just masked, not destroyed • Agents can be perceived as nuisance odors • Multiple units needed to cover a large area	0%	None/ Moderate
Adsorption (Activated Carbon)	• No chemicals or pumps • Simple system and minimal O&M • Small space requirements	• Not effective for treating ammonia • Solid waste produced if spent media is not regenerated	99%	Moderate/ Low

*Sandy soil modified with 5% hydrated lime and fine concrete
**Clayey soil
***Sandy soil

Bortone et al. (2012) evaluated the impact of odor emissions from a landfill site on nearby workers and residents in order to propose management practices for control and minimization of odors dispersing off-site in Italy. Data on weather conditions on an hourly basis was collected and analyzed to see if any patterns in frequency of odor complaints emerged. Three different locations were investigated: 2690 feet (SC-1), 4265 feet (SC-2) and 4921 feet (SC-3) from the landfill site. Results showed that odor emissions do not reach the highly-populated neighborhood (SC-3) furthest from the landfill, while a different scenario occurred for the school (SC-2). From the results presented in the Table 4, it can be observed that the highest value of 3 OUE/m^3 occurred less often than in the closest sampling area to the landfill, yet the 98th percentile concentrations exceeded the 1.5 OUE/m^3 level 200 times, attributed to complex weather conditions and topography, since it has lower elevation than the source of the odor emissions. Also, it was observed that the highest number of exceedances of the 3 OUE/m^3 threshold (n = 73) was recorded for location SC-1, which is closest to the landfill site (Table 12).

Table 12. Thresholds Exceeded in Three Different Locations, Study in Italy (Bortone et al. 2012)

Site	Times 1.5 OUE/m^3 exceeded		Times 3.0 OUE/m^3 exceeded		98th percentile (OUE/m^3)
	n	%	*n*	%	
SC-1 (2690 ft)	183	2.09	73	0.83	1.71
SC-2 (4265 ft)	200	2.28	41	0.47	1.78
SC-3 (4921 ft)	76	0.87	0	0	0.70

Figure 12 shows the spread of odor intensity in relation to the three different monitored locations. The methodology developed in this study can be helpful in accomplishing successful control system, coupled with monitoring the weather conditions (Bortone et al.

2012). Some of the odor control methods proposed were: dealing with the waste disposal as fast as possible during the day, building the cells 13-16 feet high, covering the waste with a clay layer of 1.6 feet deep minimum, keeping the volume of the waste under pressure with a biofilter, and schedule the spraying of odor masking agents on the surface of the waste.

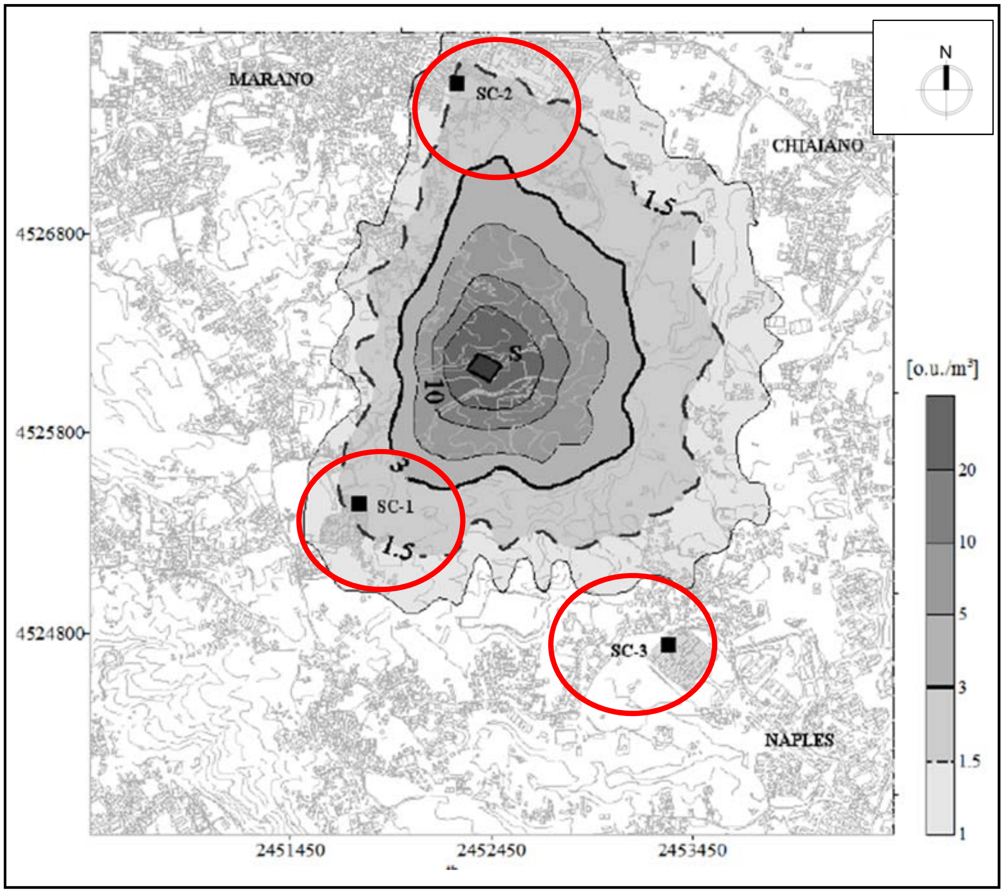


Figure 12.Spread of Odor Intensity Curves Representing More Intense Smell Perception (equals to 1.5 OUE/m^3 and 3.0 OUE/m^3), Study in Italy (Bortone et al. 2012)

1.7 Objective

The main goal of the proposed research is to investigate the influence of meteorological conditions on odor complaints from neighborhoods in close proximity to a landfill site, in order to determine the existence of patterns or trends, if any, that could lead to the development of effective odor mitigation strategies. To accomplish this goal, the study objective was to observe the impact of meteorological conditions of interest (temperature, humidity, wind direction, wind speed, pressure, precipitation, inversions, and weather stability class) on number of odor complaints.

2 METHODOLOGY

The strategy of this study was to target partner landfills located in an urban setting in South Florida. Two different landfill sites located in close proximity to residential communities were selected. Due to the confidentiality of the information provided on odor complaints, any identifying customer information was excluded, as were the identities of the two solid waste facilities participating in the study. From this point forward, the two sites will be referred to as: 1) Urban Site 1 and 2) Urban Site 2.

2.1 Site Description

The two urban landfills that participated in this study are described in further detail in the following sections.

2.1.1 Urban Site 1

Urban Site 1 is located in an area with flat terrain with highest elevation of 36 feet and a tropical climate with dry winters. Variations in temperature are typically from 59°F to 89°F throughout the year, while temperatures below 46°F and above 92°F rarely occur. Warmer periods (> 89°F) last from June to September, while the cooler period (< 77°F) occurs from December to March, as observed in Figure 13. Cloudiness varies throughout the year and is affected by seasonal changes. The period with the clearest days occurs from October to May, while more cloudy conditions are prevalent during the summer months. From May until October is the wet season, as well as the windiest part of the year, with average wind speeds of more than 5 miles per hour, and the predominant wind directions are south and east.

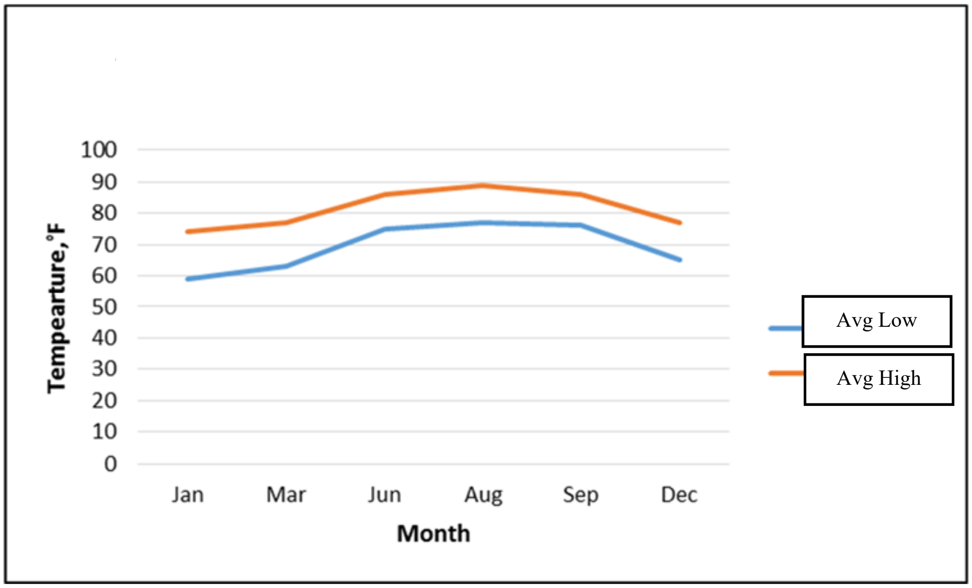


Figure 13. The Daily Average High and Low Temperature for each Month from 01/01/1980-12/31/2016: Urban Site 1(Weather Underground)

2.1.2 Urban Site 2

The location of Urban Site 2 is also situated in an area with flat terrain and a tropical climate with dry winters. For this site, the highest changes in elevation are 13 feet, and the warm period (> 86°F) is from June until October, while the cool period (< 78°F) is from December until March (Figure 14). The wet and dry season are in the same time frame as Urban Site 1- from May to October, and from November to May, respectively. The cloudier period of the year is also during summer months, with average daily wind speed of 5.3 miles per hour. The predominant wind direction in this area, on average, is east.

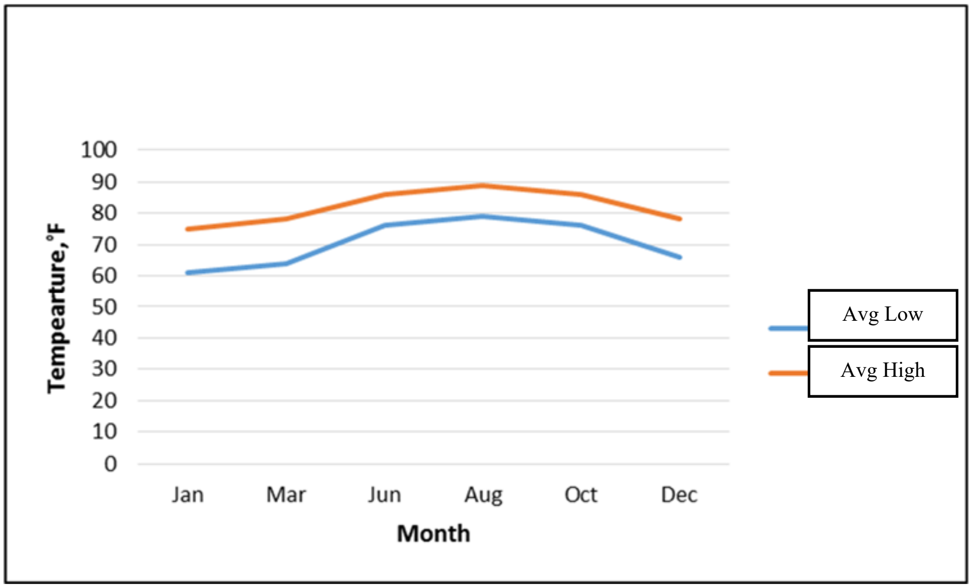


Figure 14. The Daily Average High and Low Temperature for each Month from 01/01/1980- 12/31/2016: Urban Site 2 (Weather Underground)

With the historical growth of the population in both areas (Urban Site 1 = 2% / year and Urban Site 2 = 1% / year), and the lack of enough free land space, residential communities are being built in close proximity to existing landfill sites (Public Data, 2017).

Locations of the nearby residential communities surrounding Urban Site 1 and Urban Site 2, as well as the distances from the sites, are illustrated in Figure 15.

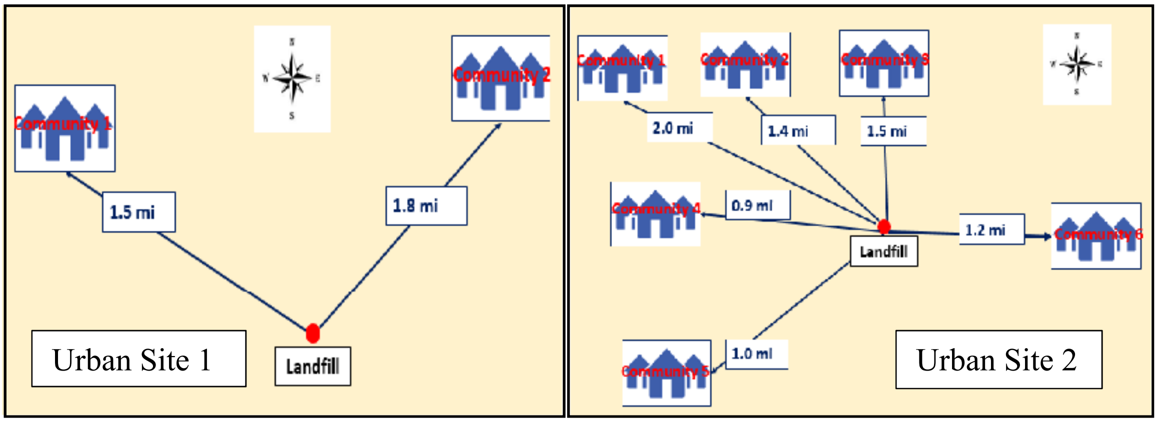


Figure 15. Approximate Locations of Nearby Communities Surrounding Urban Site 1 and Urban Site 2

2.2 Data Collection

Several solid waste facilities located in the urban setting were contacted to gather data on citizen odor complaints. Due to the sensitivity of the information involved, only two landfill sites willingly agreed to participate in the study and provide the data they have on received complaints. Since Urban Site 1 had an existing weather station (code name: KFLWESTP21), real-time access to their weather station was available to provide information on local meteorological conditions, such as: temperature, dew point, wind speed, wind gust, wind direction, precipitation accumulation, and pressure. It was necessary to select the time frame in order to collect the data of interest (Figure 16). Since the wireless real-time weather station at Urban Site 1 was installed in 2008, it could not provide information prior to 2008. Therefore, for the previous years (2005-2007), the next closest weather station at the Weather Underground web site was selected to obtain the necessary data (Weather Underground: Weather Forecasts and Report, 2017)

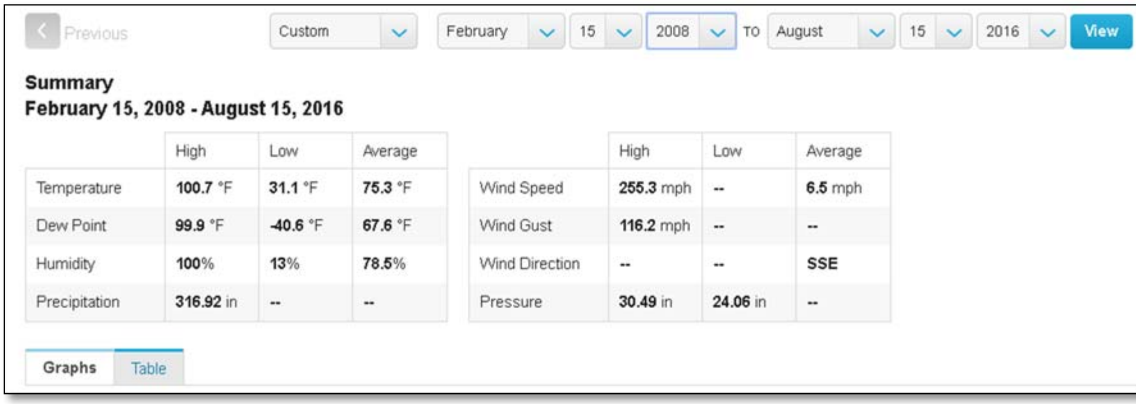


Figure 16. Weather Underground Web Site: Custom Selection of Time Period of Interest (Weather Underground: Weather Forecasts and Report, 2017)

A wireless weather station was provided by FAU iSENSE and installed at Urban Site 2 on October 21, 2016 (Figure 17). Meteorological data from Intelligent River web portal started coming being received on November 2, 2016 (Intelligent River, 2016). After selecting the location of interest (Figure 18), time period can be selected and data of interest can be downloaded. The wireless weather station provided information on wind direction, wind speed, temperature, humidity, pressure, precipitation intensity, etc.

Figure 17. Installation of FAU Wireless Weather Station at Urban Site 2

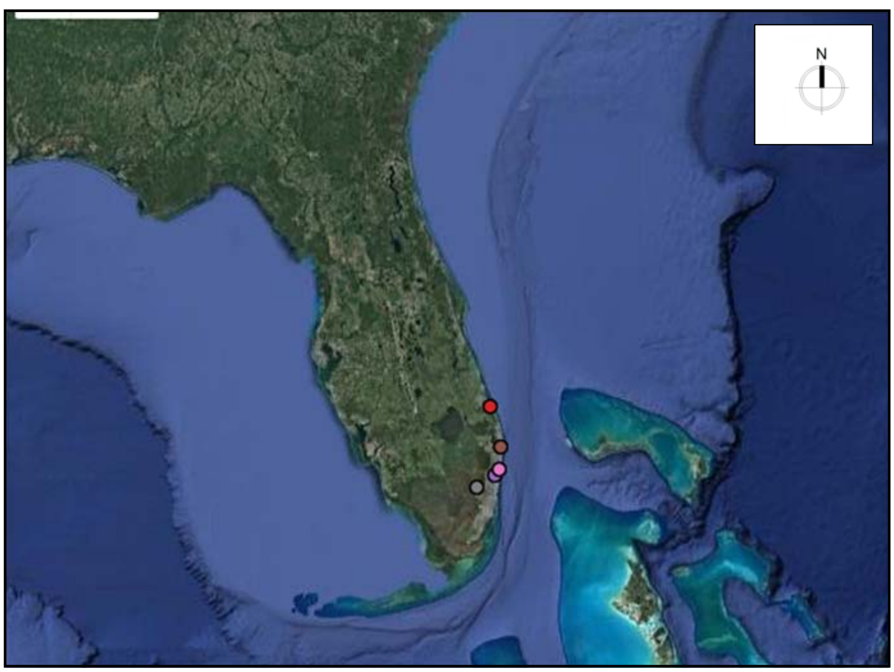


Figure 18. Intelligent River Web Portal: Selection of Location of Interest, Urban Site 2 (Intelligent River, 2016)

Since real-time access to meteorological data at Urban Site 2 was obtained after the time frame of collected odor complaints data (last date was January 2016), for both sites, historical data (2005-2016) on meteorological conditions was collected form the Weather Underground web site for the weather stations that were located physically closest to the landfill's address (code names: KFLWESTP21, KFLPALMB134, and KFLDEERF13). Meteorological data was collected for the following weather parameters: temperature, humidity, pressure, precipitation accumulation, wind direction, wind speed, conditions and events occurred (thunderstorms, rain, tornado, etc.). Data for rainfall/precipitation accumulation was collected for the 24 hours, 3 days, and 7 days prior to an odor annoyance. All other meteorological parameters were collected for the day before the odor complaint. For autocorrelation and PCA (Principal Component Analysis), 1, 2, and 3 days before the odor complaint were considered.

The odor complaint database for the Urban Site 1 was composed of 423 points with the time frame from 2005 to 2016 while the Urban Site 2 had total of 256 points from the same time period from 2005-2016. The part of the meteorological data collected is presented in the Table 13.

Table 13. Part of the Data Used for Meteorological Conditions (Urban Site 1)

Date	No of complaints	Avg T (°F)	Avg H (%)	Avg P (In)	Avg Ws (mph)	Prec Accum (In)	Events
7/5/2005	2	84	72	30.1	7	0	
7/29/2005	1	83	71	30.07	5	0.09	Rain , Thunder storm
8/4/2005	1	84	73	30.01	5	0.19	Rain , Thunder storm
8/5/2005	1	82	81	30.06	4	0.55	Rain , Thunder storm
8/11/2005	2	86	74	30.04	7	T	
8/17/2005	2	87	69	30	7	0	
8/18/2005	1	86	67	30.01	6	0	
8/31/2005	1	85	77	29.93	4	0.23	Rain , Thunder storm
9/13/2005	1	83	66	29.98	7	0	
9/15/2005	1	82	77	30.03	5	0	
9/16/2005	2	84	75	30.05	7	0	
9/24/2005	1	83	72	30.03	11	0	
9/27/2005	1	81	77	29.95	6	0.04	Rain , Thunder storm
10/7/2005	2	81	90	29.69	9	0.4	Rain
10/10/2005	3	81	84	29.79	6	0	

Urban Site 1 and Urban Site 2 each documented odor complaints differently. However, there were some similarities in the data collected between the two sites, for instance: date/time of the call, physical location, and name of the person who made the complaint. Information for the description of complaint, weather conditions at the time of the complaint (only for the wind direction) and findings that landfill personnel have noticed about the odors were inconsistent. If there was too much missing information, that part of the data set was excluded from further analysis. Also, any missing values were deleted from the spreadsheet. Parts of documented odor complaints at Urban Site 1 and Urban Site 2 are presented in Tables 14-15. As previously mentioned, due to the necessity of protecting personal information of customers who filed a complaint, any information that could possibly reveal the name of the person, address or any personal information was camouflaged (colored in black) to maintain privacy and anonymity. Parameters of interest considered and used for the research were:

- Date of the complaint;
- Time of the call;
- Location of the complaint;
- Temperature, °F;
- Humidity, %;
- Pressure, inch;
- Wind direction;
- Wind speed, miles per hour;
- Precipitation accumulation, inch;
- Weather conditions and events present

Table 14. Part of the Data Received for Odor Complaints (Urban Site 1)

COMPLAI	DATE_CALL_	COMPLAIN_1 LOCATION	ZIP	DEVELOPM	TIME_COMPL	TIME_AM_PM	WIND_DIR_1	WIND_SPEED	DESCRIPTION
Odor	2/19/2013	[redacted]	[redacted]	[redacted]	09:00	AM	SSE	Light	Odor
Odor	7/23/2013	[redacted]	[redacted]	[redacted]					Odors
Odor	10/21/2013	[redacted]	[redacted]	[redacted]				0	Odor
Odor	4/15/2014	[redacted]	[redacted]	[redacted]	09:25	AM	S - SE - SW	Light	[redacted]
Odor	8/1/2014	[redacted]	[redacted]	[redacted]	09:08			Very slight, no real directio	[redacted]
Odor	9/29/2014	[redacted]	[redacted]	[redacted]	09:50	AM	S	4	Overpowering odor
Odor	1/5/2015	[redacted]	[redacted]	[redacted]	02:30	PM	NNE	18.4	notiiceable odor si
Odor	3/18/2015	[redacted]	[redacted]	[redacted]	10:15	PM	S	2	Odor coming from tl
Odor	12/9/2012	[redacted]	[redacted]	[redacted]	11:30	AM	ESE	5	Odor in yard
Odor	3/29/2014	[redacted]	[redacted]	[redacted]	08:30	AM	SSE	Light	Odors
Odor	3/29/2014	[redacted]	[redacted]	[redacted]	08:45		SSE	Light	Odors
Odor	6/12/2014	[redacted]	[redacted]	[redacted]					[redacted]
Odor	5/24/2014	[redacted]	[redacted]	[redacted]	10:00	PM			odor of methane ga
Odor	9/22/2012	[redacted]	[redacted]	[redacted]	09:00		SSE	Slight	Odors
Odor	9/16/2014	[redacted]	[redacted]	[redacted]	06:00	PM	West SW	Calm	Strong Odor. Never
Odor	7/16/2012	[redacted]	[redacted]	[redacted]	11:30		SSE	0 - 5	Odors more often
Odor	12/15/2013	[redacted]	[redacted]	[redacted]	12:03	AM	SSE	Slight	Odors
Odor	7/17/2012	[redacted]	[redacted]	[redacted]	09:30	PM			
Odor	8/1/2012	[redacted]	[redacted]	[redacted]			SSE	Light	
Odor	9/7/2012	[redacted]	[redacted]	[redacted]	11:30	PM	SSE	Light	Odors
Odor	9/17/2012	[redacted]	[redacted]	[redacted]	11:43	PM	SSE		Odors
Odor	10/2/2013	[redacted]	[redacted]	[redacted]	10:00	PM	S - SE - E - NE	Light	Odor bad
Odor	11/18/2013	[redacted]	[redacted]	[redacted]	10:30	PM	All over	0	Odors
Odor	9/16/2014	[redacted]	[redacted]	[redacted]	09:30	PM	SW - SSW	3 - 4	Odors smelled like
Odor	3/30/2012	[redacted]	[redacted]	[redacted]	06:00	PM			Odors
Odor	3/31/2012	[redacted]	[redacted]	[redacted]	11:59	AM			Odors

Table 15. Part of the Data Received for Odor Complaints (Urban Site 2)

VIOLATIONCODE	COMPLAINANTLASTNAME	COMPLAINANTFIRSTNAMI	COMPLAINANTADDRESS	COMPLAINANTZIPCODE	RECEIVEDDATE	DESCRIPTION
Odor	[redacted]	[redacted]	[redacted]	[redacted]	1/14/2005 11:12:36 AM	Landfill odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	1/14/2005	Landfill odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	3/7/2005	Landfill odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	6/6/2012	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	6/6/2012 9:55:13 AM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	4/29/2005 9:05:46 AM	Landfill odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	6/14/2012	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	4/29/2005	Landfill odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	8/28/2012 1:59:01 PM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	11/27/2012	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	12/6/2012 12:23:17 PM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	12/14/2012 12:18:06 PM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	12/17/2012 9:45:59 AM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	1/24/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	1/24/2013 4:01:30 PM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	2/12/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	2/13/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	2/12/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	4/24/2013 11:13:53 AM	Unconfined emissions.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	5/29/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	7/9/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	7/18/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	7/18/2013	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	6/8/2005 3:00:28 PM	Nuisance odors.
Odor	[redacted]	[redacted]	[redacted]	[redacted]	7/23/2013	Nuisance odors.

2.3 Pattern Identification and Trend Analysis

Based on the odor complaints data received from Urban Site 1 and Urban Site 2, as well as using appropriate qualifiers for meteorological measurements, the datasets were analyzed to determine the existence of patterns or trends, if any, that could lead to the development of effective odor mitigation strategies.

2.3.1 Preliminary Analysis

The data from Urban Site 1 contained the following information:

- Date;
- Time of the call;
- Name of the person who made the complaint;
- Location of the complaint;
- Description of the complaint;
- Wind direction; and
- Findings from the facility personnel.

Microsoft Excel 2013 was used to perform the trend analysis using information about the local meteorological conditions obtained from the weather station located onsite (temperature, humidity, pressure, wind direction, wind speed, precipitation accumulation). The first step was to filter the data to remove entries with missing values of the parameters of interest (n = 76 or 18%). Missing data was related to missing times when the actual odor complaints were filed. In an effort to collect the missing points, site personnel were contacted. Since they did not have any additional source where the data on odor complaints was documented, it was not possible to obtain the missing information. Also, where the time was missing, it was not possible to select data on meteorological parameters that occurred without knowing the exact time. After removing the incomplete data entries, an analysis was conducted to determine what year, month, day of the week, and time of day had the most odor complaints logged. Next, the month with highest number of odor complaints was determined, and the distribution of the received complaints was identified based on the day in a week. The time in the day when the complaint calls tend to occur most often was also determined. The next step was to see how many days in the time period from 2005 to 2016 experienced more than one odor complaint in the same day, since the main focus of the study was to identify the existence of a pattern, if any, in the scenarios that odor complaints tend to occur most frequently. Since the year 2016 dataset had only three data points for Urban Site 1, it was excluded from further analysis. From the information gathered in meetings with solid waste facility personnel, three or more verified odor complaints in the same day trigger corrective action(s). For this preliminary analysis, several days with 3 or more complaints filed in the same day, presented in Table 16, were taken into consideration.

Table 16. Days with More Than Three Odor Complaint in the Same Day Considered for the Preliminary Analysis, Urban Site 1

Date	**Number of Complaints in the Same Day**
12/06/2005	6
09/16/2014	4
09/18/2014	4
09/19/2014	6
03/26/2015	6

For each of the days, the physical locations of the odor complaints were plotted to visually verify if the complaints were spread out or if there was a cluster of complaints.

Next, the meteorological conditions were examined during the time of the call, as well as for the whole day, and additional information was gathered from the nearest weather station or the station installed at the site. Since the weather station at the site does not provide information on meteorological conditions prior to 2008, for the date 12/09/2005 meteorological data was collected from the Weather Underground website, as described earlier, from the next closest location to Urban Site 1.

The second part of the preliminary analysis was conducted when a second odor complaint database was received for Urban Site 2. Data consisted of 256 files from 2005 to 2016. Each entry provided information on the date and time of the odor complaint, location where the complaint was made, and description of the odor. The inconsistency of the information provided and the incompleteness of the entries contributed to a substantial number of missing values (n=21 or 8%).

Data from both sites were entered into Microsoft Excel spreadsheets and filtered using the following parameters: date, time and location of the odor complaint. Dates with three or more complaints on the same day were identified for both sites. To investigate the relationship between the meteorological parameters on selected days, the following parameters were included: air temperature, humidity, pressure, wind direction, and wind speed. Data for each of the meteorological parameters was graphically represented for the day when complaints occurred for the previous day. Also, values were graphically represented for the exact time when the odor complaint was received and compared to the same time period for the previous day. Sample graphs are presented in Figure 19. More graphs are presented in Appendix B. A number one next to the name of the parameter represents the values for the previous day, while a number two next to the name of the parameter represents the values for the day when odor complaints actually occurred.

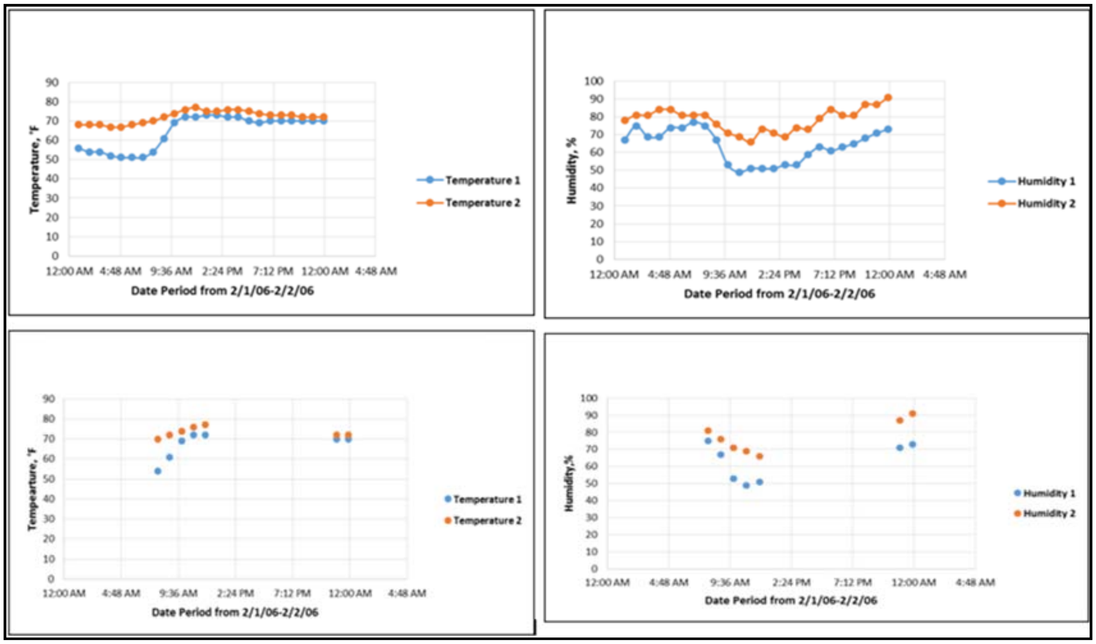


Figure 19. Meteorological Conditions: Temperature on the Day the Complaint was Filed (Upper Left) and Temperature at the Exact Time the Complaint was Filed (Lower Left) vs Previous Day; Humidity on the Day the Complaint was Filed (Upper Right) and Humidity at the Exact Time the Complaint was Filed (Lower Right) vs Previous Day (02/02/2006, Urban Site 1)

The Pearson correlation coefficient (r) measures how well two datasets are related by determining if there is a linear relationship between them. Possible values for Pearson correlation coefficients are between -1 and +1. High correlation represents the value of r in the ranges of 0.5-1 or -0.5 to -1. Medium correlation are values from 0.3 to 0.5 and -0.3 to -0.5, while a low correlation is when the r value is between 0.1 to 0.3 and -0.1 to -0.3 (Hauke & Kossowski, 2011). This analysis was done for the day of the complaint compared to the previous day. Also, relationships between temperature and humidity, temperature and pressure, and humidity and pressure were analyzed. High correlations (*r* value near ± 1) would suggest, for example, once today's temperature is known, it can be successfully used to forecast tomorrow's value. If the *r* value is near 0, there is no discernible relationship.

2.3.2 Analysis for Isolated Odor Complaints

In this section, the following analyses were conducted:

- Meteorological data for each of the days with three or more complaints was compared;
- Average values of meteorological conditions for each of the days compared to the frequency of odor complaints;
- Seasonal variations (Dry and Wet season); and
- Rainfall data for the day, three days and seven days' prior odor event was compared to the frequency of odor complaints.

Based on the collected meteorological data for three or more complaints in the same day, for both sites (Urban Site 1=25 days; Urban Site 2= 17 days), correlations were calculated for temperature, humidity, pressure and wind speed to identify if there was a significant correlation in values for every day selected. For example, the values of temperature for every day were compared, and a correlation between them was calculated. The same procedure was done for the rest of the meteorological parameters mentioned. The next step was to compare the actual number of odor complaints received per day with the average value of temperature, humidity, pressure, wind speed and rainfall. Furthermore, the number of complaints was compared to the average value of the same parameters, but in this case the actual time that the complaint was made was taken into consideration. Odor complaints were also separated based on the dry season (November until April) and wet season (May until October) to test the existence of patterns, if any, related to different seasonal variations.

Rainfall data for days with three or more complaints was also analyzed for the 24-hour period prior, three days prior and seven days prior. The next step was to identify any monthly variations. For each of the months where variations were found, historical data for the previous ten years, for that particular month, was obtained and tested for normal distribution (Appendix C) by creating normal probability plot (Q-Q plot). The aim was to single out if that year, by the amount of rainfall received in the month of interest, was an outlier. An outlier is an observation that distinguish itself from other values in a data sample tested. One useful graphical representation in detecting an outlier is creating a box plot. It uses the median and the lower (1st quartile) and upper (3rd quartile) quartiles (ITL, 2017). Defining the interquartile, as well as "fences", is required to detect extreme values (outliers). A value that exceeds an inner fence lines is considered a "mild outlier", while an observation that exceeds an outer fence is considered an "extreme outlier" (ITL, 2017):

- **Interquartile (IQ)= Q3-Q1**
- **Lower Inner Fence=Q1-1.5×IQ**
- **Upper Inner Fence=Q3+1.5×IQ**
- **Lower Outer Fence=Q1-3×IQ**
- **Upper Outer Fence=Q3+3×IQ**

Where,

IQ= Interquartile

Q1= Lower (1st) Quartile

Q3=Upper (3rd) Quartile

2.3.3 Analysis with Additional Dates with No Odor Complaints

In this section, the following analyses were conducted:

- Comparison of meteorological conditions on the days with or without odor annoyances;
- Seasonal variations (Dry and Wet season); and
- Autocorrelation analysis.

Since the collected data sets contained only dates when actual complaints were made, every missing date between the dates with complaints was assigned with a value of 0, representing the absence of odor complaints. Table 17 shows that days with no complaints comprised more that 90 percent of the days at each site.

Table 17. Summary of Total Data Points Included in the Trend Analysis

Parameter	**Urban Site 1**	**Urban Site 2**
Time frame	07/02/2005 – 03/18/2016	01/11/2005 – 09/14/2016
Dates without odor complaints	3912	4258
Dates with odor complaints	423	256
Dry season	1951	2101
Wet season	1961	2157

An autocorrelation analysis for complaint frequencies, for the whole data set, was performed to define how well the number of odor complaints from the previous day (lag 1 autocorrelation) would forecast the next day's number of odor complaints. Autocorrelation is a correlation coefficient that instead of correlating two different variables, is actually indicating if a correlation exists between two different values of the same variable at times

X_i and $X_i + k$ (X = variable, k = time selected). To detect non-randomness, usually the first autocorrelation (lag 1) is used (Keshvani, 2013). A correlation closer to ±1 would indicate that if today's number of complaints is known, the number of complaints for the next day could be predicted. If the autocorrelation is near 0, there is no possibility for prediction.

Another purpose of adding dates with no complaints was to use principal component analysis to investigate if the days with three or more complaints in the same day are distinguishable when compared to the dates when complaints have not been recorded. Meteorological data was collected on temperature (°F), humidity (%), pressure (inch), wind speed (mph), precipitation accumulation (inch) and events (rain, thunderstorm, storm, etc.).

2.3.4 Analysis of Isolated Days and Random Days with No Complaints with Similar Weather Patterns

In this section, the following analyses were conducted:

- Random days with no odor complaints with the similar meteorological conditions as the days with three or more complaints in the same day were compared;
- Wind speed and wind direction compared for both scenarios, with or without odor complaints;
- Weather conditions and events compared for both scenarios, with or without odor complaints.

To test the difference between the meteorological conditions and random days with and without complaints, the same number (n=44) of random days with very similar meteorological conditions to the days with high numbers of complaints were selected. The total number of days with three or more odor complaints in the same day for Urban Site 1 and Urban Site 2 was 27 and 17, respectively. Also, meteorological data was collected for the previous days for both complaint data and selected random days based on similar weather patterns. As an example, the value of temperature for the day the complaint was filed was subtracted from the value of temperature from the previous day. The same procedure was applied to all meteorological parameters (temperature, humidity, pressure, winds speed, and precipitation accumulation) for both random days and days with actual complaints. To identify how often the same weather pattern occurs, both with and without odor complaints, frequencies were calculated based on differences in meteorological values between the day before and the actual day of the complaint or a selected random day when complaints did not occur. Pairs (1 pair = difference in a value when complaint occurred compared to the previous day and difference in a value of a random date compared to the previous day) of the same trend (Figure 58), representing bars going in the same direction, both positive or both negative, were added together and then divided by the total number of pairs. An example calculation for temperature is presented as follows:

$$\boldsymbol{\Delta T_1 = T_1 - T_1^*}$$

$$\boldsymbol{\Delta T_0 = T_0 - T_0^*,} \text{ where:}$$

T_1= Temperature at the day when complaint was filed

T_1*= Temperature from the previous day of the day when complaint occurred

T_0= Temperature for the random day selected with similar weather conditions

T_0*= Temperature from the previous day of randomly selected day.

ΔT= Difference in values for the day of occurred odor complaint

ΔT_0= Difference in values for the random day, without odor complaint

T= Total number of points.

If both have a positive or negative sign, they create a pair and represent the same weather pattern trend, both whether a complaint was received and not (Table 18). In this case, we can identify 4 pairs going in the same direction, with the total number (T) of pairs being equal to 6. By dividing those two values and multiplying by 100, the result of 66.6% frequency of temperature values being similar on the days when complains have and have not occurred, is achieved.

Table 18. Sample Calculation to Identify Frequency of Same Weather Patterns, Both with and Without Odor Complaints

ΔT	**ΔT_0**
-1	-5
0	4
6	1
3	4
2	-6
3	-9

Frequency, %= 4 pairs/T= (4/6) *100= 66.6%

To investigate how the wind direction is related to odor complaints, data was collected for every day when there was a complaint, as well as for the random days previously selected (Table 19).

Table 19. Summary of Data Points included in the Analysis of Isolated Days and Random Days with No Complaints based on Similar Weather Patterns

Parameter	**Urban Site 1**		**Urban Site 2**	
	With Complaints	**No Complaints**	**With Complaints**	**No Complaints**
Number of days	27	27	17	17
Wind direction	596	636	402	474
Wind speed	596	636	402	474
Weather conditions	600	642	404	434*
Events	600	642	404	450

*Data included also points marked as "Unknown" (n=16), so those points were excluded from the analysis.

Also, wind speed was included in the analysis to determine the most frequent wind speeds that occur in each scenario. The most common method for characterizing wind speeds is the Beaufort scale (NOAA, 2017); therefore, the same was used to categorize wind speeds present in the data sets. The Beaufort wind speed scale is summarized in Table 20.

Table 20.The Beaufort Wind Speed Scale (NOAA, 2017)

Beaufort Number	Description	Wind Speed mph
0	Calm	<1
1	Light air	1-3
2	Light breeze	4-7
3	Gentle breeze	8-12
4	Moderate breeze	13-18
5	Fresh breeze	19-24
6	Strong breeze	25-31

The data sets consisted of wind speed points described as "Calm", so those points were replaced with 0.9 mph since, based on the Beaufort scale, "Calm" wind speed is below 1 mph. All hourly values for wind speeds were sorted based on a specific speed and attributed to the appropriate speed range, according to the Beaufort scale. From the obtained data, six wind speed ranges have been classified: <1 mph, 1-3 mph, 4-7 mph, 8-12 mph, 13-18 mph, 19-24 mph and highest 25-31 mph. The frequency of each wind direction was calculated based on the total count of that particular wind direction and divided by the total number of all wind direction points in the data set. The values used were hourly values for each of the days selected. Frequencies were computed as follows:

$$\textbf{Frequency, \%} = (X_i / Y_T) * 100, \text{ where:}$$

X_i= Count of how many times a specific wind direction was noticed at a specific wind speed;

Y_T= Total count of points in the dataset.

The values were expressed in percentages. The same was done for the wind speed categories. Wind direction and wind speed combined together would reveal which tend to occur the most often. The most frequent wind directions and wind speeds were compared to those on the days where there were no odor complaints. Communities where most of the complaints were received were identified and compared to the predominant wind directions. Weather conditions, as well as the events for the days with complaints and with the absence of same, were also compared. Weather conditions described if, on the day of the complaint or absence of same, the conditions were: clear sky, scattered clouds, mostly cloudy sky, etc. Events described (if present) included: thunderstorms, rain, no rain, etc. Frequency was calculated based on the amount each condition or event occurred and subtracted from the total number of observed values.

2.3.5 Correlation Matrix, Principal Component Analysis (PCA) and Linear Regression

XLStat® was used for more advanced computing such as correlation analysis, principal component analysis (PCA), and linear regression to evaluate the relationship between parameters. The first task was to use all the data to create an understanding of the number of data points and to eliminate missing data. Appendix E includes the summary statistics for the data used for PCA.

Correlation analysis indicates whether the variable is related to other variables on an individual basis. The benefit of this analysis is to identify parameters that are clearly correlated. However, this works best when there are a limited number of variables. For this analysis, there were 18 variables:

- Number of complaints: number of files reported in any given day (most commonly 0)
- Days -1: lag of 1-day from the previous with regard to complaints
- Days -2: lag of 2-days from the previous with regard to complaints

- Days -3: lag of 3-days from the previous with regard to complaints
- Temperature High for the given day
- Temperature Chg: change in high temperature from the prior day
- Temperature Avg for the given day
- Temperature Low for the given day
- Humidity High for the given day
- Humidity Chg: change in average humidity from the prior day
- Humidity Avg for the given day
- Humidity Low for the given day
- Pressure High for the given day
- Pressure Avg for the given day
- Pressure Low for the given day
- Wind Speed Avg for the given day
- Wind Speed Low for the given day
- Precipitation for the given day

Note that hourly or more frequent data was not available.

Because there are so many variables, the potential is that each contributes a small amount and those variables that are actually correlated (and therefore measure the same thing), are not exposed. Hence, a more complex multivariate analysis was suggested. Data was first modified so that there were no zeros within the data set. Any zeros left in the data set will cause some statistical tests to either fail to calculate or output invalid solutions. The next step was cleaning up the data to remove any place that lacked data as the absence of data would also be interpreted as a zero within the data set. After this process, there were 3910 days remaining with complete data for the analysis.

Given the large number of variables (18), principal component analysis (PCA) was used to reduce the number of variables. PCA does this by creating an orthogonal transformation of the data using eigenvalues and eigenvectors. The orthogonal transformation provides a series of “factors,” which are combinations of the larger set of variables used. For example, a factor might combine all temperature, humidity or even all weather data if variation in that data explains the variations in the parameter of concern. In this case the parameter of concern is odor complaints, so weather and other data can be mined to find out which ones might contribute more to the variance and which ones measure the same things (those would be part of a given factor based on correlations). The goal is to reduce the 18 variables to a very few that explain most of the variance. PCA takes the variables and determines combinations of factors that create the best fit for the observation set. A Scree plot is used to determine how many factors create 70% of the variation. The aim is to find a smaller number of interpretable factors that explain the maximum amount variability in the data set. With PCA, all factors in excess of 1 are kept. Those with factor values under 1.0 are assumed to contribute little to the overall explanation of the results and can be neglected. It is desirable that the factors represent at least 70 percent of the resulting eigenvalues. Once the factors are identified, eigenvalues are analyzed to determine which set of variables contributes most to the factor. Ideally, the investigator should look for values that are greater than 0.6 – 0.7. A Varimax diagram is used to visualize which factors are correlated and how strongly. It shows vectors pointing away from the origin to represent the original variables. The angle between the vectors is an approximation of the correlation between the variables. A small angle indicates the variables are positively correlated, an angle of 90 degrees indicates the variables are not correlated and an angle close to 180 degrees indicates the variables are strongly negatively correlated (Smith, 2002). The length of the line from the center of a Varimax plot indicates the variable's contribution to the overall analysis. If the line is short, the variable has little impact on overall variability (Smith, 2002).

A regression model was also performed in order to estimate the relationship among variables. XLStat can also be used to generate a linear regression equation which can confirm some of the PCA findings. The concept is to create a weighted equation whereby one can predict results based on the factors included in the regression equation. However, unlike PCA, all the variables are included. Hence strongly correlated variables would have less weight individually since they measure the same thing (the idea with PCA is to use the factors to find surrogates). This technique is used for modeling equations and analyzing several variables at once when the focus is on a relationship between a dependent variable and multiple independent variables. In this case the dependent variable is the number of odor complaints, and the independent variables are related to the meteorological conditions of interest. Based on the dependent variable being numbers of odor complaints, the linear regression and PCA allow for investigation of which independent variables create the variability in the number of complaints each day. The fact that most days are zero does suggest challenges if the days preceding the complaint are similar to the day the complaint was received. This is why variables for t-1, t-2 and t-3 days were created.

3 RESULTS AND DISCUSSION

This chapter presents the results and discusses the relationship between odor complaints and meteorological parameters of interest, namely: temperature, humidity, pressure, wind direction, wind speed, precipitation accumulation, weather conditions and events.

3.1 Preliminary Analysis

Results for the first part of the analysis, obtained from the odor data set received for Urban Site 1 and Urban Site 2 (Figure 20), revealed that the year 2014 experienced the largest number of odor complaints (n=98) in the case of Urban Site 1, with the most number of complaints (Figure 21) logged in the month of September (n=51); followed by December (n=44) and February (n=43). For Urban Site 2, year with highest number of odor complaints was 2005 (n=76), with next large rise in frequency of odor complaints in 2012 (n=60) and 2013 (n=55). Both, large number of odor complaints in 2005, followed by 2012 and 2013, could be related to hurricane events, due to substantially greater amounts of waste received and flooding occurred at the area (Personal communication with site personnel). Frequency of odor complaints, for Urban Site 1, showed that most odor complaints occur during the dry season, from November until April (Figure 21). Urban Site 2 had highest frequency of complaints in July, with total number of 60 (Figure 21). Next highest ranked months were January and November with total of 39 and 32, respectively.

Error bars shown are representing one standard deviation from the mean value for the month, both Urban Site 1 and Urban Site 2 (Figure 22). March, December, September and May had the highest variations from the mean value of odor complaints for the month for Urban Site 1, while January, April, July and November for Urban Site 2.Working days of the week (Monday through Friday) had more odor complaints than the weekends, possibly because people were home more on the weekend and the olfactory impacts did not allow them to smell the odors, unlike evenings during the week where being away all day caused their olfactory processes to notice the odor more (Figure 23). Slightly more odor complaints were received in the afternoon hours (Urban Site 1: 52%, n=164; Urban Site 2: 54%, n=142) compared to the morning hours (Urban Site 1: 48%, n=150; Urban Site 2: 44%, n=114) which may be related to people coming home from work in the afternoon and spending more time at home rather than in the morning hours on the rush to work, but the frequency of occurrence is essentially the same.

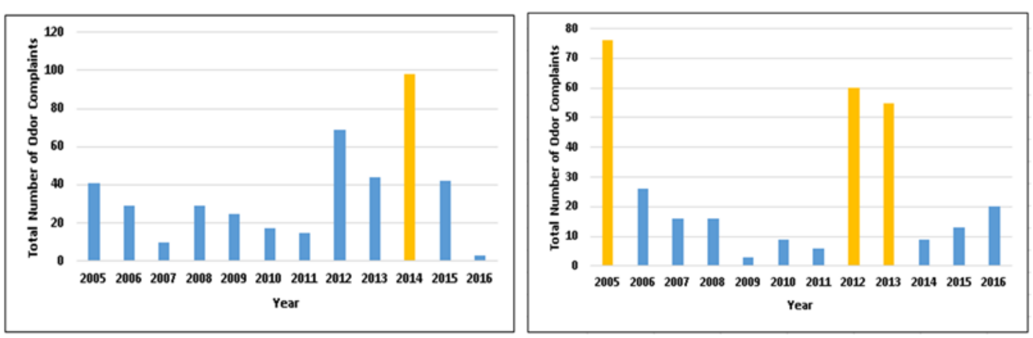


Figure 20. Incidence of Odor Complaints by Year: Urban Site 1, July 2005-March 2016 (left); Urban Site 2, January 2005-September 2016 (right)

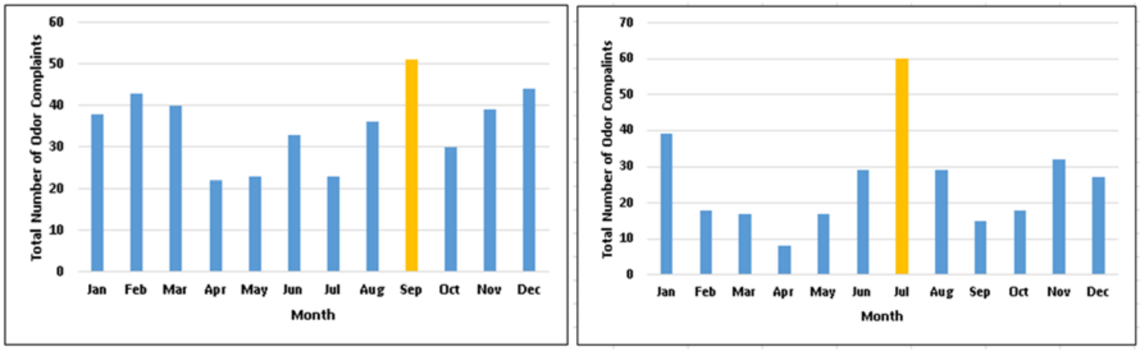


Figure 21. Incidence of Odor Complaints by Month: Urban Site 1, July 2005-March 2016 (left); Urban Site 2, January 2005-September 2016 (right)

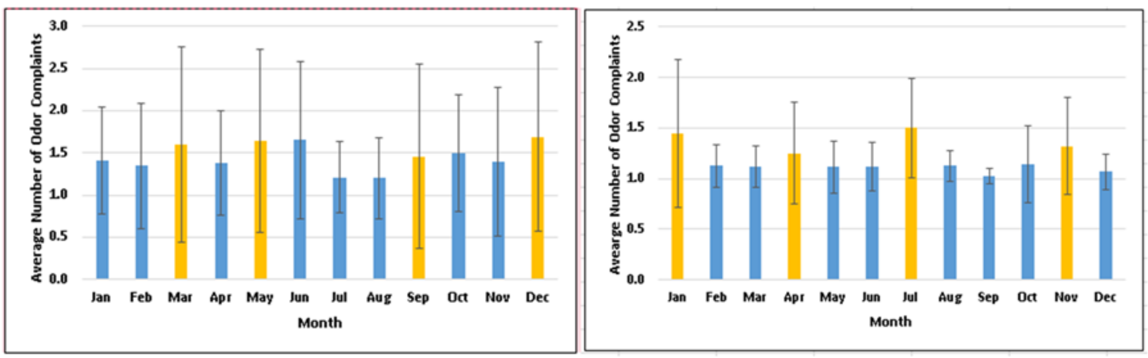


Figure 22. Highest Variations from the Mean Value of Odor Complaints for the Month: Urban Site 1(left) with March, December, September and May; and Urban Site 2 (right) with July, January, April and November

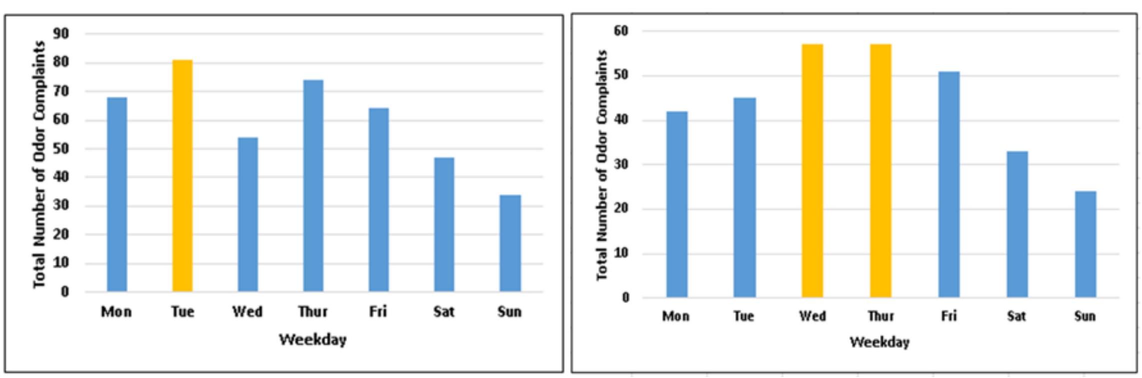


Figure 23. Incidence of Odor Complaints by Day of the Week: Urban Site 1 (left) July 2005-March 2016; and Urban Site 2 (right), January 2005-September 2016

The next step was to see how many days during the time period (2005-2016) had more than one odor compliant in the same day. Since the year 2016 had only three data points for Urban Site 1, it was excluded from further analysis, while the year 2005, even though it was also a year with partial data, had a larger range of dates (07/05/2005-12/28/2005) and a total of 41 odor complaints so it was included in the analysis. Results at Urban Site 1 showed that the most odor complaints in the same day were in 2005, 2006, 2009 and from 2012-2015, while for Urban Site 2 similar years were recognized: 2005, 2006 and 2013 (Figure 24). As per Urban Site 2, days with highest number of odor complaints recorded in the same day were in July, 2013 (n=16 calls); January, 2006 (n=14 calls) and November, 2005 (n=11 calls), contributing to finding that those months, in time period of 10 years (2005-2016), were the most critical ones. Dates with recorded highest number of odor complaints in the same day were: 11/21/2005 with 5; 07/15/2013 with 5; and 07/28/2013 with 6 complaints. By looking at the spread of the odor complaints in the years that experienced highest frequency of odor annoyances (2005, 2012, 2013), it could be observed that most of the complaints were filed during wet season (Figure 26). Also, it was interesting to note that even though year 2012 was the second highest, based on the number of complaints received, no date with 3 or more complaints in the same day has been recorded (Figure 26). At Urban Site 1, the most number of complaints were filed on December 9, 2005 with 6, and an additional 3 more were made on December 5 and 6 of that same year. February 2, 2006 had 4 odor complaints in the same day, while on February 13, 2006 had 3 more of them. Year 2009 had up to 4 odor complaints in almost consecutive days, on May 26 and May 28, 2009. Year 2012 had 4 odor complaints on June 7, 2012. The most active year for reporting frequency on the same day was 2014 (Figure 25) with

September 16, 18, and 19, 2014 having a total of 10 complaints filed altogether. According to the facility manager for Urban Site 1, this episode was due to the landfill operation class 1/ class 3, yard waste processing, compost operations and sludge pelletizer towards the end of the dates noted, which all may have contributed to odors. Urban Site 2 also had a WTE tipping floor backup, which led to high odors. Year 2015 also had multiple odor complaints in the same day throughout the whole year, with the largest number (n=6) occurring on March 26, 2015. Odor complaints decreased after 2014, since Urban Site 1 changed the type of waste that it was receiving. They no longer had the organic fraction of the waste, since converting to 100% incineration (ash monofill) and stopped the practice of receiving recovered screen material (RSMs) containing high quantities of drywall (sulfur). This change in waste composition resulted in substantially lower frequency of odor complaints (from n=98 in 2014 to n=42 in 2015).

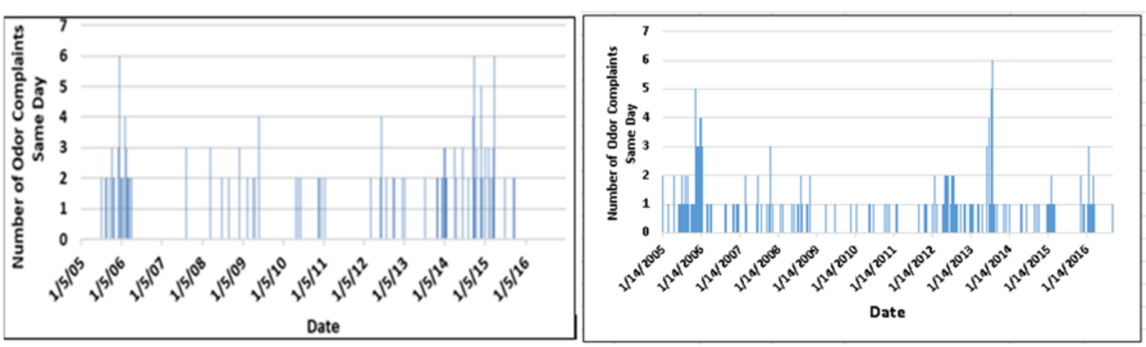


Figure 24. Dates with Most Odor Complaints Recorded in the Same Day for Urban Site 1(left) and Urban Site 2 (right)

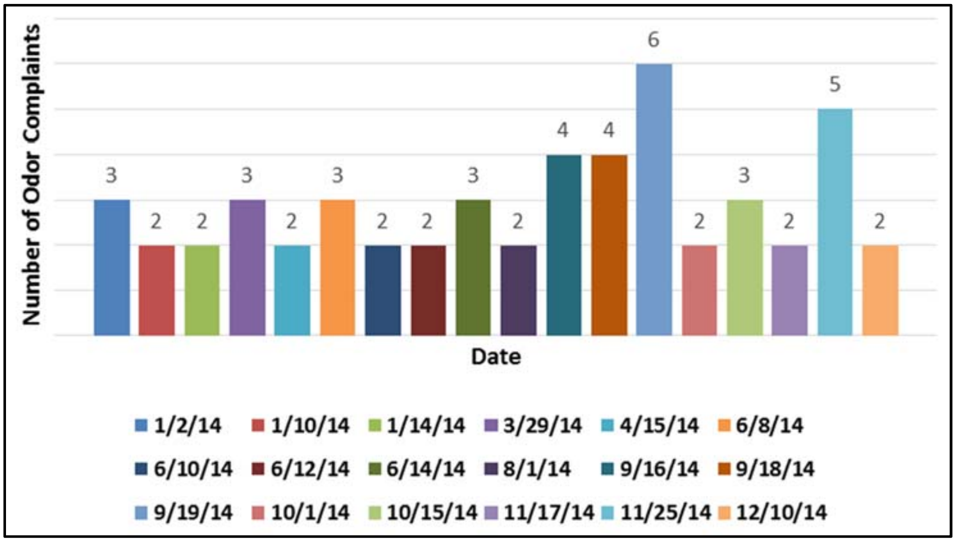


Figure 25. Frequency of Odor Complaints in the Same Day for 2014 (Urban Site 1)

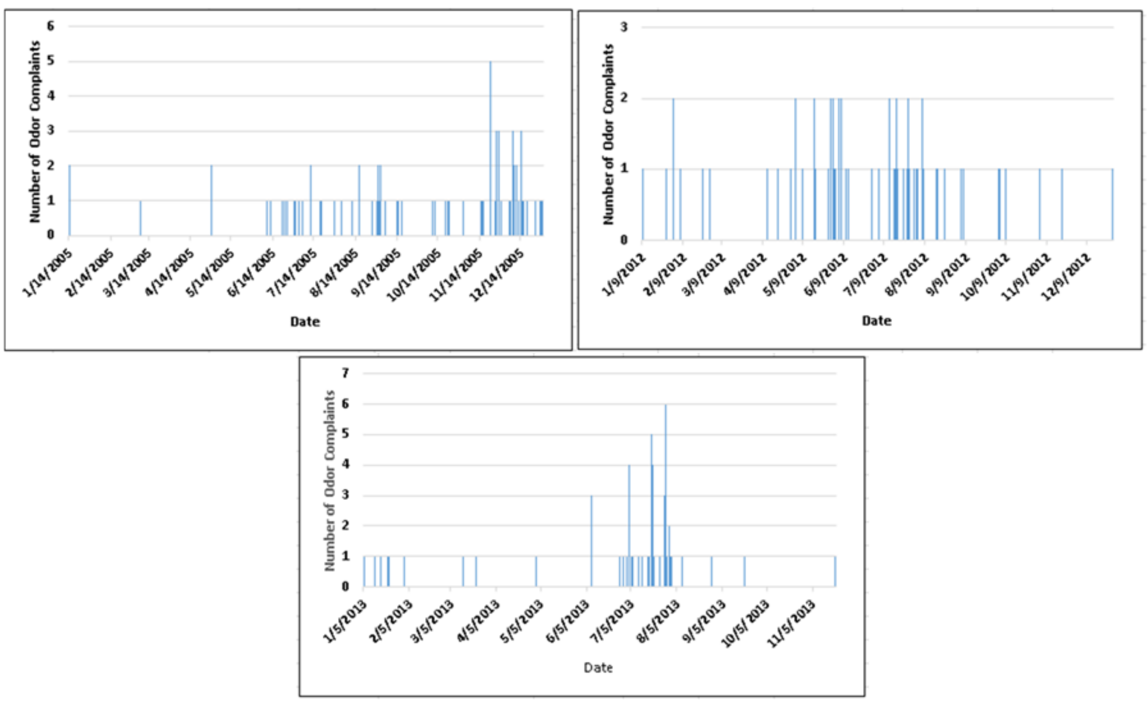


Figure 26. Frequency of Odor Complaints Filed for Urban Site 2: Year 2005 (left); Year 2012 (right), and Year 2013 (middle): Odor Complaints Mostly Occurred during Wet Season (May until October)

Since three or more odor complaints in the same day trigger corrective action (Personal communication with site personnel), for further analysis days with the largest number of complaints (6) in the same day were investigated (Urban Site 1). The year 2014 had three days in a row with a large number of complaints in the same day that could be related. Dates taken for analysis were: 12/09/05 (6 complaints), 09/16/14 (4 complaints); 09/18/14 (4 complaints); 09/19/14 (6 complaints) and 03/26/15 (6 complaints). When mapping the locations of the odor complaints received for each date, it was observed that the largest number of complaints is coming from the same neighborhood for all cases (Figure 27). The next step was to examine the meteorological conditions at the time the odor complaint was received, as well as for the whole day. Meteorological conditions, in Table 21, showed a possibility for a correlation between odor complaints and weather conditions since for all cases, meteorological conditions were very similar. In all examined cases, the wind speed was weak, the wind direction was south, temperature and pressure dropped from the previous day and there was no precipitation, while stable weather conditions were present (Appendix A). Only in the case of September 19, 2014, according to weather station data, average wind direction was ENE, but the exact time of the odor complaint reported that the wind direction was also from the south.

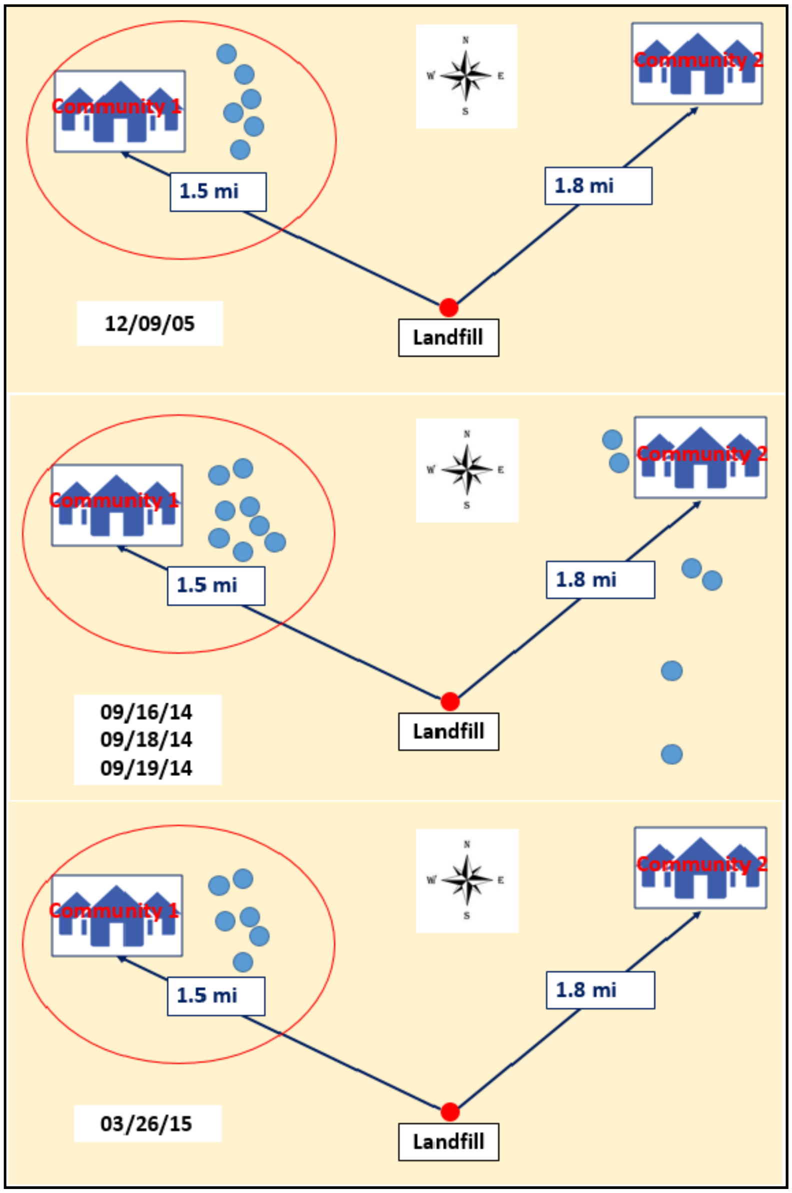


Figure 27. Cluster of Odor Complaints from Communities Surrounding the Landfill Site (Urban Site 1)

Table 21. Summary of Meteorological Conditions at the Time of Occurred Odor Complaints, Urban Site 1 (Weather Underground)

Date	**Number of Complaints**	**Rain, Inch**	**Wind Direction**	**Wind Speed, mph**	**Avg T, °F**	**Avg H, %**	**Avg P, Inch**	**Weather Condition**
12/09/2005	6	0.00	South, SSW	5.7	75.0	93.0	30.2	Partly cloudy
09/16/2014	4	0.00	South, SSW	3.0	82.0	77.2	30.0	Mostly cloudy
09/18/2014	4	0.00	South	10.6	83.3	73.6	29.9	Mostly cloudy
09/19/2014	6	0.00	South	1.4	76.9	92.6	29.9	Mostly cloudy
03/26/2015	6	0.11	South, WSW	6.5	75.7	83.2	30.0	Mostly cloudy

T = Temperature, H = Relative Humidity, P = Pressure

The second part of the preliminary analysis investigated the correlation between consistencies in values on the day complaints were filed when compared to the conditions on the day before. Odor complaint data from both sites, Urban Site 1 and Urban Site 2, were used, and days with three or more complaints in the same day were retrieved. Urban Site 1 had total of 26 days with three or more complaints in the same day for the time frame of 2005 – 2016, while Urban Site 2 had a total of 17 days for the time period of 2005 – 2015. Meteorological parameters (temperature, humidity, pressure, wind direction and wind speed) were tested both for the day of the complaint as well as for the exact time when the complaint was filed and compared with the same conditions from the day before (Figures 28, 29, 30 and 31). Correlations between parameters showed that wind direction and wind speed have the lowest correlations when compared to the values from the day before, which is expected since those are meteorological parameters with the highest variability (Sakawi et al. 2011), while temperature, humidity, and pressure had constantly higher correlation values (Tables 22 and 23) because these values tend to be relatively constant within a narrow range for South Florida (Climate Data- Florida, 2017).

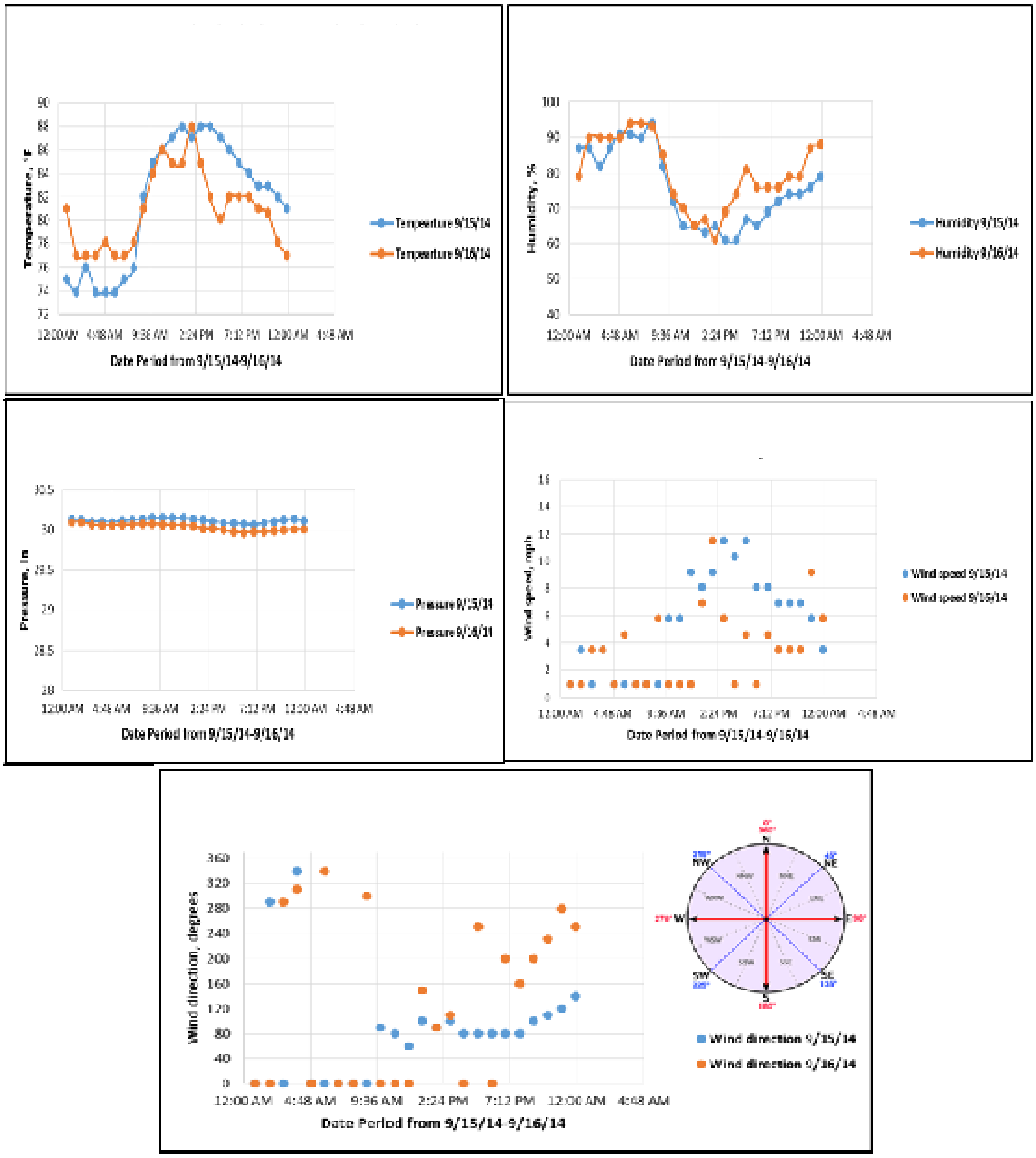


Figure 28. Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Wind Direction (Bottom), for the Day the Complaint was filed on 09/16/2014 vs Previous Day, Urban Site 1

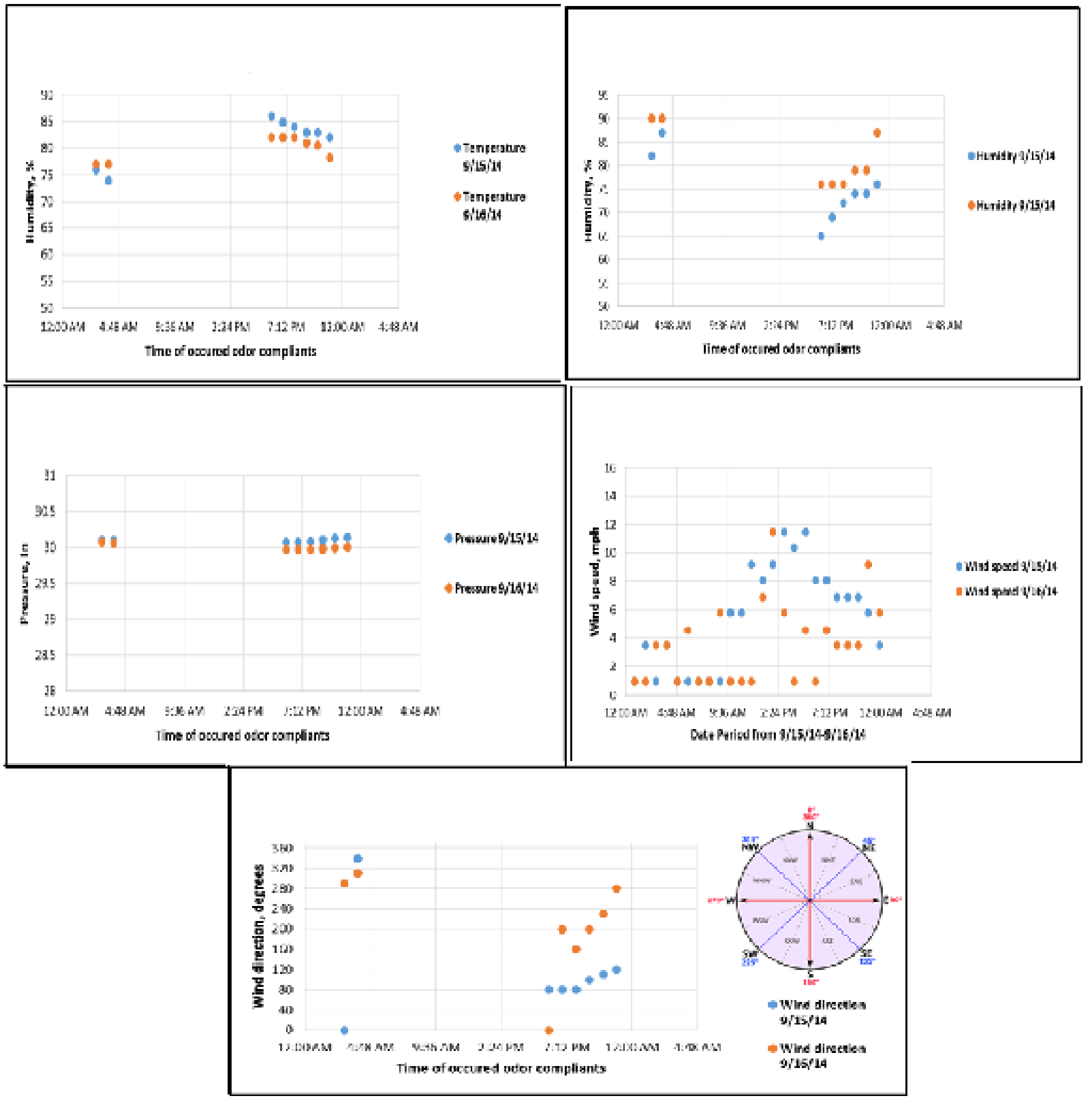


Figure 29. Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Wind Direction (Bottom), at the Time the Complaint was Filed for 09/16/2014 vs Previous Day, Urban Site 1

Table 22. Correlations of Meteorological Parameters at the Time of Occurred Complaint and for the Entire Day, 09/16/2014 (Urban Site 1)

	T	**H**	**P**	**W s**	**W d**
Correlation (Occurred Time)	0.910	0.898	0.428	-0.091	0.339
Correlation (Entire day)	0.808	0.876	0.683	0.266	0.146

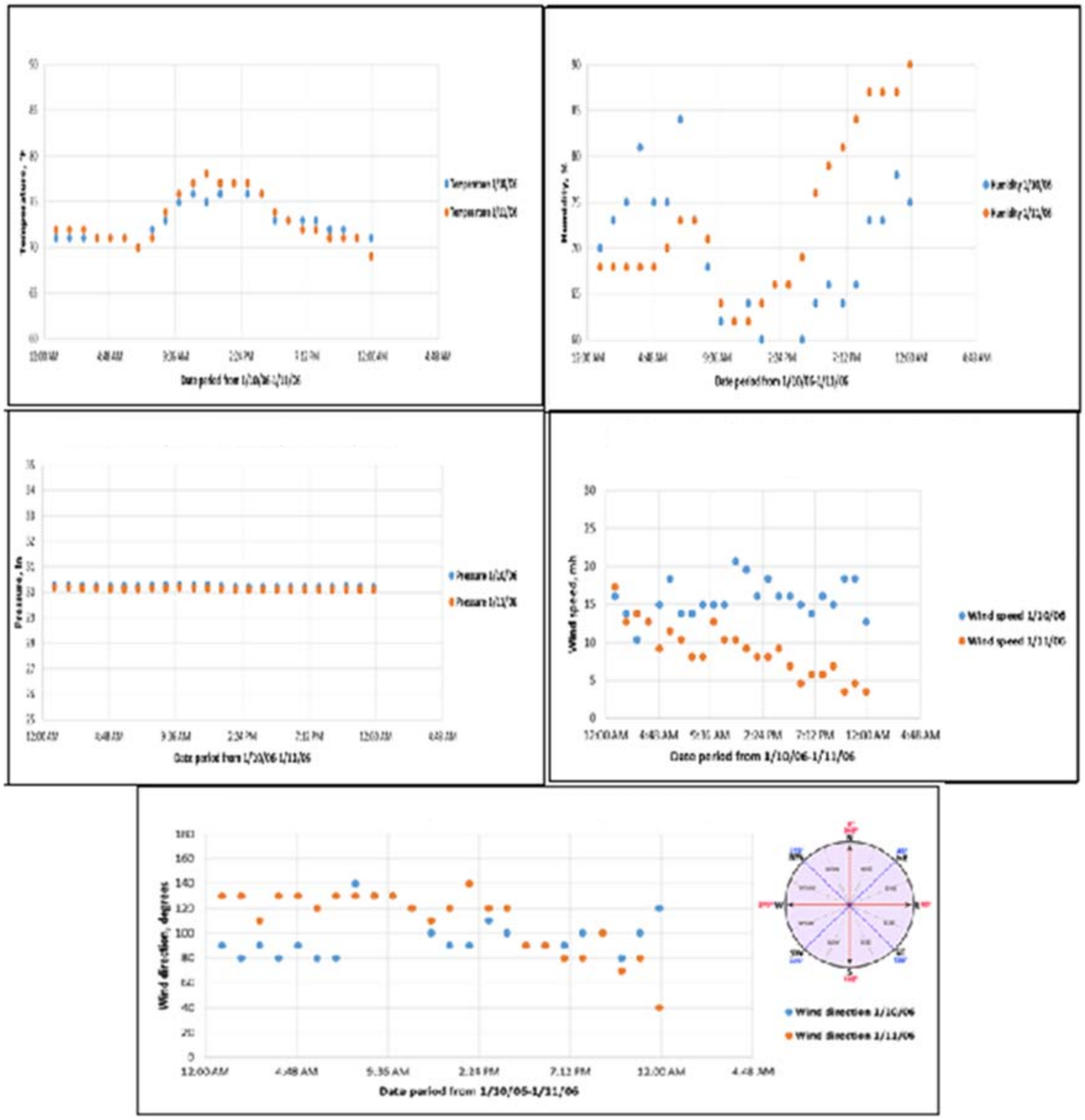


Figure 30. Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Wind Direction (Bottom), for the Day the Complaint was filed on 01/11/2006 vs Previous Day, Urban Site 2

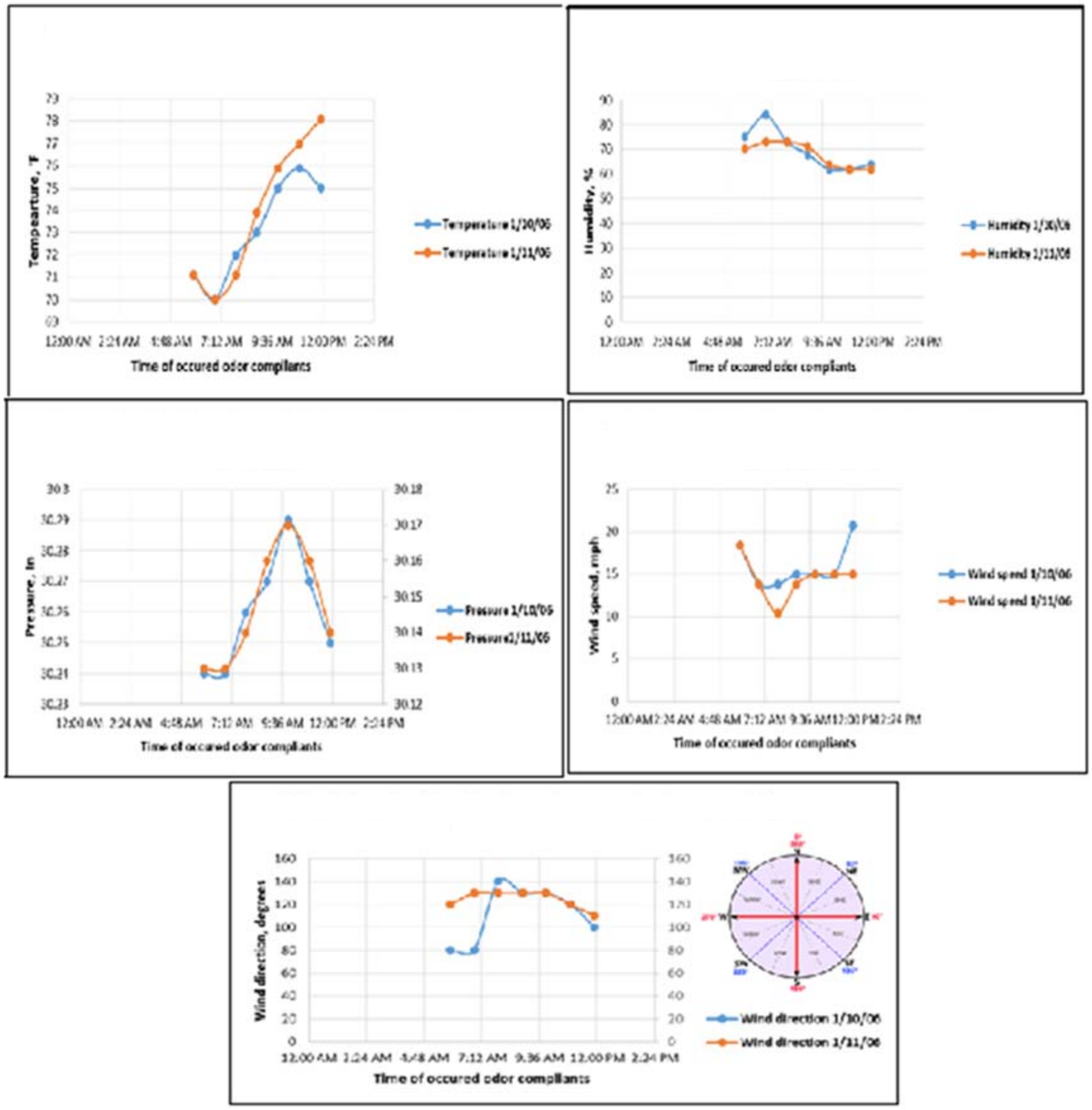


Figure 31. Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Wind Direction (Bottom), at the Time the Complaint was Filed for 01/11/2006, Urban Site 2

Table 23. Correlations of Meteorological Parameters at the Time of Occurred Complaint v. the Entire Day, 01/11/2006 (Urban Site 2)

	T	H	P	W s	W d
Correlation (Occurred Time)	0.957	0.836	0.968	0.293	0.391
Correlation (Entire Day)	0.931	0.362	0.939	-0.179	0.018

Also, correlations between temperature and humidity, temperature and pressure, and humidity and pressure were tested. Results in Tables 24-25 showed that strongest relationship was between temperature and humidity, which was negatively correlated (Urban Site 1: r=-0.94; Urban Site 2: r=-0.73). No relationship was noticed between temperature and pressure. Results for some of the dates, for each site, are presented in Figure 32.

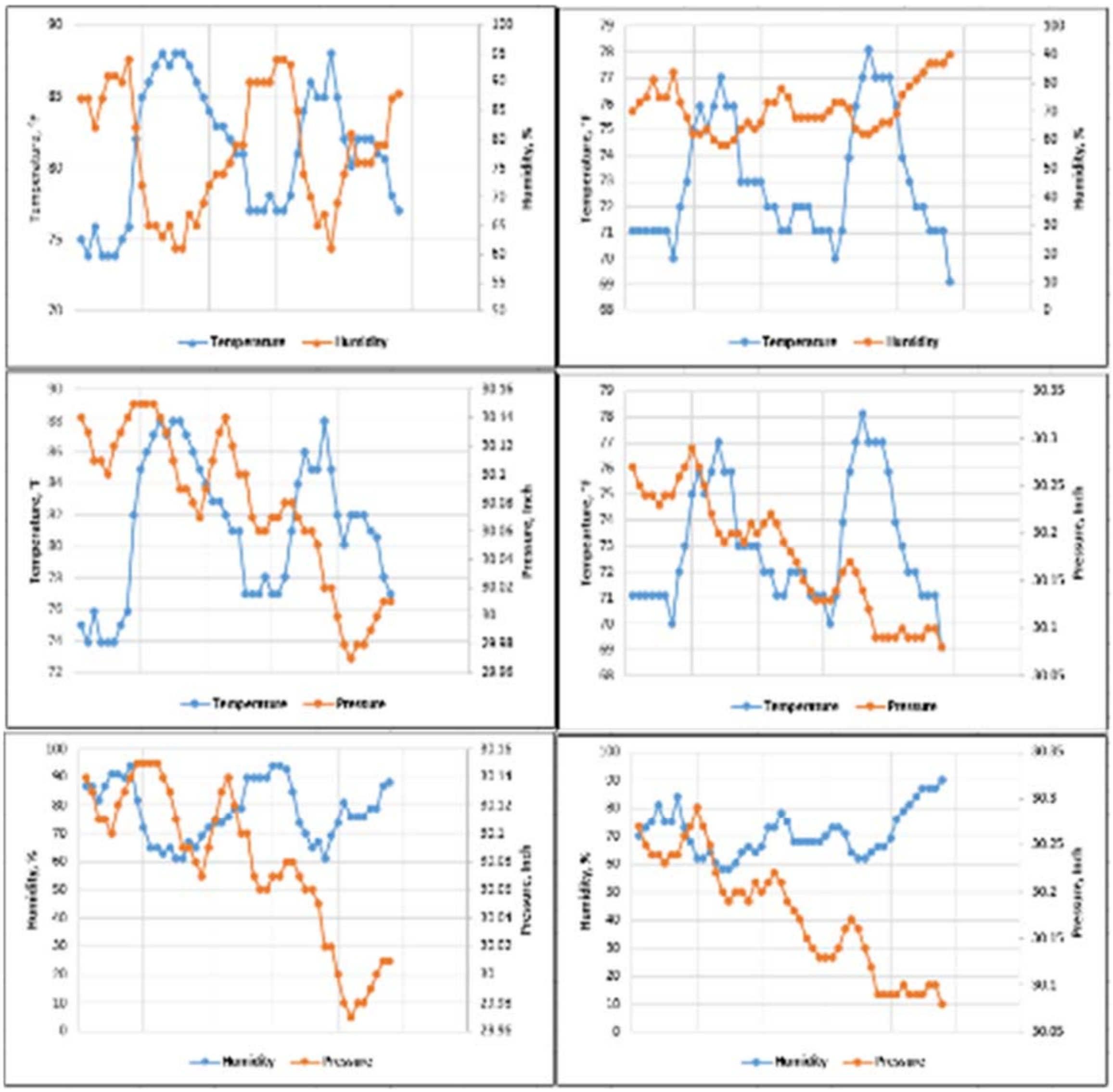


Figure 32. Relationship between Temperature, Humidity and Pressure: Urban Site 1, 09/16/2014 (Left) and Urban Site 2, 01/11/2006 (Right)

Table 24. Correlation between Meteorological Parameters, 09/16/2014 (Urban Site 1)

Temperature	**T**	**Humidity**	**Pressure**
	1	-0.94	-0.02
Humidity	-0.94	1	-0.004
Pressure	-0.02	-0.004	1

Table 25. Correlation between Meteorological Parameters, 01/11/2006 (Urban Site 2)

Temperature	**T**	**Humidity**	**Pressure**
	1	-0.73	-0.042
Humidity	-0.73	1	-0.339
Pressure	-0.042	-0.339	1

3.2 Analysis for Isolated Odor Complaints

Frequency of odor complaints was compared to the average value of temperature, humidity, pressure, wind speed and rainfall for each day when three or more complaints were received in the same day. Results presented in Table 26 showed that there is no correlation between frequency of odor complaints and meteorological conditions. No data was available for precipitation accumulation from the nearest weather station located to Urban Site 2, so it was excluded from further analysis. Since the next closest weather stations were much further away, it was decided that the differences would be too great compared to the location of interest, so data from the next nearest weather station was not considered.

Table 26. Correlation for Urban Site 1 and Urban Site 2 with Temperature, Humidity, Pressure, Wind Speed and Precipitation Accumulation (only for Urban Site 1)

	Average Temperature	**Average Humidity**	**Average Pressure**	**Average Wind Speed**	**Precipitation Accumulation**
Urban Site 1	0.24	0.37	-0.30	<-0.01	0.05
Urban Site 2	0.12	0.17	-0.21	-0.19	N/A

Dividing the data set into dry season (November until April) and wet season (May until October) obtained the same result for Urban Site 1-in that no correlation was detected between the number of odor complaints and meteorological parameters (Table 27). Results obtained for Urban Site 2 showed that the meteorological parameter that had the greatest influence on odor complaints was pressure. Furthermore, higher number of odor complaints consistently occurred during the dry season, for both sites, and one of the factors that could potentially influence such events, for Urban Site 2, could be pressure drop (Sadowska-Rociek et al. 2009).

Table 27. Correlation for Urban Site 1 and Urban Site 2 based on the Wet and Dry Season

	Urban Site 1		**Urban Site 2**	
	Wet Season	Dry Season	Wet Season	Dry Season
Number of Complaints	$n = 40$	$n = 42$	$n = 15$	$n = 27$
Average Temperature	0.20	0.26	-0.66	0.36
Average Humidity	0.52	0.24	-0.07	0.15
Average Pressure	-0.34	-0.29	0.68	-0.73
Average Wind Speed	-0.29	0.31	-0.37	0.03
Precipitation Accumulation	0.13	-0.23	0.13	N/A

Precipitation accumulation data analyzed, based on the previous 24 hours, 3 days before and 7 days before the day when three or more odor complaints occurred in the same day, showed no correlation between the frequency of odor complaints and amount of precipitation measured for Urban Site 1. Results for Urban Site 2 showed that number of odor complaints could be related to the amount of precipitation that has been accumulated three days prior to the odor complaint. Even though more odor complaints tend to occur when there is an absence of rain, this information revealed that rainfall accumulated from couple of days before could trigger odors and eventually failing a complaint. Reason for such an event could be related to heavier rainfall that washes away the dirt covering, responsible for retaining down the odor, and resulting in more intense odors. Results are presented in the Table 28. Different results from two separate sites could indicate how odor complaints are occurring randomly and attempting to analyze only one scenario in which they could potentially occur might be an oversimplification of a complex phenomenon.

Table 28. Correlation for Urban Site 1 and Urban Site 2 with 24h, 3 days before and 7 days Precipitation Accumulation before the Odor Complaint

Parameters	Urban Site 1	Urban Site 2
Number of Complaints	***n* = 101**	***n* = 62**
24 hours	**0.16**	**0.65**
3 days	**0.10**	**0.75**
7 days	**0.10**	**0.58**

Rainfall data collected for 24 hours, 3 days and 7 days prior to an odor episode was analyzed for Urban Site 1 and Urban Site 2, and dates that differed from the rest of the sample were identified. The rainfall distribution for Urban Site 1 revealed three dates (05/26/2009; 05/28/2009 and 06/14/2014) with rainfall amounts different than the rest of the dates considered. Months identified for further analysis were May 2009 and June 2014 (Appendix C). Historical data of 10 years for May (1999-2009) and June (2004-2014) were tested for normal distribution by creating Q-Q plot (Normal Probability plot). Results revealed that in the case of May, the data set differs slightly from but generally approximates a normal distribution, while in the case of June, the data set is normally distributed (Appendix C). No outlier was identified for the month of June (time period 2004-2014). Analysis of historical data of 10 years prior (1999-2009) revealed that May 2009 (Figure 33) could be recognized as an outlier. Since the upper outer fence was calculated to be 15.14, the observation of 15.70 inches of rainfall (May 2009) is categorized as an "extreme outlier" (Appendix C). The month of May 2009 (circled), received 70% greater amount of rain when compared to the average value for the previous ten years (1999-2009), shown in Figure 34. In those ten years, for the month of May, the average rain accumulation was 4.75 inches, while May of 2009 recorded a total of 15.70 inches of rain (Appendix C). This finding is corroborated by the report of the National Weather Service (NOAA, 2017), which identified May of 2009, in the location of Urban Site 1, as the second wettest May on record (with 15.69 inches). It is also important to note that the amount of 15.69 inches fell in just 14 days (May 18 to May 31).

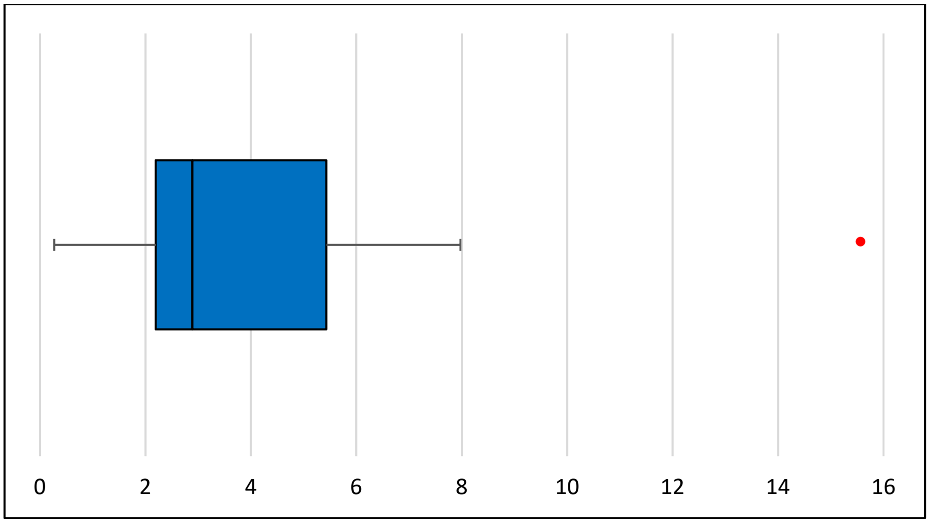


Figure 33. Identifying May of 2009 as an "Extreme Outlier" with Rainfall Accumulation of 15.70 Inches (Urban Site 1)

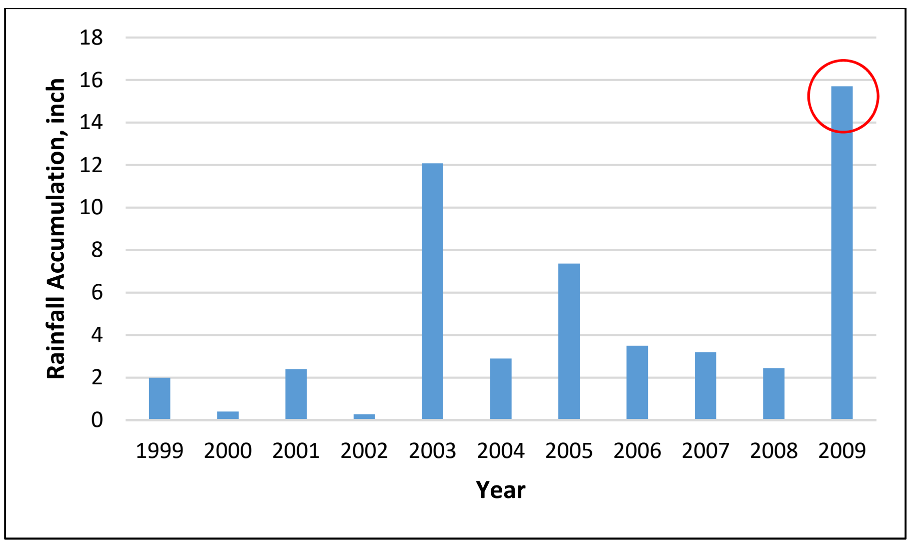


Figure 34. Total Monthly Rainfall Accumulation for Month of May, Time Period from 1999-2009 (Urban Site 1)

3.3 Analysis with Additional Dates with No Odor Complaints

Investigation of the days with three or more complaints in the same day revealed no relationship between the frequency of odor complaints and meteorological conditions (Table 29).

Table 29. Correlation for Urban Site 1 and Urban Site 2 with Meteorological Conditions: Original Data Set of Odor Complaints with Additional Dates Representing an Absence of Odor Complaints

Parameters	**Urban Site 1**	**Urban Site 2**
Average Temperature	0.05	0.03
Average Humidity	0.08	0.09
Average Pressure	-0.06	<0.01
Average Wind Speed	-0.09	-0.03
Precipitation Accumulation	0.02	0.05

Results using this modified data from comparing wet and dry season for both sites revealed that Urban Site 2 had more odor complaints (n=168) in the wet season compared to Urban Site 1, which had more odor complaints in the dry season (n=246). The largest variations were related to humidity and temperature when compared to the average value (Table 30). The reason why both temperature and humidity have the highest variations could be because these two meteorological parameters are related to each other. Temperature and humidity are negatively correlated, which means-if ones increases, the other one will decrease, and vice versa. Changes in temperature create changes in the humidity of the ambient air (Linden, 2013).

Table 30. Comparison of Dry and Wet Season for Urban Site 1 and Urban Site 2: Original Data Set of Odor Complaints with Additional Dates Representing an Absence of Odor Complaints

Parameters	**Urban Site 1**		**Urban Site 2**	
	Dry Season	**Wet Season**	**Dry Season**	**Wet Season**
Number of Complaints	*n* = 246	*n* = 232	*n* = 140	*n* = 168
Average Temperature	70.9 ± 7.2	81.8 ± 3.5	71.3 ± 6.8	81.2 ± 4.5
Average Humidity	69.1 ± 9.2	72.9 ± 6.8	70.3 ± 10.8	73.8 ± 8.2
Average Pressure	30.1 ± 0.1	30.0 ± 0.1	30.1 ± 0.1	30.0 ± 0.7
Average Wind Speed	9.9 ± 3.5	8.3 ± 3.4	9.8 ± 3.6	8.0 ± 3.6
Precipitation Accumulation	194.6 ± 0.4	441.1 ± 0.2	192.2 ± 0.4	370.3 ± 0.5

Note that in both cases (Urban Site 1 and Urban Site 2), meteorological conditions happened to be similar. Also, it was observed that more stable weather conditions tend to occur in the dry season, while in the wet season, there was more frequent rain and thunderstorm events. For both sites, conditions observed during the dry season were: lower rainfall, slightly stronger winds, lower humidity and temperature, and higher pressure when compared to the wet season. Results are presented in Figures 35-37, for both Urban Site 1 and Urban Site 2.

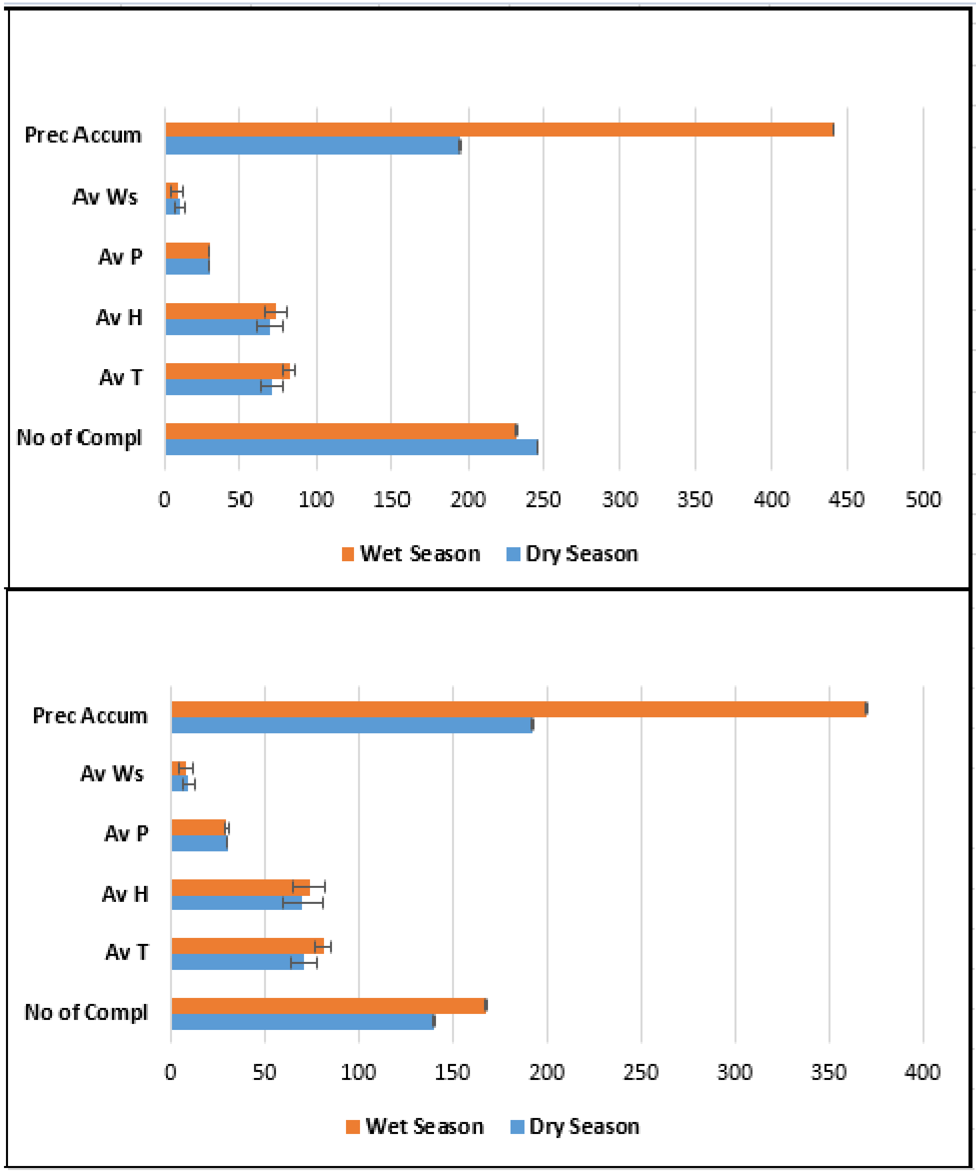


Figure 35. Comparison of Meteorological Conditions for Dry and Wet Season: Urban Site 1 (Top) and Urban Site 2 (Bottom)

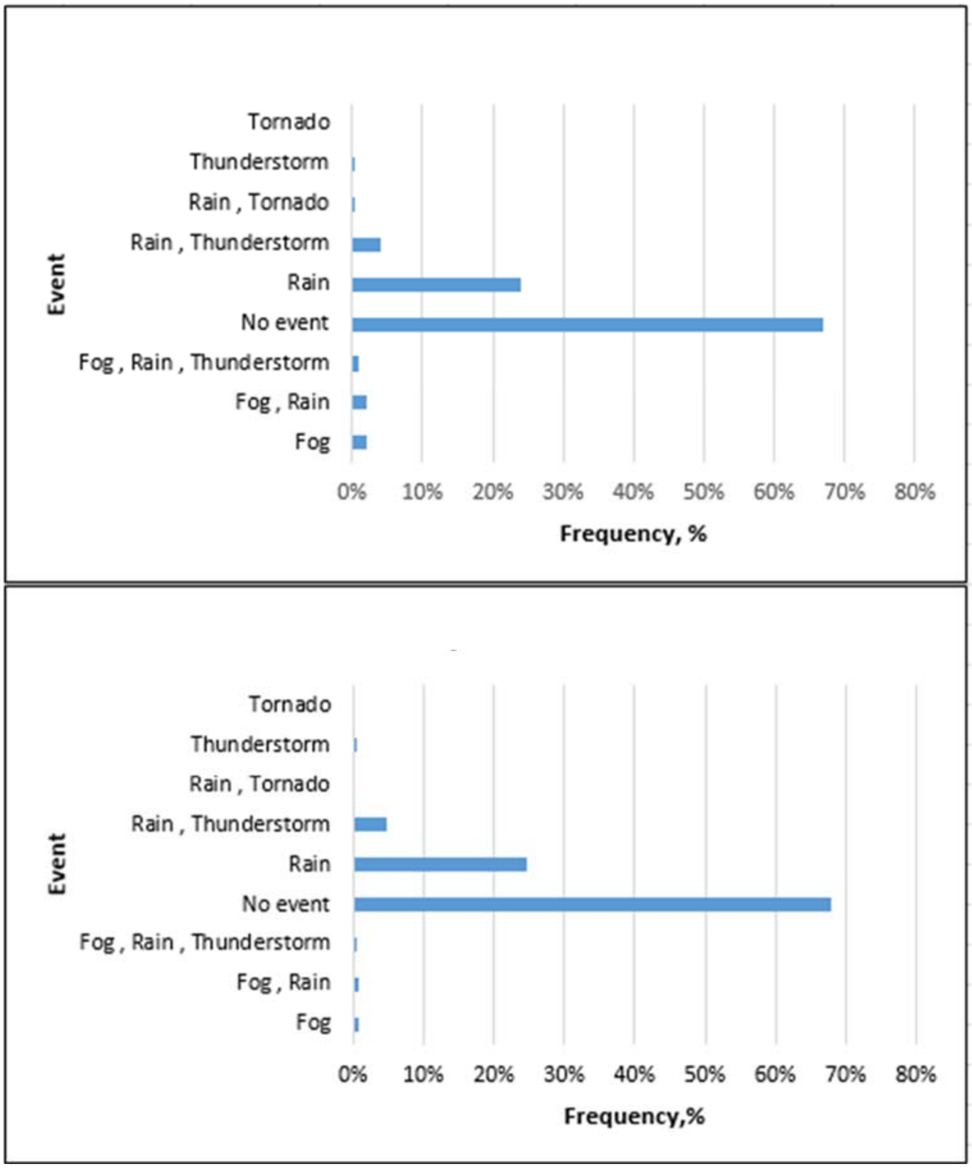


Figure 36. Events for Dry Season (November until April): Urban Site 1 (Top) and Urban Site 2 (Bottom)

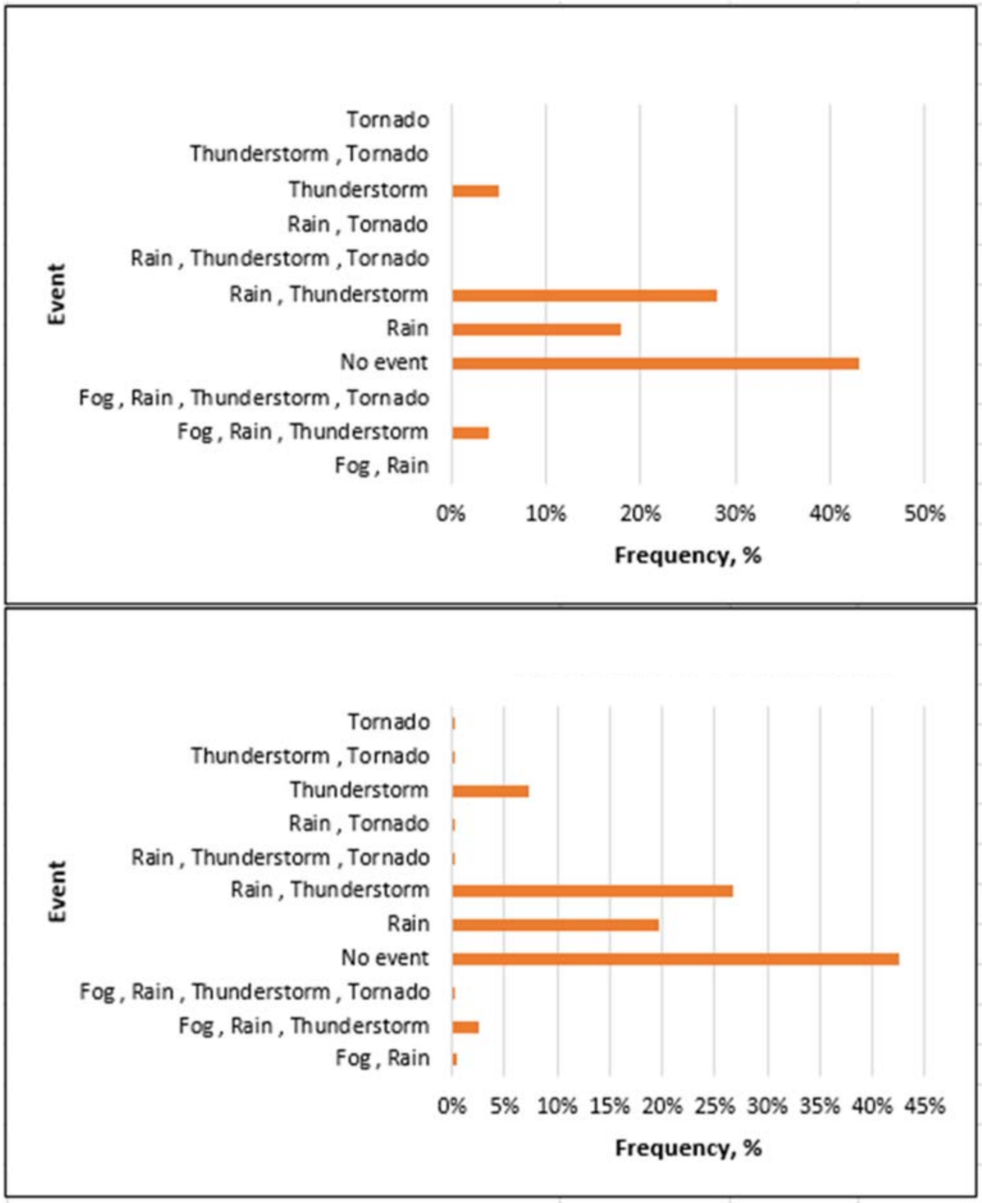


Figure 37. Events for Wet Season (May until October): Urban Site 1 (Top) and Urban Site 2 (Bottom)

Autocorrelation analysis of odor complaint frequencies revealed that previous day complaint records were not good predictors of the following day's citizen reported odor annoyances. Autocorrelation analysis revealed the lag 1 day correlation was 0.11 for Urban Site 1 and 0.23 for Urban Site 2. Lag 2 and 3 for both sites showed even lower correlations:

for lag 2 the values were 0.08 and 0.16 for Urban Site 1 and Urban Site 2, repetitively. Lag 3 correlations were 0.05 for the Urban Site 1 and 0.10 for the Urban Site 2. Results indicated no potential for predicting the number of odor complaints from one day to the next.

3.4 Analysis of Isolated Days and Days with No Complaints with Similar Weather Patterns

Summary statistics revealed that the mean values for the meteorological parameters (temperature, humidity, pressure, wind speed and precipitation accumulation), both for the days when complaints occurred as well as for the days without complaints, were very similar (>95%), except for precipitation accumulation (Table 31). Tables with descriptive statistics for Urban Site 1 and Urban Site 2 are present in Appendix D. Results revealed that the tendency of odor complaints could be related to slightly higher temperature and humidity with lower pressure and windy days. Also, higher precipitation accumulation was noticed for the days when odor complaints occurred and that was a parameter that showed the highest difference when compared to days without odor complaints.

Table 31. Similarity between Mean Values of Weather Conditions for Days with Complaints vs Days Without Complaints

Parameter	**Urban Site 1**	**Urban Site 2**
Temperature	99.8%	98.8%
Humidity	99.5%	99.3%
Pressure	100%	99.9%
Wind speed	94.8%	95.3%
Precipitation accumulation	58.3%	46.5%

Days with three or more complaints in the same day were compared with the days with no odor complaints. For each of those days, meteorological data was collected for the previous day. The goal of this analysis was to distinguish weather patterns when complaints occur compared to the days when complaints were not received. Results revealed that on average around 61% of the meteorological conditions were similar, both when the complaint occurred and when no complaint was filed, for Urban Site 1. For Urban Site 2, the average value of the trend was 40%. Meteorological parameters that had the highest percent of the same trend in both scenarios were temperature with 67% and humidity with 78% for Urban Site 1, while for Urban Site 2, those were precipitation accumulation with almost 50% and temperature and pressure with 41% (Table 32). Results are presented in Figures 38 and 39, demonstrate that there is no specific weather pattern that can be used to predict odor complaints. For example, in Figure 38 top left, the temperature difference for the days with complaints and the temperature difference for the days without complaints are both moving in the same direction (first two bars looking down), while we expected to see that they move in opposite directions if it was showing a way to distinguish the situation contributing to making a complaint. The percentage of 67% in Table 32 reflects the frequency of both bars moving in the same direction. The differences between the two sites is likely related to the lower amount of data for Urban Site 2, since Urban Site 2 had only 17 days with 3 or more complaints in the same day, while Urban Site 1 had 27.

Table 32. Percentage of Days with Similar Weather Trends (Complaint and Noncomplaint) for Urban Site 1 and Urban Site 2

Parameter	**Urban Site 1**	**Urban Site 2**
N	54	34
Temperature	67%	41%
Humidity	78%	35%
Pressure	52%	41%
Wind speed	48%	35%
Precipitation accumulation	59%	47%
Average	61%	40%

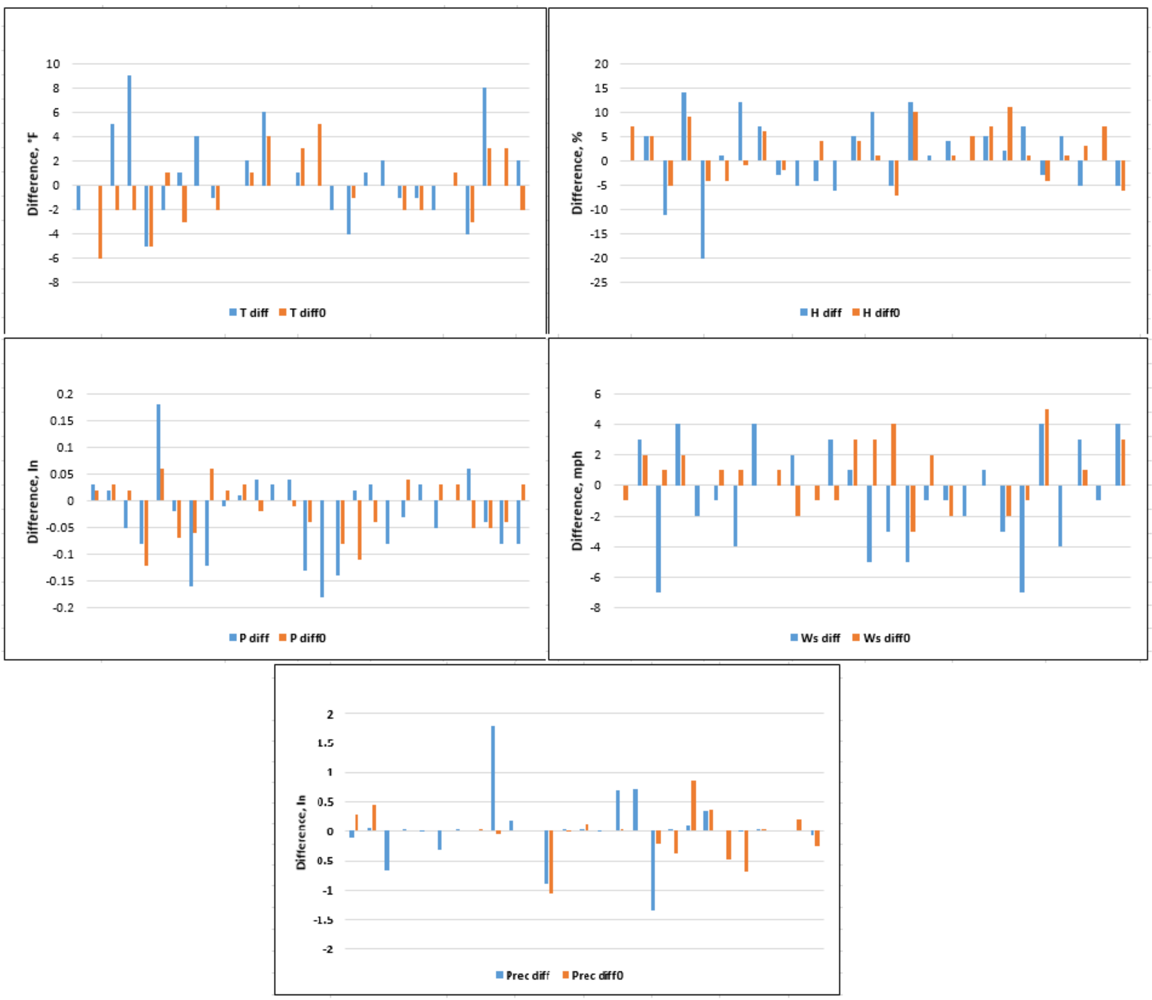


Figure 38. Differences in Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Precipitation Accumulation (Bottom), with and without Odor Complaints: Urban Site 1

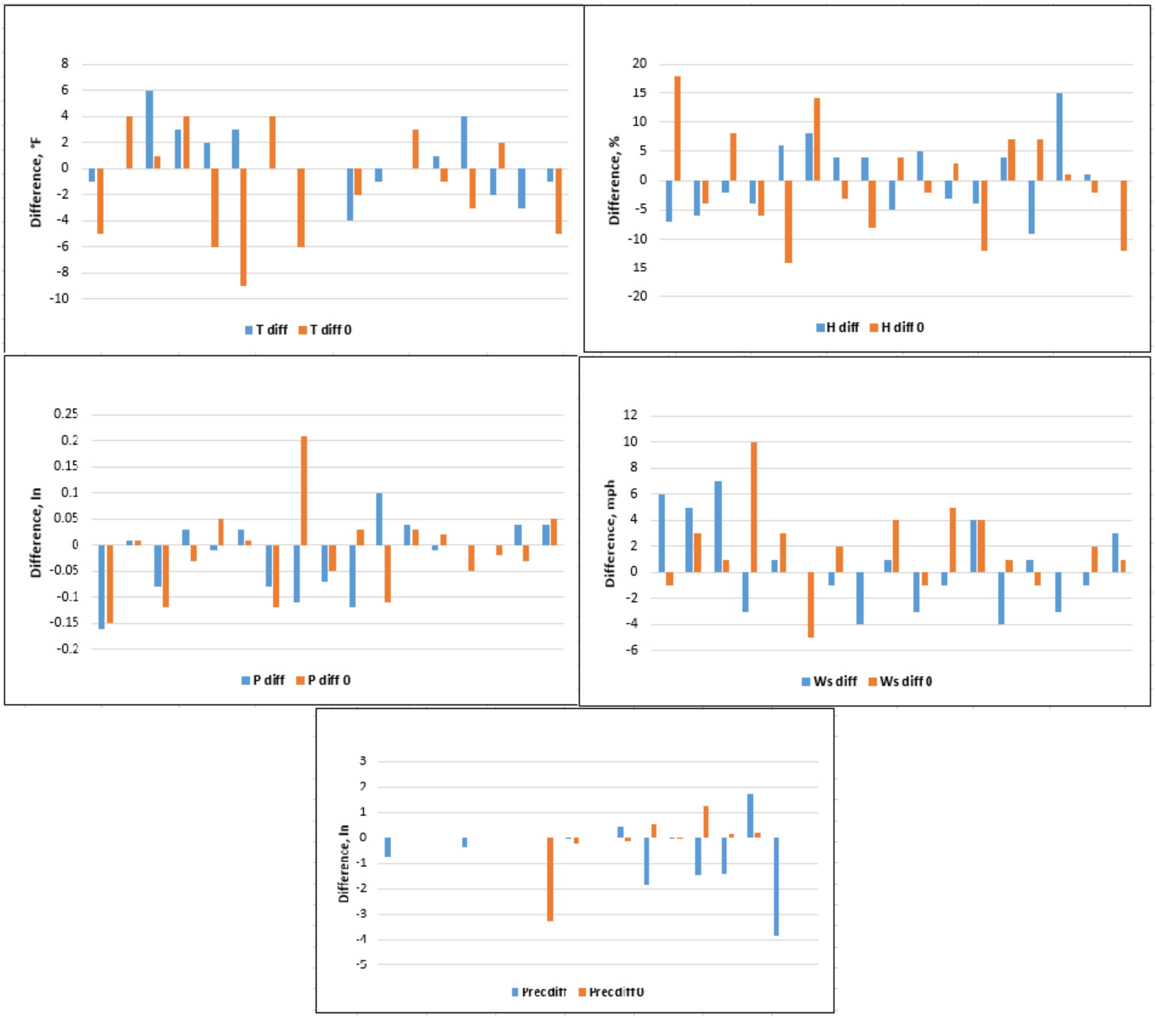


Figure 39. Differences in Meteorological Conditions: Temperature (Upper Left), Humidity (Upper Right), Pressure (Lower Left), Wind Speed (Lower Right) and Precipitation Accumulation (Bottom), with and without Odor Complaints: Urban Site 2

Analysis of wind direction and wind speed revealed which winds and at which speeds were the most frequent on the days when odor complaints occurred as well as for the days when there was an absence of same, for both Urban Site 1 and Urban Site 2. As previously stated in the site description chapter, the location of Urban Site 1 has predominant wind directions of south and east, while Urban Site 2 has predominantly easterly winds. Clusters of odor complaints confirmed the influence of predominant wind directions since the greatest number of odor complaints occurred in the same locations. Cluster of odor complaints for Urban Site 1 were already presented in Figure 27 (3.1 Preliminary Analysis), while the clusters for Urban Site 2 are presented in Figure 40.

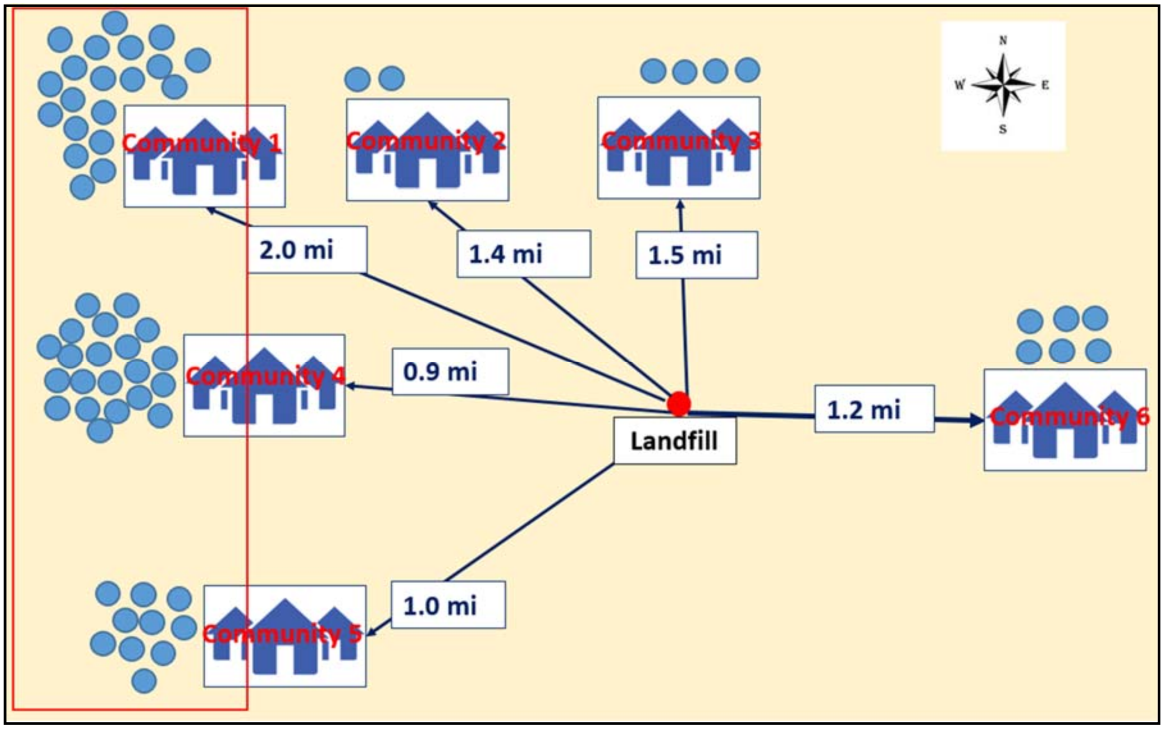


Figure 40. Cluster of Odor Complaints from the Communities Surrounding the Landfill Site (Urban Site 2).

For Urban Site 1, on the days when odor complaints occurred, the most frequent wind directions were SSE and South, or there was no wind, and for the random days with similar meteorological conditions but no odor complaints, the most frequent winds were East, SE, ESE, and the presence of very calm wind or no wind (Figures 41-42). The most frequent wind speed range in both scenarios was from 8-12 miles per hour, and the second highest was from 4-7 miles per hour (Figure 43). Urban Site 2 showed a similar relationship. In the scenario with odor complaints, the most frequent wind directions were ESE, SE or no wind, while for the second scenario in the absence of odor complaints, the most frequent wind directions were East, ESE, SE and SSE (Figures 44-45). The range with most frequent wind speeds was from 8-12 miles per hour, while the second highest was 13-18 miles per hour (Figure 46). Notably in the case for both sites, the wind directions were very similar when odor complaints occurred as well as when complaints were not received. The strength of the winds was the same in both scenarios.

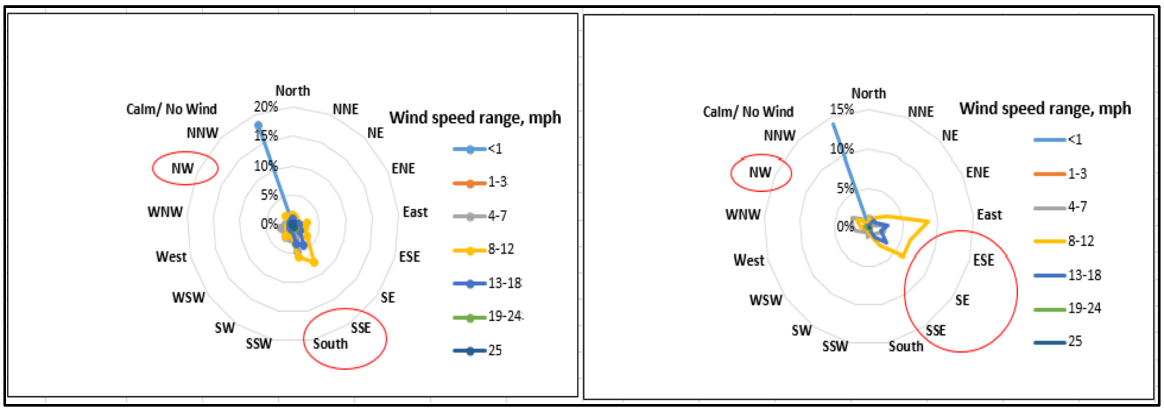


Figure 41. Wind Rose for Urban Site 1: Days with Odor Complaints (Left) and Days without Odor Complaints (Right)

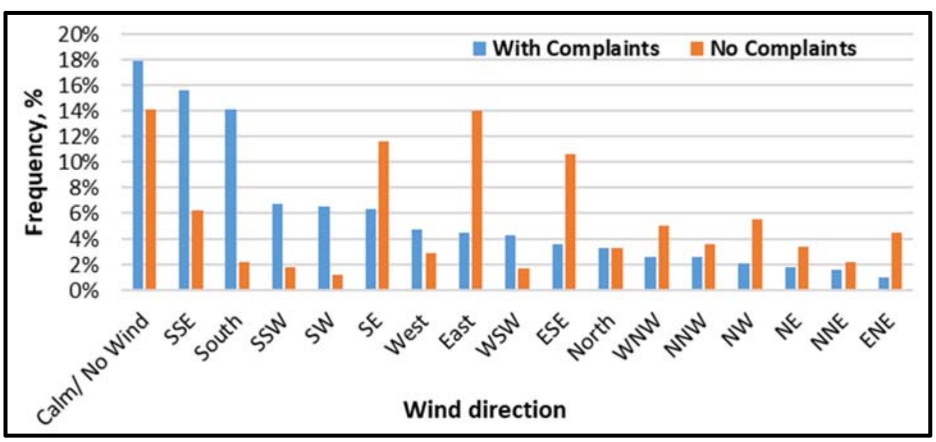


Figure 42. Most Frequent Wind Directions, With or Without Odor Complaints (Urban Site 1)

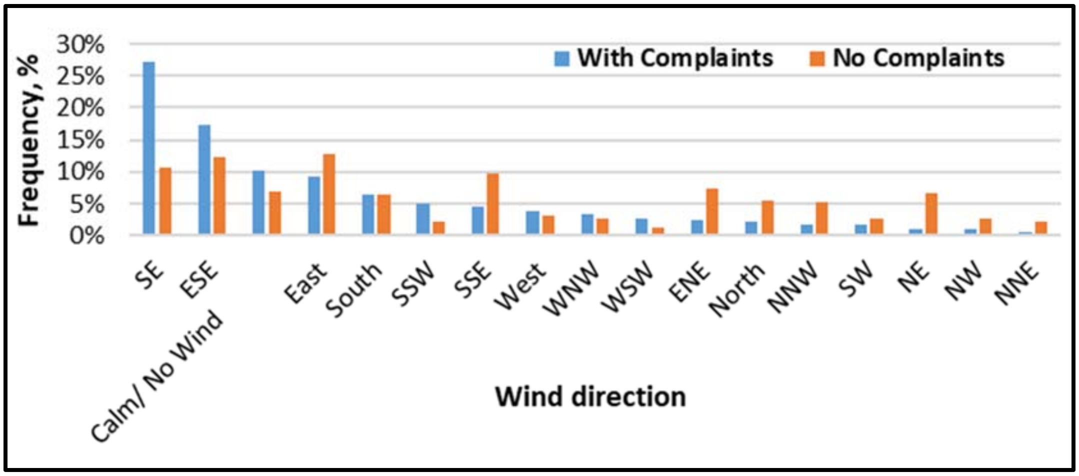


Figure 43. Most Frequent Wind Directions, With or Without Odor Complaints (Urban Site 2)

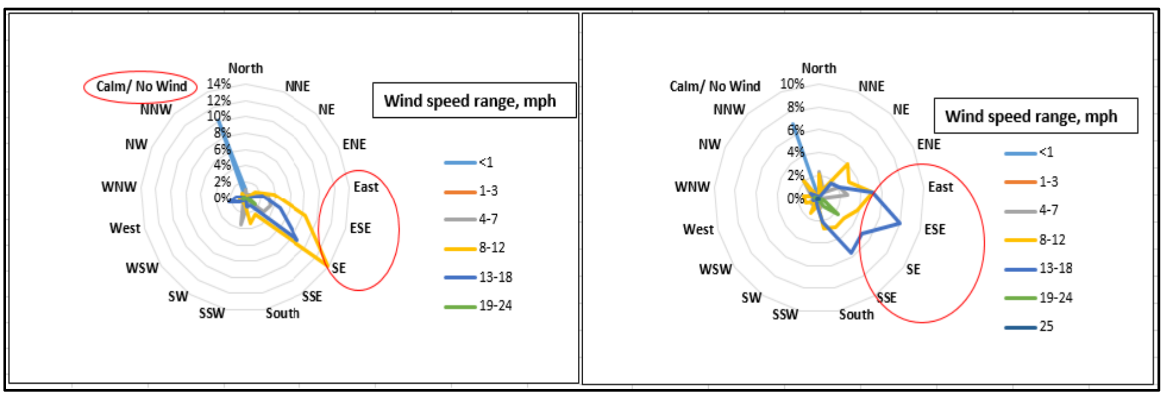


Figure 44. Wind Rose for Urban Site 2: Days with Odor Complaints (Left) and Days Without Odor Complaints (Right)

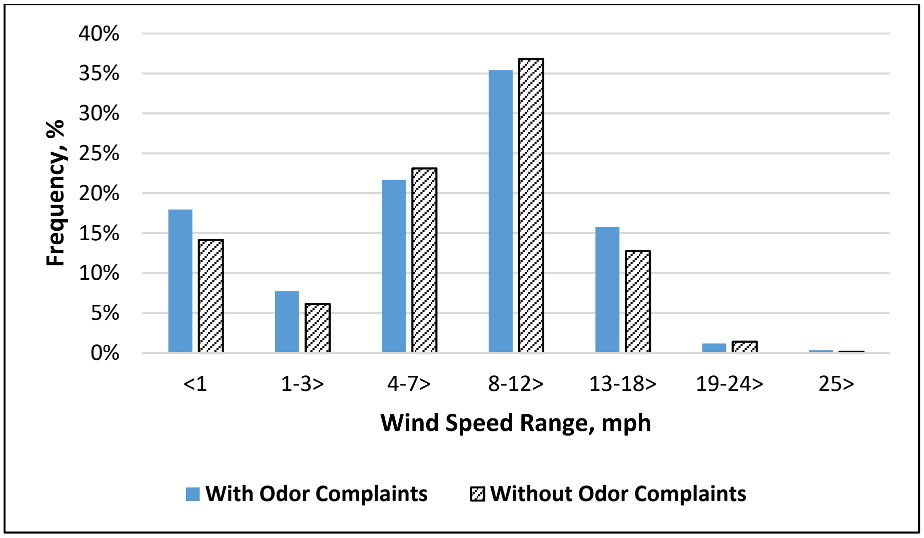


Figure 45. Most Frequent Wind Speeds, Urban Site 1: With and Without Odor Complaints

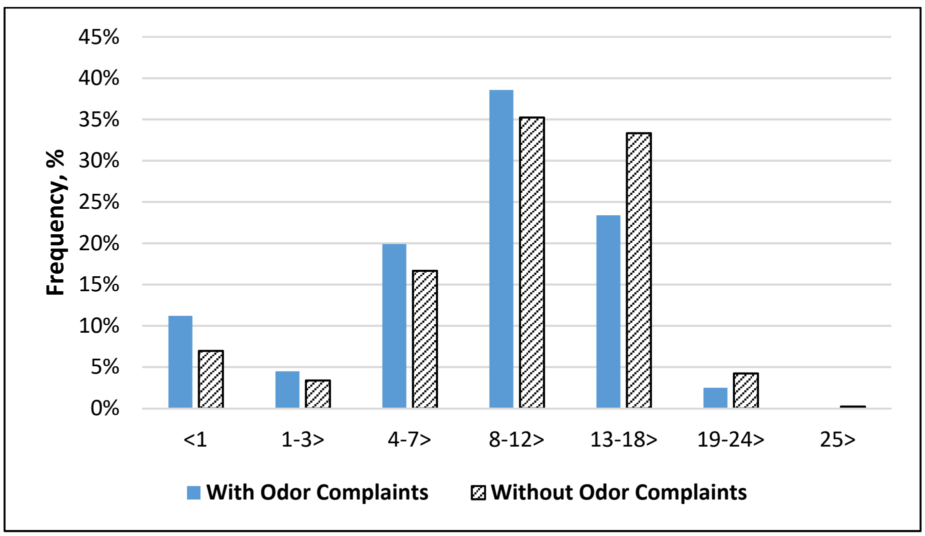


Figure 46. Most Frequent Wind Speeds, Urban Site 2: With and Without Odor Complaints

Weather conditions and the most frequent events for both scenarios revealed that, in the case for Urban Site 1, mostly cloudy sky conditions prevailed on the days when odor complaints occurred, while scattered clouds were more prevalent when odor complaints were not received. In the case of the Urban Site 2, it was opposite situation. On the days when odor complaints were received, clear sky conditions prevailed, while on the days without complaints, mostly cloudy skies were most common. In the case of most frequent events, both sites had the same trend. On days with or without odor complaints, the most frequent event identified was presence of no events or no rain. Also, it was noticed that on the days when there was an absence of complaints, the rain was more frequent. Results are presented in Figures 47-50.

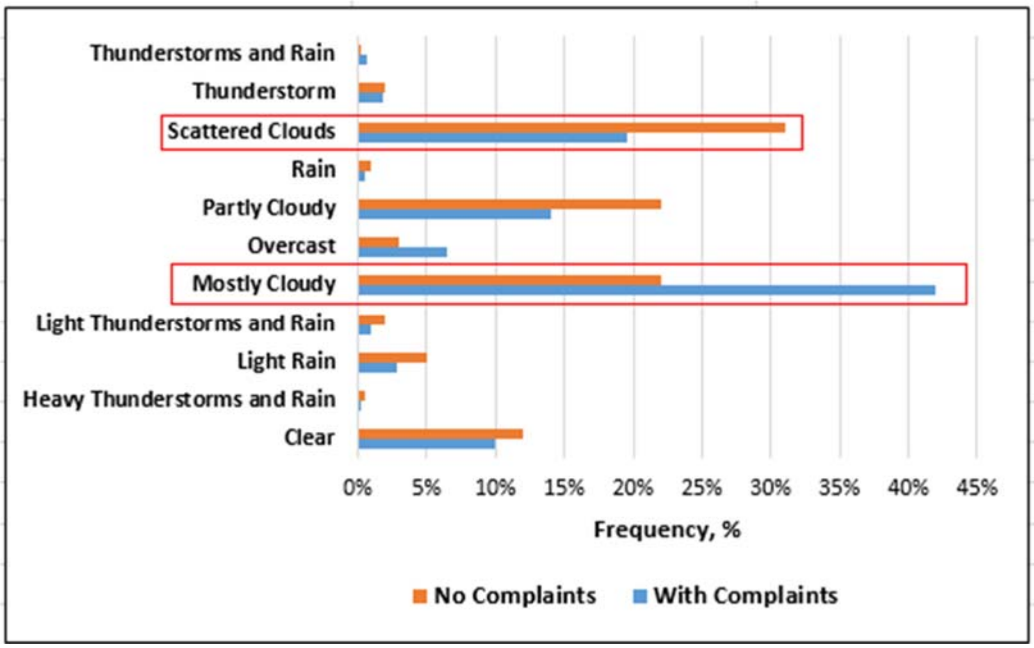


Figure 47. Weather Condition, with or without Odor Complaints (Urban Site 1)

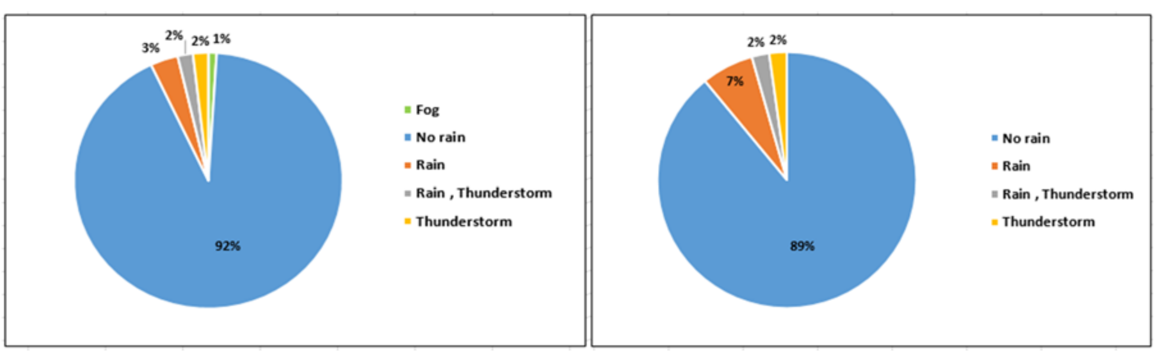


Figure 48. Frequency of Events for Urban Site 1: Days with Odor Complaints (left) and without Odor Complaints (right)

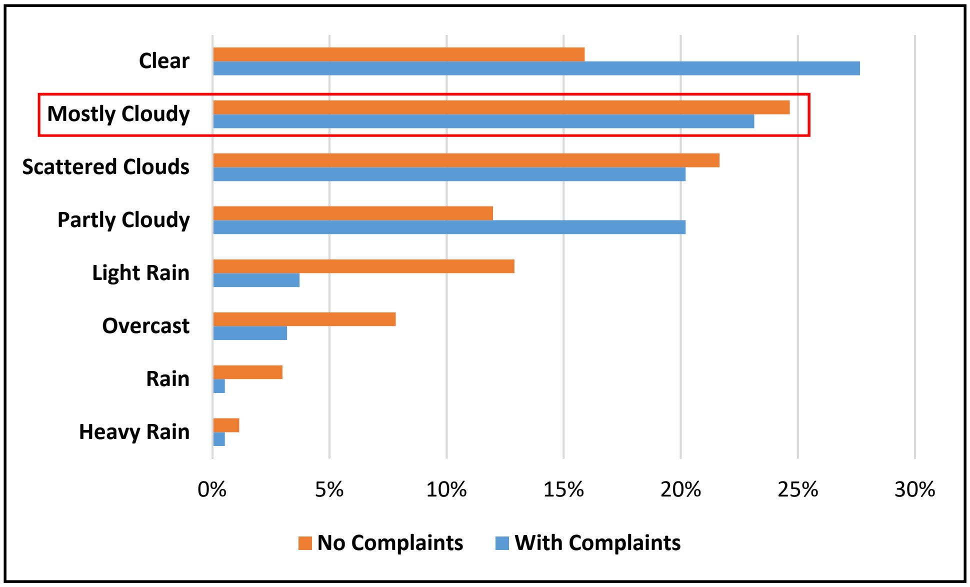


Figure 49. Weather Condition, with or without Odor Complaints (Urban Site 2)

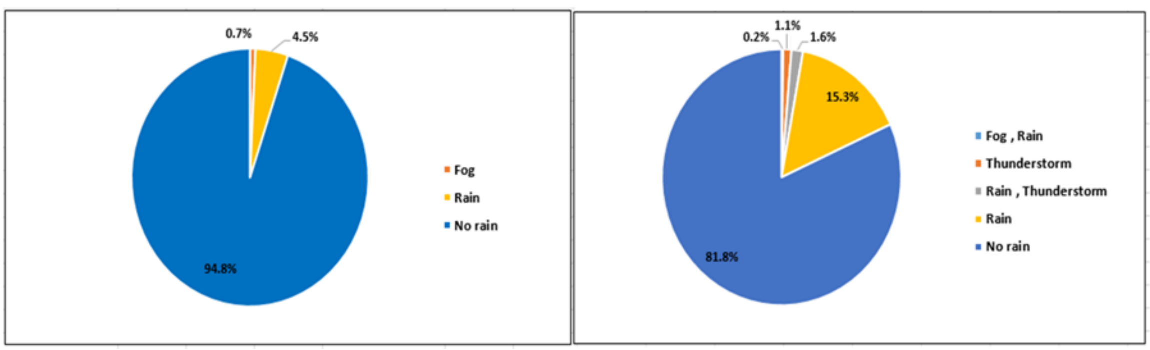


Figure 50. Frequency of Events for Urban Site 2: Days with Odor Complaints (left) and without Odor Complaints (right)

3.5 Correlation Matrix, Principal Component Analysis and Linear Regression

A correlation matrix was used to test dependency among various meteorological variables and odor complaints from the solid waste sites. With so many variables the table was reduced to reflect those impacts on the number of complaints. Table 33 represents the correlation matrix produced by XLStat. The bold values meet the $p<0.05$ test, but none of the correlations could be defined as “strong.” (greater than 0.7). The full matrix showed relationships between heat, wind, humidity and pressure on a given day, and some relationships between those variables but none with the number of complaints on a given day, nor with weather patterns on prior days. In part, this may be because so many days were zero complaints.

Table 33. Correlation Matrix: Relationship between Frequency of Odor Complaints and Parameters of Interest

Variables	No of Complaints
Days -1	0.112
Days -2	0.081
Days -3	0.052
Temp High	0.053
Temp Chg	0.051
Temp Avg	0.045
Temp Low	0.034
Hum High	0.063
Hum Chg	**0.022***
Hum Avg	0.081
Hum Low	0.070
P High	-0.058
P Avg	-0.055
P Low	-0.058
Wind Speed Avg	**0.005***
Wind Speed Low	-0.086
Precip	**0.021***

*Statistically Significant (p<0.05)

As noted in section 2.3.5, PCA is designed to take a large number of variables, and use the eigenvalues that measure variability to create new factors. A scree plot is sued to determine how many factors contribute significantly to the overall variance. Figure 51 is a scree plot for the meteorological data as relevant to the number of odor complaints. It shows that the first 7 factors are greater than 1 and it takes 12 to account to 70% of the variance. This suggested that the odor complaints are random since no limited number of factors accounts for the majority of the variance.

Table 34 shows the eigenvalues/ factors for the data represented in the Scree plot (Figure 51). Table 35 shows the eigenvectors for the first 11 Factors– Factor 1 is all related to weather issues but none are strong contributors. In fact, across all 11 factors there is no significant (>0.7) contribution by any one or group of variables to a factor, which suggests the variable of interest – odor complaints, is random.

The Factor loadings in Table 36 are used to determine relative weight. For example, the temperature and humidity may be large numbers, while precipitation is small. The factor loading indicate if a given variable or group of variables is significant to the explanation of variance. The Factor loading shows that for Factor 1, temperature and pressure were the major contributors, albeit negatively to another (high pressure is low temperature and vice versa). Warm, high humidity and low pressure days are suggested as potential explanations for explaining complaints. No other factor had weights above 0.7.

A Varimax graph (Figure 52) is useful to visualize the relationships. Here temperatures were correlated, humidity was correlated, and pressure was correlated, but they were not correlated with each other (within 45 degrees on one another). Low wind and pressure had some relationship. Odor complaints did not correlate to any of these variable (it is at the central axis). Hence the complaints appear to be random, and not related to weather.

Table 34. Eigenvectors/ Factors: Measure of the Relative Contribution of the Variable to the Factor

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Eigenvalue	6.87	2.63	2.46	1.88	1.79	1.4	1.24	1.2	1.17	1.17	1.16
Variability (%)	20.83	7.99	7.47	5.71	5.43	4.25	3.77	3.63	3.56	3.54	3.53
Cumulative %	20.83	28.83	36.3	42	47.45	51.71	55.48	59.12	62.68	66.23	69.77

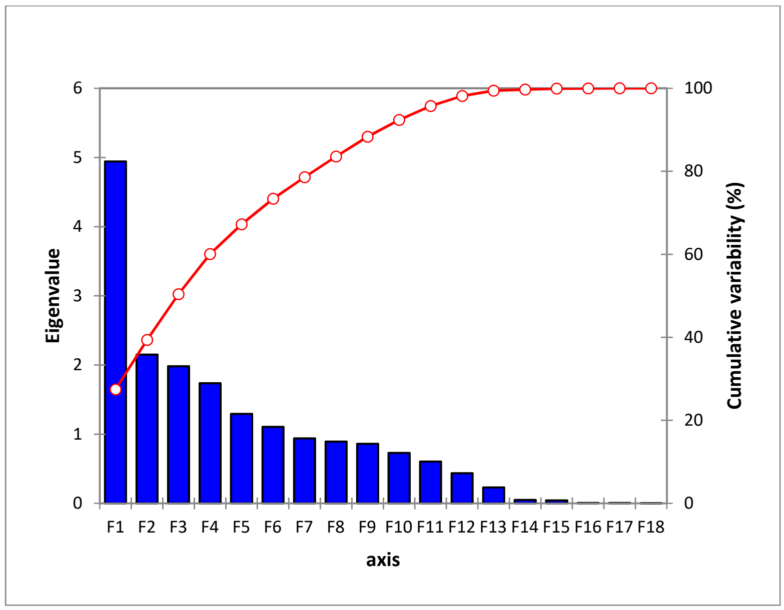


Figure 51. Scree Plot that Shows the Relative Strength and Contribution of the Factors Toward the Total Variance in the Odor Complaint Data

Table 35. Eigenvectors Representing the First 11 Factors

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
No of complaints	0.035	-0.145	-0.044	0.606	-0.27	-0.011	0.035	-0.031	-0.026	0.018	0.011
No of Comp (0 or 1)	0.038	-0.142	-0.036	0.6	-0.28	0.003	0.057	-0.023	-0.027	0.031	0.005
compl t-1	0.033	-0.11	-0.022	0.124	-0.06	-0.062	-0.242	0.281	0.102	0.006	0.011
compl t-2	0.017	-0.089	0.031	0.09	-0.04	-0.199	-0.396	0.146	-0.128	-0.024	-0.005
compl t-3	0.004	-0.049	0.063	0.066	0.001	-0.275	-0.295	-0.075	0.088	-0.096	-0.017
Sat	0.001	-0.018	0.016	-0.046	0.063	0.002	-0.112	0.147	-0.051	0.524	0.615
Sun	-0.004	0.022	0.028	-0.081	0.077	-0.124	-0.09	-0.12	-0.058	-0.219	-0.018
Mon	-0.003	0.03	0.018	0.041	-0.01	-0.077	0.337	-0.48	-0.26	0.333	-0.363
Tue	0	0.013	-0.018	0.077	-0.07	0.044	0.476	0.172	0.195	-0.308	0.399
Wed	0.001	-0.004	-0.027	-0.012	-0.03	0.132	-0.069	0.623	-0.148	0.229	-0.493
Th	0.002	-0.026	-0.01	0.009	-0.03	0.07	-0.347	-0.182	-0.459	-0.495	0.091
Fr	0.003	-0.017	-0.006	0.013	-0.01	-0.048	-0.196	-0.159	0.781	-0.063	-0.23
Rain t-1	0.076	-0.064	-0.206	0.005	0.136	-0.093	-0.066	-0.063	0	0.138	0.037
Rain t-2	0.053	-0.034	-0.115	0.026	0.048	-0.078	-0.221	-0.226	0.005	0.243	0.121
Rain t-3	0.042	-0.018	-0.063	0.037	0.019	-0.087	-0.195	-0.237	0.066	0.257	0.072
Temp t-1	0.332	0.156	0.13	0.003	-0.04	0.024	-0.017	0.031	-0.007	0	0.009
Temp t-2	0.31	0.175	0.146	-0.015	-0.04	-0.051	-0.043	0.016	-0.02	-0.003	-0.002
Temp t-3	0.287	0.186	0.147	-0.013	-0.04	-0.05	-0.047	-0.018	-0.009	0.017	0.005
ow wind -1	-0.141	0.378	-0.279	0.088	-0	0.032	-0.046	0.001	-0.003	0.006	0.016
low wind -2	-0.133	0.258	-0.289	0.086	0.016	0.412	-0.133	-0.06	0.034	0.002	0.021
low wind -3	-0.114	0.136	-0.248	0.059	0.019	0.498	-0.163	-0.088	0.038	0.011	-0.011
Temp High	0.327	0.159	0.149	0.034	-0.04	0.106	-0.011	-0.013	0.025	0.01	0.006
Temp Avg	0.324	0.244	0.121	0.085	0.032	0.087	-0.015	-0.005	0.017	0.003	0.004

Temp Low	0.301	0.291	0.094	0.115	0.084	0.068	-0.017	0.001	0.011	-0.003	0.001
Hum High	0.177	-0.389	-0.126	-0.022	0.236	0.115	0.018	-0.004	-0.002	-0.024	-0.014
Hum Avg	0.229	-0.217	-0.166	0.122	0.436	0.092	0.037	0.016	-0.006	-0.049	-0.026
Hum Low	0.198	0.006	-0.146	0.209	0.467	0.043	0.038	0.026	-0.006	-0.051	-0.029
P High	-0.278	0.098	0.266	0.187	0.287	-0.057	-0.012	0.026	-0.002	0.011	-0.002
P Avg	-0.256	0.115	0.316	0.204	0.301	-0.021	-0.016	0.019	0	0.012	0
P Low	-0.235	0.127	0.343	0.207	0.307	0.011	-0.02	0.01	0.006	0.014	0.001
Wind Speed Avg	0.019	0.216	-0.339	0.051	0.038	-0.452	0.083	0.119	-0.03	-0.028	-0.016
Wind Speed Low	-0.121	0.393	-0.247	0.051	-0	-0.29	0.011	0.069	-0.028	-0.031	0.001
Precip	0.091	-0.048	-0.268	0.044	0.248	-0.216	0.124	0.058	-0.021	-0.082	-0.031

Table 36. Factor Loadings Representing the Weights for Each Input Parameter

	F1	F2	F3	F4	F5	F6	F7
No of complaints	-0.107	-0.065	-0.079	-0.026	0.388	0.437	-0.584
days -1	-0.106	-0.138	-0.043	-0.03	0.489	0.339	-0.158
Days -2	-0.019	-0.124	-0.009	0.011	0.631	-0.04	0.088
Days -3	0.022	-0.042	-0.056	0.014	0.512	0.147	0.707
Temp High	**-0.759***	0.517	-0.158	-0.204	0.005	0.07	0.05
Temp Chg	-0.077	0.237	-0.308	-0.24	-0.311	0.643	0.159
Temp Avg	**-0.748***	0.629	-0.131	-0.045	0.048	-0.021	0.014
Temp Low	**-0.693***	0.671	-0.101	0.073	0.077	-0.089	-0.013
Hum High	**-0.591***	-0.598	-0.342	0.072	-0.046	-0.014	0.065
Hum Chg	-0.296	-0.383	-0.351	0.088	-0.338	0.394	0.135
Hum Avg	-0.723	-0.291	-0.378	0.412	0.019	-0.13	-0.02
Hum Low	-0.597	0.074	-0.285	0.574	0.071	-0.188	-0.088
P High	**0.812***	0.163	-0.429	0.305	0.029	0.013	-0.013
P Avg	**0.773***	0.238	-0.504	0.274	0.031	0	-0.015
P Low	**0.725***	0.29	-0.55	0.24	0.023	-0.008	-0.01
Wind Speed Avg	-0.097	0.094	0.559	0.602	-0.048	0.323	0.064
Wind Speed Low	0.29	0.345	0.539	0.494	-0.038	0.183	0.045
Precip	-0.322	-0.223	0.122	0.534	-0.107	0.065	0.02

*Group of variables significant for explaining variance of odor complaints

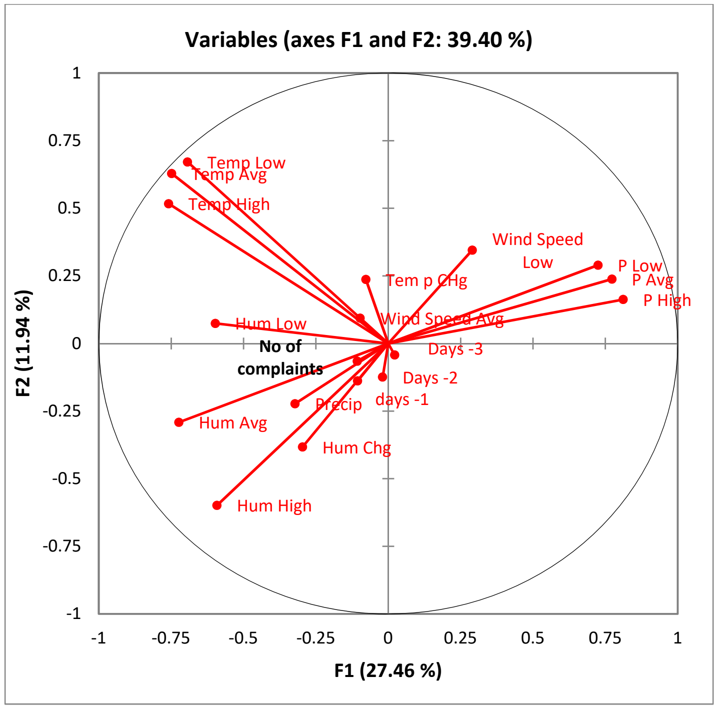


Figure 52. Varimax Graph Illustrating the Relationship between the Variables

Table 37 shows the coefficients used for the regression model to predict the complaints. Table 37 is not very useful in highlighting the major issues, so Figure 53 shows the coefficients compared to one another. The largest coefficients are for temperature, wind speed, pressure and humidity (note they are also higher values) so this may or may not be meaningful.

Table 37. Standardized Coefficients used in Regression Modeling

Source	Value	Standard error	t
Day -1	0.091	0.016	5.705
Days -2	0.069	0.016	4.319
Days -3	0.037	0.016	2.296
Temp High	-0.228	0.186	-1.226
Tem p Chg	0.077	0.019	4.111
Temp Avg	0.421	0.406	1.035
Temp Low	-0.229	0.246	-0.931
Hum High	0.002	0.101	0.016
Hum Chg	-0.004	0.019	-0.217
Hum Avg	-0.079	0.172	-0.458
Hum Low	0.132	0.113	1.165
P High	-0.176	0.108	-1.63
P Avg	0.542	0.195	2.783
P Low	-0.418	0.119	-3.518
Wind Speed Avg	0.062	0.022	2.767
Wind Speed Low	-0.135	0.026	-5.225
Precip	-0.019	0.018	-1.041

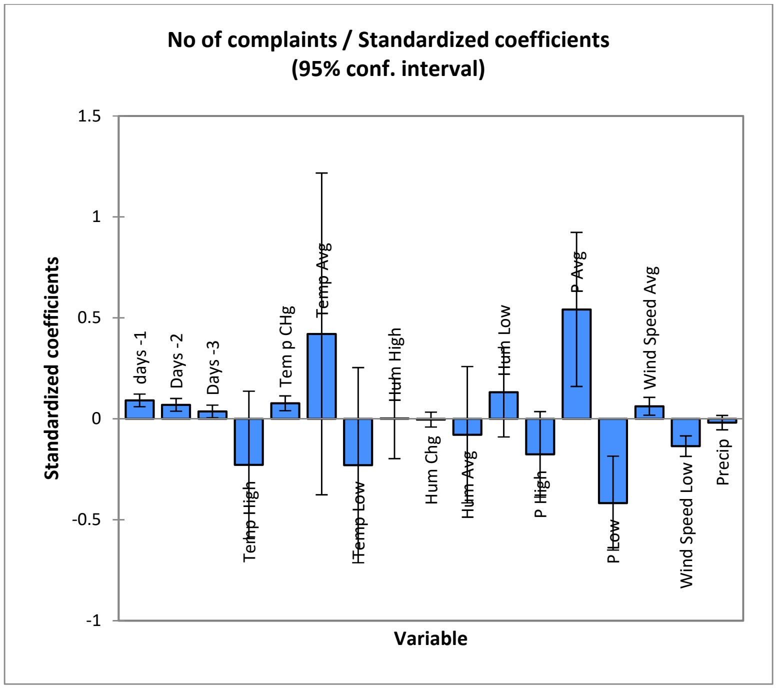


Figure 53. Standardized Linear Regression Coefficients

4 CONCLUSION AND RECOMMENDATIONS

4.1 Summary of Findings

Databases on odor complaints were provided from two different landfill sites, both operating in close proximity to residential areas. Data in this study was used with the aim to investigate the existence of patterns or trends, if any, in the relationship between frequencies of odor complaints with the influence of meteorological parameters of interest: temperature, humidity, pressure, wind direction, wind speed, precipitation accumulation, weather conditions and events present at the time.

Preliminary analysis of the days when odor complaints occurred at Urban Site 1 showed the possibility for pattern identification since there was a presence of a trend that occurred in all the situations when odor complaints were received. In all scenarios, odor complaints were received while the wind speed was weak (<1 mph), wind direction was from the south, temperature and pressure decreased from the previous day and the absence of precipitation or rain events was noted. Also, the weather conditions were stable with mostly cloudy skies. The dry season, from November until April, showed higher frequency of odor complaints for Urban Site 1, while for Urban Site 2 it was the wet season (May until October). Slightly more odor complaints were made in the afternoon hours and during working days, probably because on the weekends people tend to spend their time outside the house and in the afternoon hours, since people are coming home from work and spending more time at home. Locating the odor complaints on the map revealed clusters of complaints and communities with the highest frequency of complaints, in a relationship with the predominant wind directions for that particular location. Correlations between meteorological parameters, both for Urban Site 1 and Urban Site 2, showed that wind direction and wind speed were the parameters with lowest correlations when compared to the values from the day before, which is expected since those are meteorological parameters with the lowest expected predictive ability, while temperature, humidity, and pressure had constantly higher correlation values. Also, a highly negative Pearson correlation coefficient (r_1 = -0.73; r_2= -0.94) was identified between temperature and humidity, which results in increases in temperature if humidity decreases and vice versa.

Analysis of isolated odor complaints (three or more complaints in the same day) with meteorological parameters, for both sites, revealed there is an absence of correlations between them. An analysis was also performed based on dividing the data set into dry (November until April) and wet (May until October) season, which showed that higher frequency of odor complaints, in the case of both sites, tended to occur in the dry season. Results obtained for the dry season for the Urban Site 2 identified pressure drop as a parameter with the highest observed correlation with frequencies of odor complaints. Precipitation accumulation data analyzed for the day before, three days and seven days before showed no correlation with number of odor complaints for Urban Site 1. However, for Urban Site 2, results showed that the number of complaints could be related to the amount of precipitation that has been accumulated three days prior the odor complaints, which could indicate a different type of odor source.

Since until this point in the analysis, strong correlation between meteorological conditions and frequency of odor complaints was not identified, additional dates with days when odor complaints did not occur have been added to the original complaint data set. Results obtained also showed no correlation between the frequency of odor complaints and meteorological conditions. When segregating the data set into dry and wet season, Urban Site 2 showed higher number of odor complaints in the wet season, which could be related to the influence of precipitation accumulation this site is experiencing. Meteorological parameters for both sites showed the same trend for dry and wet seasons, except the difference in higher number of complaints, which for Urban Site 1 occurred in dry season and for Urban Site 2 in the wet season. Also, it was noticed that more stable weather conditions tended to occur in dry season. Autocorrelation analysis of odor complaint frequencies indicated no potential in predicting the number of odor complaints from one day to the next.

Analysis of the isolated days (three or more complaints in the same day) and random days without complaints but with similar meteorological conditions was performed with the goal to potentially distinguish the weather patterns when complaints actually occurred compared to those when no complaints were filed. Results revealed that the pattern for weather conditions when odor complaints could potentially occur cannot be identified since there is a presence of the same trends in meteorological conditions, both when complaints actually occurred as well as when there was an absence of same. Wind directions in the case of Urban Site 1 were related to the odor complaints since most of the complaints were coming from the communities located south and SE from the landfill site. In the case of the Urban Site 2, a different pattern was observed. Both, on the day with or without complaints, the most frequent wind directions were very similar. Wind speeds prevailing in both locations were from 8-12 miles per hour. For weather conditions, both sites again showed different patterns. In the case of the Urban Site 1, odor complaints were related to mostly cloudy skies, while in the case of the Urban Site 2 clear skies were dominant. When analyzing the meteorological events occurring for each scenario, both sites had the same trend. The most frequent event identified, whether or not complaints were present, was the absence of rain. Also, it was noticed that on days with no odor complaints, rain was more frequent.

Principal Component Analysis suggested warm, humid and low pressure days as potential explanations for frequency of odor complaints. It showed relationships between heat, wind, humidity and pressure on a given day, and some relationships between those variables but none with the number of complaints on a given day, nor with weather patterns on prior days, which suggested that the odor complaints are random since no limited number of factors accounts for the majority of the variance. Linear regression showed that temperature, pressure, wind speed and humidity had the largest impact (note they were also higher values) on frequency of odor complaints, so this may or may not be meaningful.

From the results obtained, it could be noticed that meteorological parameters alone do not have the ability to predict when odor complaints could potentially occur. The decision to file an odor complaint is affected by many other factors, not just with the presence of meteorological conditions. There could conceivably be a situation when odor was detected, and the person would immediately file a complaint to site personnel, and in a similar situation, it could be that the person will procrastinate for some time or even days after first detecting the odor to make a complaint, and in a third possibility, the person may detect the odor but not bother to, or not know how to, file an official complaint, which makes it very difficult to verify and relate to the presence of complex weather conditions. Even though more odor complaints tend to occur when there is an absence of rain, information in this study revealed that rainfall accumulated from up to three days before could trigger odors and eventually a filing of a complaint. Different results from the two separate sites could indicate that odor complaints are occurring randomly and attempting to analyze only one scenario in which they could potentially occur might be an oversimplification of a complex phenomenon. Other reasons could be related to the variability of the data sets collected, the presence of outliers, more detailed data collection on odor complaints, etc.

After the detailed analysis of the data sets, some of the findings suggested empirical but not statistically significant relationships between complex meteorological conditions and frequency of odor complaints. Those found were similar to ones recognized in the literature review (Table 38). More odor complaints were noticed during weak winds and stable weather condition (mostly cloudy skies) because odors tend to linger longer with less mixing and less diffusion. When there was an absence of rainy events, odor complaints were more frequent since rain serves as a cleanser of the air. Dry season, from November to April, was identified with higher potential for odor annoyances. Possibly related to the lack of rain or residents spending more time outside, increasing potential exposure time. Pressure drop was also identified as a potentially interesting factor, since on the days when pressure values would decrease compared to the previous day, there was a tendency of finding more odor complaints filed.

Table 38. Summary of the Findings from This Study Relevant to the Literature Review

Factor	**Conditions**	**Impact**	**Reference**	**Findings (This Study)**
Wind speed and direction	• Weak wind, stable conditions • Clear, strong wind, low variability in wind direction	• Highest odor detection • Significantly lower odor detection	(Capelli, 2008)	More odor complaints noticed on days with weak winds (<1 mph or 8-12 mph most frequent)
Temperature	High	• Higher odor detection • Unstable conditions	(USEPA, 2000)	Heat stimulates odor complaints
Precipitation	Low	• Wet soil prevents LFG migration • Rain seepage into the pore spaces pushes out gases into the atmosphere	(ATSDR, 2017)	Absence of rainy days resulted in higher frequency of odor complaints
Humidity	High or foggy	• Higher odor detection • Warm humid air enhances human sense of smell • Traps smells so they linger longer	(Berglund, 1998)	Higher humidity related to tendency of occurring odor annoyances
Weather conditions	• Clear sky, sunny and windy • Overcast, no wind, high humidity/fog, thermal inversions	• Complaints rarely received • Complaints are more common	(MassDEP, 2007)	Cloudy skies revealed higher potential for odor annoyance

Factor	Conditions	Impact	Reference	Findings (This Study)
Thermal inversions	Season changes (Fall → Winter, Winter→Spring)	During the period of the year in which inversions are more common, odors are held more closely to the ground and are more likely to be detected	(NSWMA, 2008; Energy and Environmental Affairs, 2016)	Dry season (November-April) revealed higher frequency of odor annoyances
Pressure	Low	More LFG seeps into the air	(USEPA, 2000)	Pressure drop revealed higher tendency of occurring odor complaints

4.2 Recommendations

Odor complaints can help site personnel to identify conditions and events that potentially lead to a nuisance odor complaint. Considering that residents living close to the landfill site can be present 100% of the year, they can provide valuable input. Once awareness about specific activity that could trigger an odor event is recognized, site managers can investigate the source and implement suitable actions. Any site activity prone to producing odors should take into consideration complex weather conditions, especially wind direction and wind speed, since those are parameters responsible for physically dispersing odors off-site. Installation of a weather station at the site and collecting relevant meteorological data can help to identify if the site could be responsible for causing the odor event. Keeping an extensive internal odor report log at all times, making a note of all site activities that could lead to producing odors, would be a valuable tool to be used when investigating the sources of odor complaints.

With the aim of better identifying the relationship between the odor complaints and meteorological conditions, it is necessary to obtain data about the solid waste operations at the site. One of the limitations of this study was inconsistent information about the time that the odor was first noticed (not just the time of a complaint), so it can be related to meteorological condition and site activities. Another major limitation was an absence of comprehensive site records about waste operations, limiting the possibility to track historical records. With that being said, there is a need to substantially improve the amount of valuable information provided in odor complaint logs as well as in the site records. Implementing an effective site diary to keep track of the activities present at the site would be a valuable asset for dealing with odor episodes. In order to successfully identify the source of odor, perceived by the people living and working close to the landfill site, data on solid waste operations should be recorded so that it could be mined. Insufficiency of both, suitably exhaustive site and complaints documentation, prevented better interpretations of the data collected in this study.

Odor complaints and data on solid waste operations should be compared using a detailed analysis of meteorological conditions and operations cross-compared to the actual time of the odor episode not the time the complaint was filed. In addition, further investigation of the influence of pressure drop and atmospheric stability class on odor complaints should be performed because these parameters are not routinely recorded in most typical weather stations. Atmospheric stability class for each day could be identified through temperature gradient or temperature lapse rate method. This method uses the vertical temperature gradient ($\Delta T/\Delta z$) between two levels: in this case, at the top of the hill (landfill body) and at the ground level (fence line). By knowing those values, calculated temperature gradients can be compared to Table 39 with Pasquill Stability classes (A-F) to identify the stability class of that particular day. An example of this calculation is presented as follows:

T1=10ºC   T2=2ºC

z_1=3000 m

z_2=5000m

Temperature gradient=(ΔT/Δz);

Temperature gradient= (10-2)/ (3000-5000)

Temperature gradient= -0.4ºC/100m

Then by the looking in the table, we can see that gradient of -0.4ºC/100m falls under category "E" or "Slightly Stable" for atmospheric stability class.

Table 39.Pasquill Atmospheric Stability Classes

Pasquill Classes		**Temperature Gradient** **($\Delta T/\Delta z$) (◦CK/100m)**
A	Extremely unstable	**($\Delta T/\Delta z$) <-1.9**
B	Moderately unstable	**-1.9≤($\Delta T/\Delta z$) <-1.7**
C	Slightly unstable	**-1.7≤($\Delta T/\Delta z$) <-1.5**
D	Neutral	**-1.5≤($\Delta T/\Delta z$) <-0.5**
E	Slightly stable	**-0.5≤($\Delta T/\Delta z$) <1.5**
F	Moderately stable	**1.5≤($\Delta T/\Delta z$) <4**

Installation of temperature and pressure sensors at the top of the hill and at the fence line would be the first step in collecting this potentially useful information. Finally, the strength of statistical correlations will always be dependent upon the size of the data set. If more urban landfill sites would participate by providing the necessary data, it would allow for more powerful analyses.

4.2.1 Revised Odor Complaint Verification Form

Since the human sense of smell is highly subjective (Philpott et al. 2006), an effective procedure to odor investigation must be developed. In an effort to gain more useful information from odor complaint logs with the aim of identifying patterns that could lead to the detection of nuisance odors in the community, the following recommendations should be considered. The main limitation of this study was that the databases that were provided only contained limited or inconsistent information on the environmental and operational conditions present at the site when the odor was actually detected offsite. Consistent odor complaint databases with relevant information at the exact time of the event would improve the understanding of why an odor complaint was filed. Background information is key to identifying the source of the odor and its frequency, duration and strength, when the odor was first observed as well as the most common descriptors about the odor that people detected. The following information is recommended to be included in the odor complaint verification form:

- Identifying if the person who made the complaint is a repeat reporter who calls often to complain because of hypersensitivity or because a real odor problem exists.
- Information on odor characteristics described by people who made a complaint could be used to help identify what are the most common odor descriptors and compare it to the days with highest number of complaints in the same day.

- Documenting time of an odor event when it was actually noticed, and not when the complaint is filed.
- Impact of weather data collected on parameters of interest: temperature, humidity, pressure drop, rain, wind speed, wind direction, etc. at the time of detected odor.
- Weather at the time of an odor event (Calm, fog, windy, rain, combination of weather conditions, additional).
- Asses the frequency of odor annoyances (Single incident or daily).
- Asses the intensity of odor (Likert scale: very light to very strong).
- Determine total duration of the odor (Example: 1 minute to 24 hours).
- Asses the frequency of odor complaints in respect with site operational activities known to produce odors (delivery and handling the waste, delays in covering an odorous waste, etc.)
- Asses the frequency of whether people would/do complain to distinguish if sufficient management practices have been employed or people normally do not complain (Odor events could be rare or poor strength).
- Determine if odor events are related to seasonal variations by differentiating between the diverse components (weather, time of the year, etc.), which could lead to odors (Dry season: November until April, Wet season: May until October).

All of this information would be valuable in resolving the source and transport pathway of the odorant. A proposed odor complaint log is presented in Figure 54 that follows. The proposed form is intended to be filled out by landfill personnel during a verification visit interview with the resident who filed the complaint.

ODOR COMPLAINT LOG FORM FOR LANDFILL ODORS

General Information

Date of Odor Complaint:

Name of the Person:

Address of Odor Complaint:

Time of Odor Complaint:

Time AM/PM:

Day in a Week:

Landfill in Proximity to Odor Observation:

Possible Source of Odor (Check the box that applies):

Waste receiving and processing ☐ Drilling Gas Wells Cover ☐

Scraping Daily or Intermediate Cover ☐ Digging Trenches ☐

“Other”____________________________________

Description of Odor

What Time was Odor First Detected?

What Time was Odor Last Detected?

Duration of Odor (minutes or hours):

Location: Indoors/Outdoors:

Strength (1-5, with 1 being very light and 5 being very strong):

Character (Type):

Meteorological Conditions at Time of Odor Observation

Temperature (◦F): Wind speed (MPH):

Wind Direction: Sky Conditions:

Precipitation Accumulation (In): Pressure (In):

Humidity (%):

VERIFIED: YES / NO **Signature:**

Figure 54. Recommended Odor Complaint Log

4.2.2 Operational Adjustments

If the odor complaints received have a trend of describing the same odor, it could potentially indicate that people are perceiving a common problem, suggesting a more appropriate action to be taken by the landfill manager. For example, by knowing which solid waste operations were involved, the best management and operational practices will be applied to minimize odor issues. Typical solid waste management operations that should be included are:

- Biosolids disposal
- LFG well drilling
- Excavating trenches
- Insufficient vacuum on the landfill to extract gas
- Adequate cover- (daily or intermediate cover type and thickness)
- Leachate seeps
- Collector clogging
- Waste receiving and processing activities (for example full tipping floor)
- Overly odorous loads.

4.2.3 Odor Threat Assessment

In this study, the researchers were unable to develop a way to predict when an odor event will occur from individual meteorological parameters alone; however, certain key parameters have been noted in the literature and have demonstrated empirical relationships in this study, leading to the development of a proposed "Odor Threat Assessment Index".

Assessment of potential key weather conditions for occurrence of odor complaints could assist landfill site personnel in deciding whether or not to alter daily operations on a particular day. Meteorological parameters considered are:

- Wind speed/wind direction
- Temperature/Humidity
- Precipitation
- Atmospheric Stability Class (A-F; with A=being extremely unstable and F=moderately stable)
- Pressure drop over the previous 24 hours.

The threat level is divided into five different categories, representing the level of possibility of an odor complaint. Those five categories are as follows (Figure 55):

1. Critical: Odor complaints are expected immediately (Red color)
2. Severe: Odor complaints are highly likely (Orange color)
3. Substantial: Odor complaints are a strong possibility (Yellow color)
4. Moderate: Odor complaints are possible, but not likely (Green color)
5. Low: Odor complaints are unlikely (Blue color).

Figure 55. Odor Threat Assessment Levels based on the Possibility of an Odor Event

No wind or weak wind speeds, lower than 3 miles per hour, are identified and ranked as critical for expecting a complaint. Low wind days also contribute to finding that stable weather conditions tend to have higher frequency of odor complaints. Lowest ranked are days with strong wind speeds of 18 miles per hour or greater (Figure 56).

Rank	Beaufort Number	Wind Speed, mph	Description
Critical	0-1	<3	Strong Breeze
Severe	2	4-7	Moderate breeze
Substantial	3	8-12	Gentle breeze
Moderate	4	13-18	Light breeze
Low	5+	>18	Light calm

Figure 56. Categories of Wind Speed Ranges Based on the Critical Level of Odor Complaint Occurrence

Receptors located directly downwind from the source have highest possibility of becoming sensitive to dispersed odors. Key receptor locations are ranked as follows:

1. Critical: Directly downwind
2. Severe: Slightly downwind (±45º)
3. Substantial: Crosswind (±90º)
4. Moderate: Slightly upwind (±135º)
5. Low: Directly upwind (±180º).

Warm and humid conditions enhance the human sense of smell so that odors are perceived more intensely. Dew point temperature was selected as a parameter to reflect the relationship between humidity and temperature. By knowing the values for temperature and relative humidity, a value for dew point can be easily read from Table 40, which is adapted from the ASHRAE Psychrometric Chart.

Table 40. Relationship between Relative Humidity, Temperature and the Dew Point

Dew-Point Temperature (°F)															
Relative Humidity	Deign Dry Bulb Temperature (°F)														
	32°F	35°F	40°F	45°F	50°F	55°F	60°F	65°F	70°F	75°F	80°F	85°F	90°F	95°F	100°F
100%	32	35	40	45	50	55	60	65	70	75	80	85	90	95	100
90%	30	33	37	42	47	52	57	62	67	72	77	82	87	92	97
80%	27	30	34	39	44	49	54	58	64	68	73	78	83	88	93
70%	24	27	31	36	40	45	50	55	60	64	69	74	79	84	88
60%	20	24	28	32	36	41	46	51	55	60	65	69	74	79	83
50%	16	20	24	28	33	36	41	46	50	55	60	64	69	73	78
40%	12	15	18	23	27	31	35	40	45	49	53	58	62	67	71
30%	8	10	14	16	21	25	29	33	37	42	46	50	54	59	62
20%	6	7	8	9	13	16	20	24	28	31	35	40	43	48	52
10%	4	4	5	5	6	8	9	10	13	17	20	24	27	30	34
Adapted from ASHRAE Psychrometric Chart, 1993 ASHRAE Fundamentals Handbook															

As an example, if the temperature is 32ºF with relative humidity 80%, a dew-point temperature is equal to 27ºF. Temperature values higher than 75ºF are ranked as critical, while temperature vales below 50ºF as low potential for an odor episode (Figure 57).

Rank	Dew Point (°F)
Critical	>75°F
Severe	65 - 75
Substantial	60 - 65
Moderate	50 - 60
Low	<50

Figure 57. Categories of the Dew Point Temperatures Based on the Critical Level of Odor Complaint Occurrence

Rainfall accumulation from 3 days prior to an odor complaint was identified as a possible indicator for higher frequency of odor complaints. Days with more than 15 mm/hr of rain accumulation in a 3-day period reflect the scenario of torrential rainy days (Figure 58). Those levels of rainfall are categorized as critical for odor complaint occurrence. Dry days with accumulated levels of rainfall less than 0.5 mm/hr over a 3-day period are categorized as a low-level threat for odor complaint (Figure 58).

Rank	Precipitation Previous 3 days (mm/hr)	Descriptor
Critical	>15	Intense/torrential
Severe	7.5-15	Heavy
Substantial	2.5-7.5	Moderate
Moderate	0.5-2.5	Light
Low	<0.5	Dry

Figure 58. Categories of Precipitation Accumulated Previous 3 Days, Based on the Critical Level of Odor Complaint Occurrence

Atmospheric stability class could be identified by measuring the local adiabatic lapse rate, which is the rate of temperature change occurring with a rising or descending air parcel. The vertical temperature gradient is a function of elevation and temperature. The instability of the atmosphere increases as the temperature decreases with elevation. When the temperature decreases slowly, or even momentarily increases, with elevation- the atmosphere is considered stable. This information is highly site-specific and is rarely reported at weather stations unless they are located at airports, which publish hodographs showing wind vectors at altitude. At landfills, for example, the vertical temperature gradient could be collected using multiple temperature sensors: one on the hill (landfill body) and one at the ground level (fence line). In addition, iSense has proposed to collect balloon measurement devices or drone collected devices at landfill sites to collect this data. Since stable weather conditions (cloudy skies, low wind days) are related to more frequent odor complaints, those conditions were attributed with a higher level of threat for occurrence of odor complaints (Figure 59). An increase in temperature by more than 1.5ºC/100m is identified as strongly stable atmospheric class F, while a decrease in temperature by less than 1.9 ºC/100m is considered as extremely unstable atmosphere class A (“Low” threat for odor complaints). Finally, the location of a temperature inversion layer must also be taken into consideration, since if an inversion layer is found aloft, then potential for fumigation of the ground level would increase the threat of odor complaints, while an inversion layer below the source would negate any threat to residents.

Rank	Pasquill-Gifford Scale	Vertical Temp Gradient ΔT/Δz (°C/100m)	Descriptor
Critical	F	> +1.5	Moderate/strongly stable
Severe	E	-0.5 to +1.5	Slightly stable
Substantial	D	-1.5 to -0.5	Neutral
Moderate	B-C	-1.9 to -1.5	Moderate/slightly unstable
Low	A	< -1.9	Extremely unstable

Figure 59. Categories of Atmospheric Stability Classes Based on the Critical Level of Odor Complaint Occurrence

Overnight pressure drop seems to be a useful indicator. However, more study is needed to develop useful scale. Low pressure days are considered as a "Critical" threat for occurrence of odor complaints (Figure 60).

Rank	Pressure drop	Descriptor
Critical		Low
Severe		Falling
Substantial		Neutral/normal
Moderate		Rising
Low		High

Figure 60. Categories for the Pressure Drop Based on the Critical Level of Odor Complaint Occurrence

Odor threat levels can be calibrated locally by solid waste personnel to adapt to their site specific conditions by taking into consideration their past experiences with odor issues and by identifying weather patterns characteristic to their specific site. Based on that, landfill site managers can change the bins within each threat level to better represent situations relevant to their location. An example of how odor threat levels can be used is presented in Table 41. Let’s say the local conditions are as follows: wind speed is 1.5 mph, wind is blowing directly downwind from the odor source, temperature is 85ºF, precipitation is greater than 15 mm/hour, and the atmospheric stability class “F” or “moderately stable” is identified, the threat for a possible odor complaint is severe (all fields in red color).

Table 41. Example How to Use and Interpret “Odor Threat Levels”

WS	WD	DP	P	ASC
5 mph	crosswind	72°F	1.5 mm/hr	D
<3	Directly downwind	>75°F	>15	F
13 – 18	Slightly downwind	65 – 75	7.5 – 15	E
8 – 12	Crosswind	60 – 65	2.5 – 7.5	D
4 – 7	Slightly upwind	50 – 60	0.5 – 2.5	B-C
>18	Directly upwind	<50	<0.5	A

4.2.4 Alternative Technology Assessment

Once the source of odor is identified, a technology assessment can be performed to establish the preferred strategy to implement for odor control. Technologies considered in the assessment should be selected based on appropriate threshold criteria, such as minimum required removal efficiency of hydrogen sulfide, one of the most common odor causing compound recognized for generating odors at landfill site (Ko et al. 2015). Different sources of information should be accessed to gather valuable input, such as research journals, articles, U.S. EPA, and other landfills or industrial facilities practicing odor control. Since odor challenges are not exclusive to waste facilities, research articles related to technology assessment for odor control in wastewater treatment applications should also be considered. The criteria selected and ranked for the assessment should be based on sound engineering judgment, technical research, and valuable suggestions received from solid waste professionals. Some of the criteria selected could be related to:

- Odor Removal Efficiency: Technology with higher odor removal efficiency receives highest rank
- Frequency of Use: Importance of how often these technologies are successfully used in practice
- Cost Factors: Related to the capital cost and O&M cost; Detailed cost analysis should be supplied by the vendors; The technology with the lowest costs should be assigned with highest score in this criterion
- Energy Usage: Higher energy usage receives a lower score
- Land Footprint: Technology that requires smallest amount of land area receives higher score
- Chemical Requirements: Lower chemical necessity receives higher score, and
- Water Usage: Rewards those technologies that require the least amount of water for adequate performance.

The scores for each of the technology options should be compiled, and an unweighted matrix constructed to identify the most preferred alternative with the highest score. Furthermore, a weighted matrix should be created by considering the assigned weight of each established criterion. The preferred option could be identified by the highest total score (unweighted and weighted), when compared to other technologies. Lastly, a sensitivity analyses should be performed by removing the highest ranked criterion since it has the highest weight on the final decision.

5 APPENDICES

Appendix A: Meteorological Conditions (Preliminary Analysis: Urban Site 1)

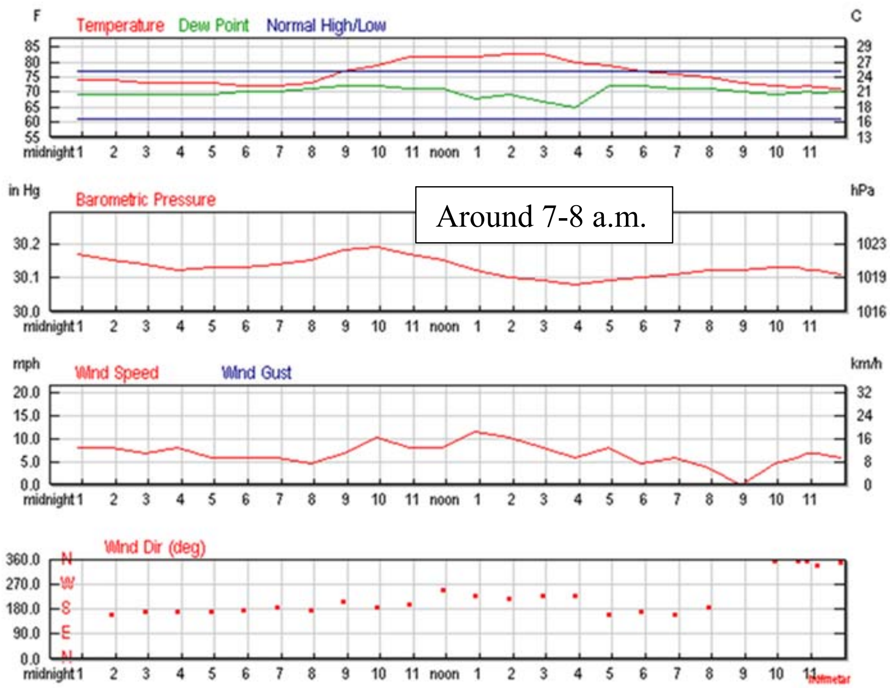


Figure 61.Meteorological Conditions, 12/09/2005 (Weather Underground)

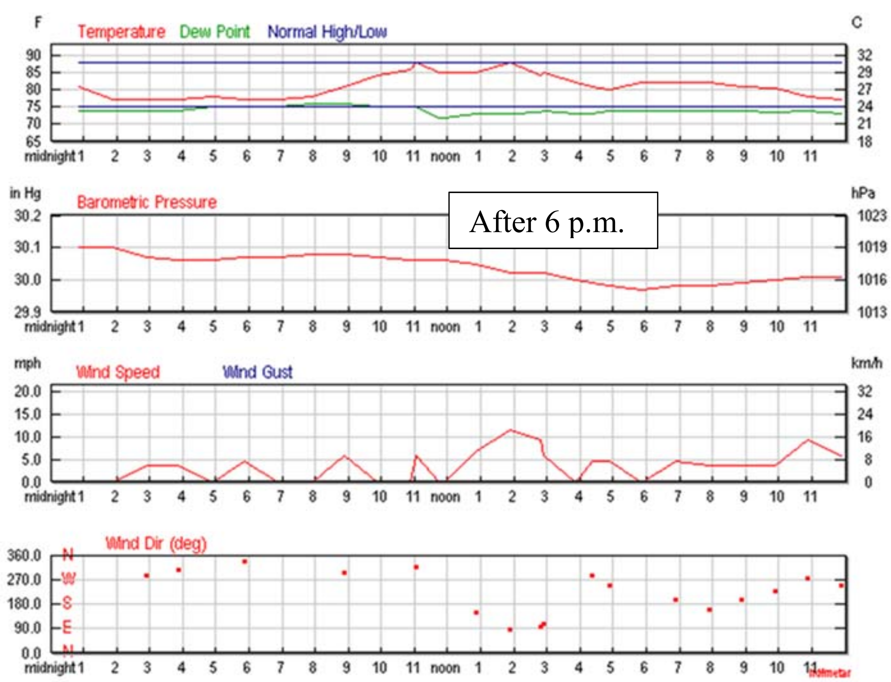


Figure 62. Meteorological Conditions, 09/16/2014 (Weather Underground)

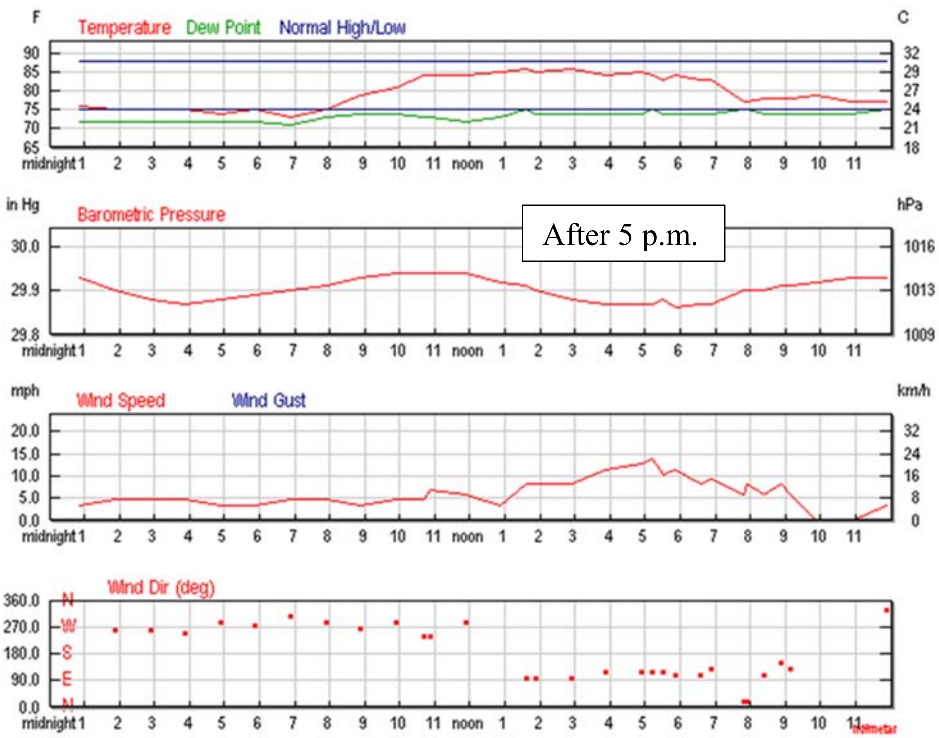


Figure 63. Meteorological Conditions, 09/18/2014(Weather Underground)

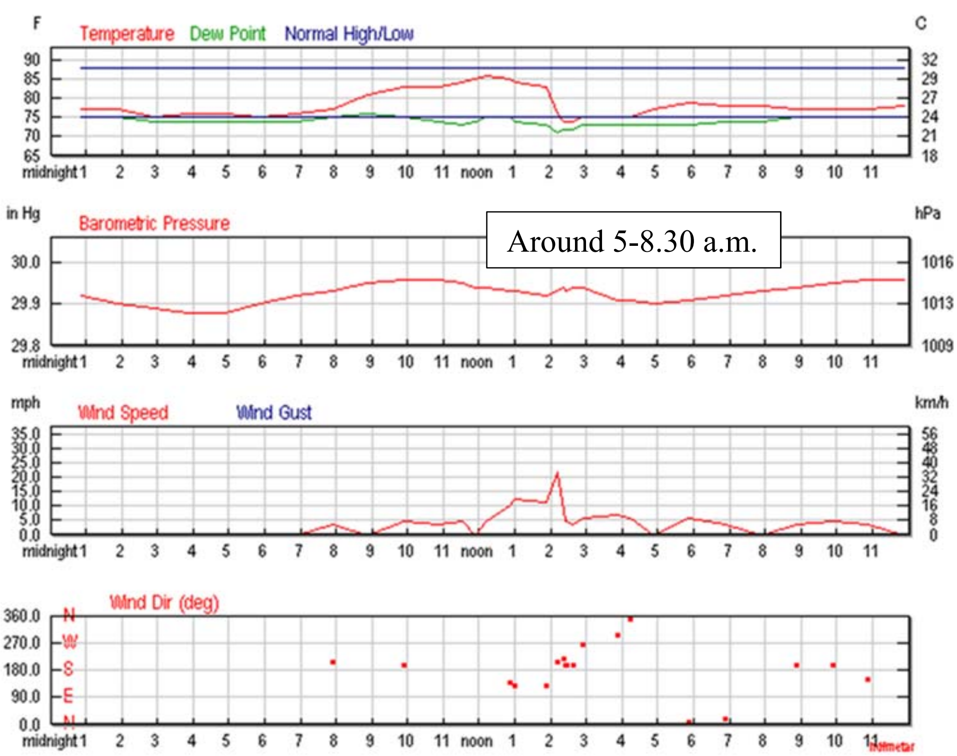


Figure 64. Meteorological Conditions, 09/19/2014(Weather Underground)

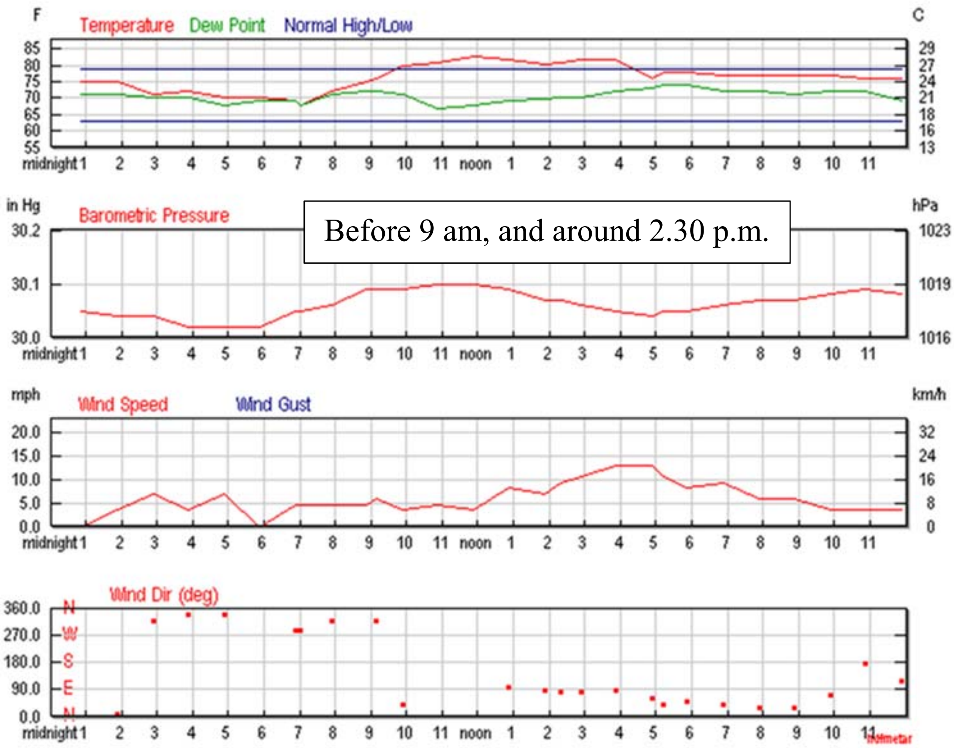


Figure 65. Meteorological Conditions, 03/26/2015 (Weather Underground)

Appendix B: Relationship between Meteorological Conditions: On the Day and at the Exact Time Odor Complaint was Filed, vs Previous Day

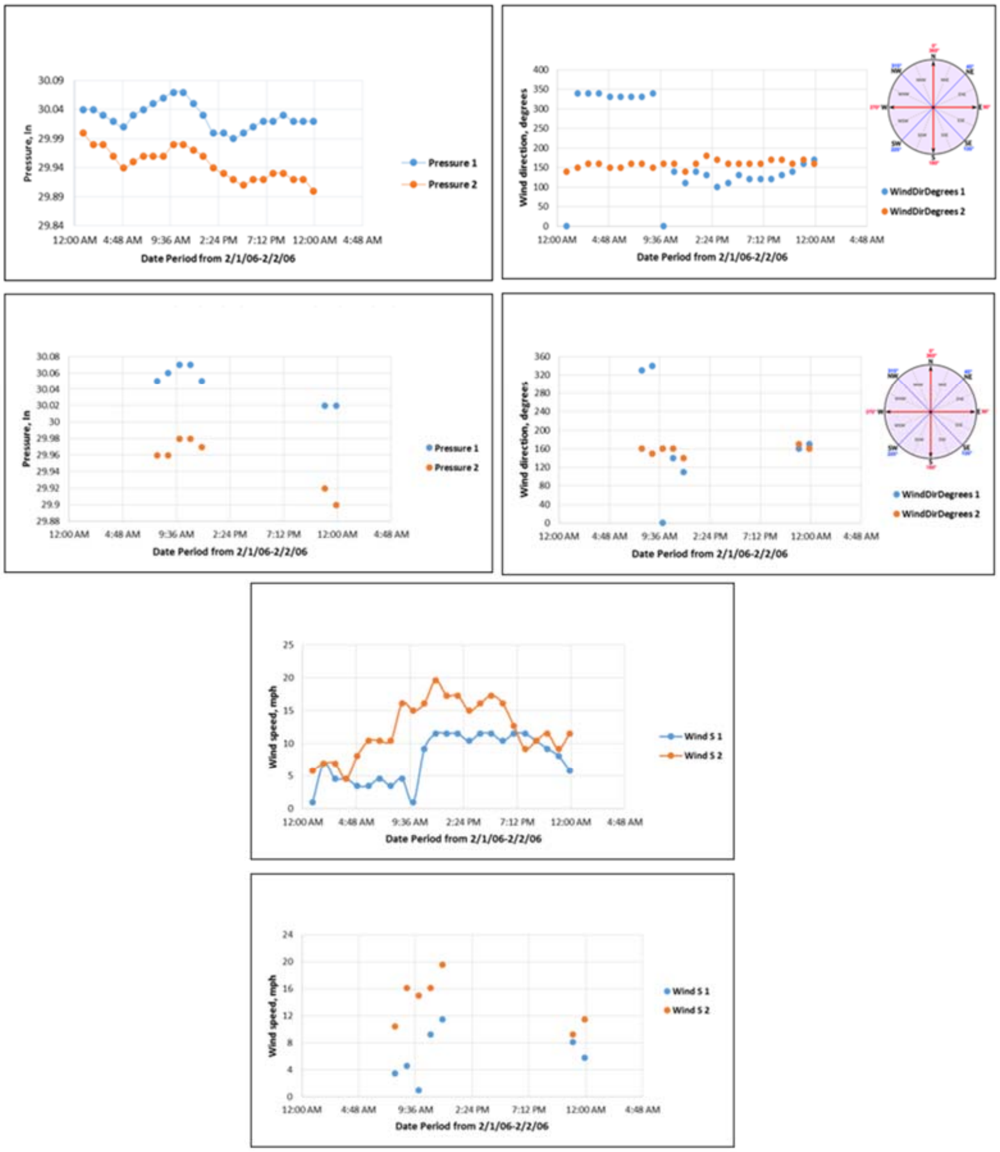


Figure 66. Meteorological Conditions: Pressure on the Day the Complaint was Filed (Upper Left) and Pressure at the Exact Time the Complaint was Filed (Lower Left); Wind Direction on the Day the Complaint was Filed (Upper Right) and Wind Direction at the Exact Time the Complaint was Filed (Lower Right); Wind Speed on the Day the Complaint was Filed (Middle Top); Wind Speed at the Exact Time the Complaint was Filed (Middle Bottom), vs Previous Day (02/02/2006, Urban Site 1)

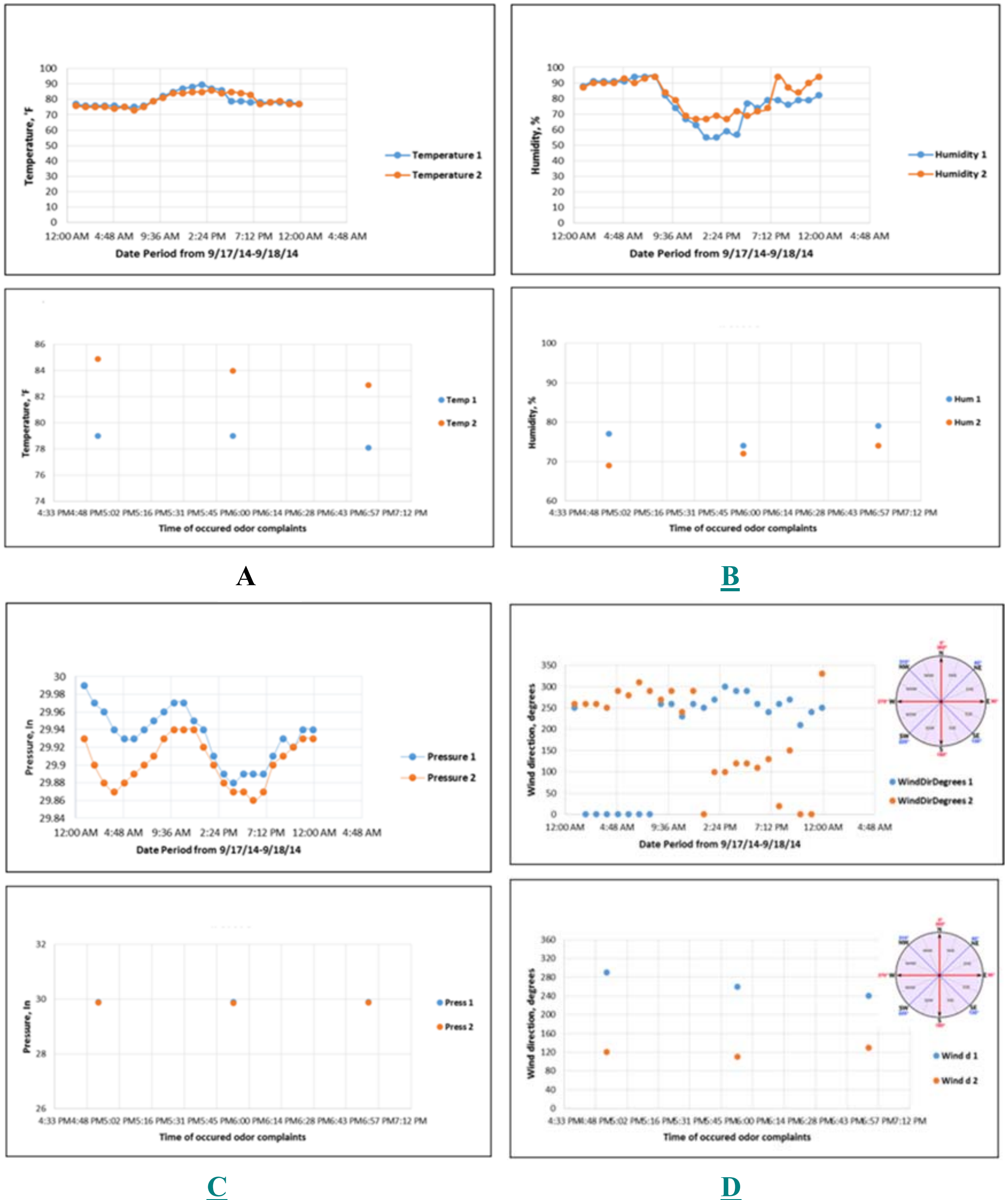
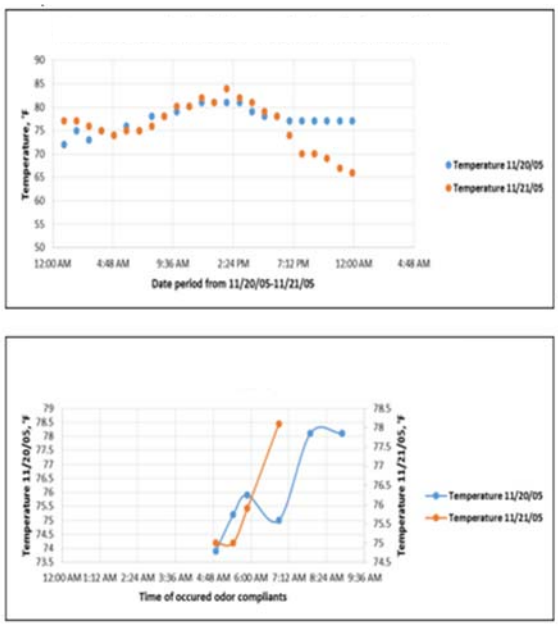
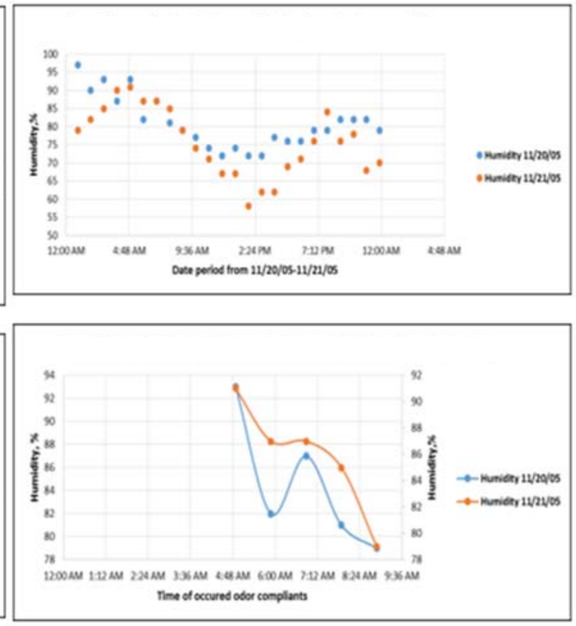


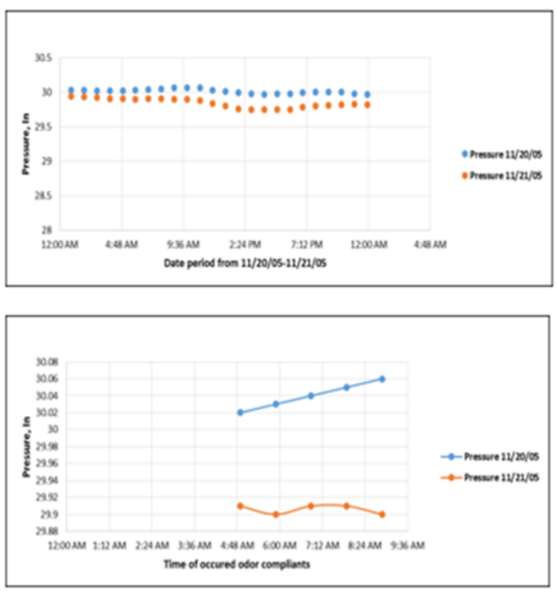
Figure 67. Meteorological Conditions: Temperature on the Day the Complaint was Filed (Upper A) and Temperature at the Exact Time the Complaint was Filed (Lower A); Humidity on the Day the Complaint was Filed (Upper B) and Humidity at the Exact Time the Complaint was Filed (Lower B); Pressure on the Day the Complaint was Filed (Upper C); Pressure at the Exact Time the Complaint was Filed (Lower C); Wind Direction on the Day the Complaint was Filed (Upper D) and Wind Direction at the Exact Time the Complaint was Filed (Lower D), vs Previous Day (09/18/2014, Urban Site 1)

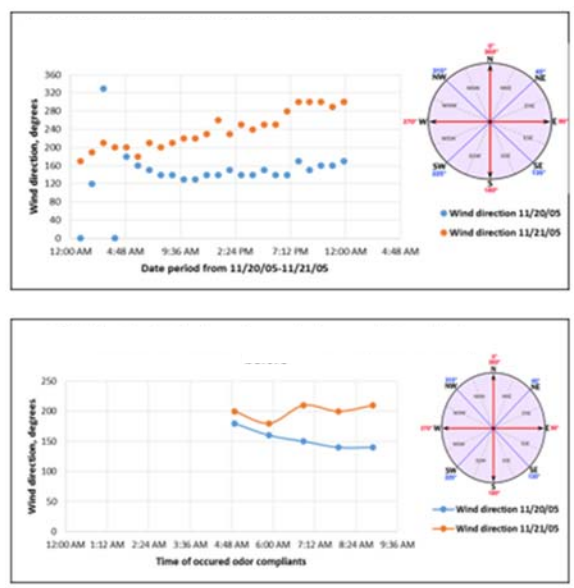




A

B

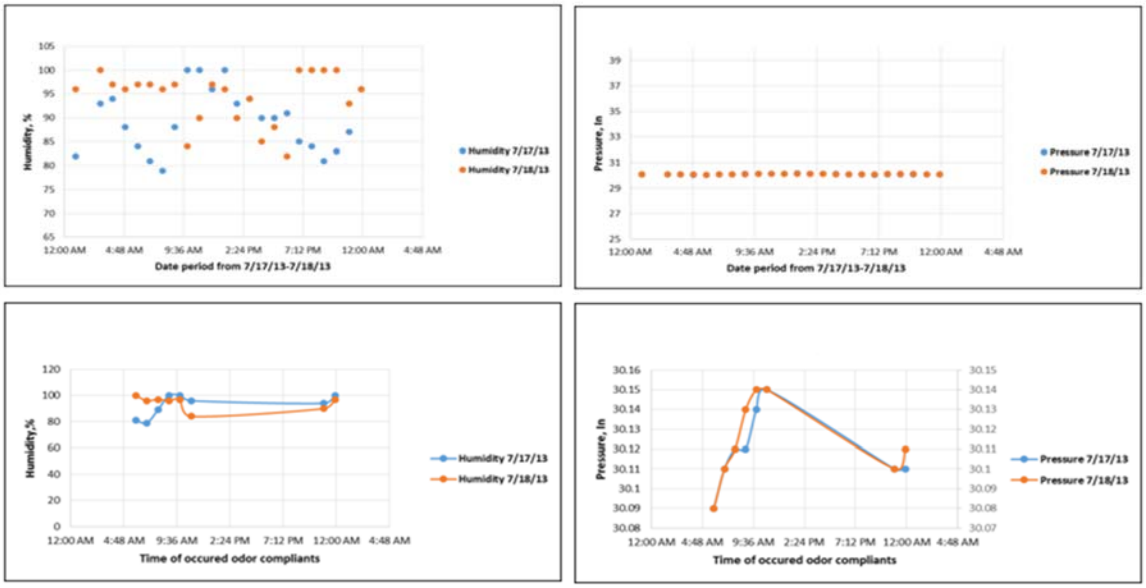




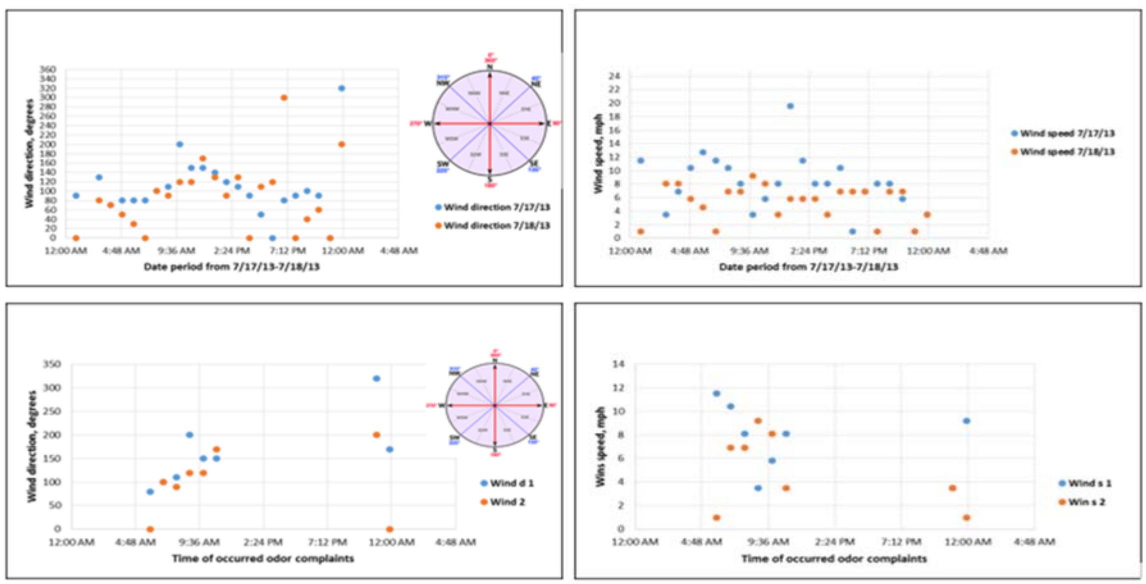
C

D

Figure 68. Meteorological Conditions: Temperature on the Day the Complaint was Filed (Upper A) and Temperature at the Exact Time the Complaint was Filed (Lower A); Humidity on the Day the Complaint was Filed (Upper B) and Humidity at the Exact Time the Complaint was Filed (Lower B); Pressure on the Day the Complaint was Filed (Upper C); Pressure at the Exact Time the Complaint was Filed (Lower C); Wind Direction on the Day the Complaint was Filed (Upper D) and Wind Direction at the Exact Time the Complaint was Filed (Lower D), vs Previous Day (11/21/2005, Urban Site 2)



A **B**



C **D**

Figure 69. Meteorological Conditions: Humidity on the Day the Complaint was Filed (Upper A) and Humidity at the Exact Time the Complaint was Filed (Lower A); Pressure on the Day the Complaint was Filed (Upper B) and Pressure at the Exact Time the Complaint was Filed (Lower B); Wind Direction on the Day the Complaint was Filed (Upper C); Wind Direction at the Exact Time the Complaint was Filed (Lower C); Wind Speed on the Day the Complaint was Filed (Upper D) and Wind Speed at the Exact Time the Complaint was Filed (Lower D), vs Previous Day (07/18/2013, Urban Site 2)

Appendix C: Historical Rainfall Data Analysis (Urban Site 1)

Table 42. Total Monthly Rainfall Accumulation for Month of May, Time Period from 1999-2009

Year	**Monthly Precipitation May, Inch**	Max	Min	Average/ month
1999	1.99	0.86	0.00	0.06
2000	0.40	0.18	0	0.01
2001	2.40	0.76	0	0.08
2002	0.27	0.12	0	0.01
2003	12.08	5.49	0	0.39
2004	2.89	1.73	0	0.09
2005	7.37	1.83	0	0.24
2006	3.50	1.65	0	0.11
2007	3.19	1.03	0	0.10
2008	2.44	1.53	0	0.08
2009	**15.71***	5.33	0	0.51

*Highest amount of rain recorded in May 2009 exceeded fences in Table 45

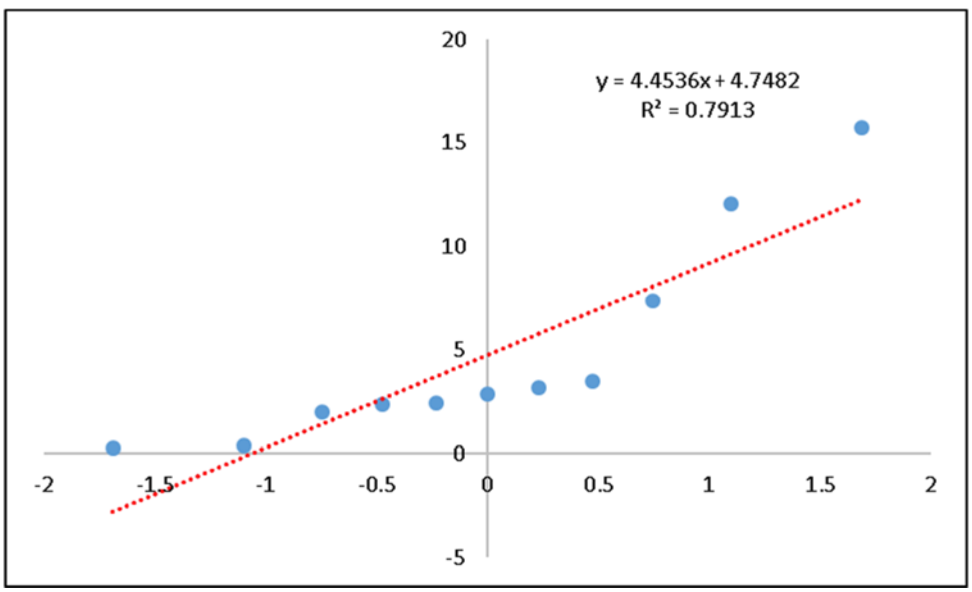


Figure 70. Normal Probability Plot: Rainfall Accumulation for Month of May (1999-2009) based on Calculated Standard Normal Scores (Values) Revealing Slight Change from Normal Distribution

Table 43. Summary Statistics for Rainfall Accumulation for Month of May (1999-2009): Slight Change from Normal Distribution

Mean	4.748181818*
Standard Error	1.493939008
Median	2.89*
Mode	#N/A
Standard Deviation	4.95483515
Sample Variance	24.55039136
Kurtosis	1.383184032*
Skewness	1.504170789*

* Mean and Median values not close to each other; Kurtosis and Skewness values are better if closer to 0

Table 44. Minimum Value, Lower Quartile, Median, Upper Quartile and Maximum Value for Total Monthly Rainfall Accumulation for May, Time Period from 1999-2009

		Differences
Min	0.27	0.27
Q1	2.195	1.93
Med	2.89	0.695
Q3	5.4325	2.5425
Max	**15.71***	10.27

*Rainfall Accumulation for May 2009 of 15.71 inches excides upper outer fence (Table 45) of 15.145 inches

Table 45. Calculated "Fence" Values to Identify an "Extreme Outlier" for the Month of May, Time Period from 1999-2009

Interquartile Range	3.2375
Lower Inner Fence	-2.66125
Upper Inner Fence	10.28875
Lower Outer Fence	-7.5175
Upper Outer Fence	**15.145**

Table 46. Monthly Rainfall Variations in June from 2004-2014

Year	**Monthly Precipitation June, Inch**	Max	Min	Average/ month
2004	2.91	0.7	0	0.10
2005	**11.84**	1.88	0	0.38
2006	4.27	1.3	0	0.14
2007	**14.93**	3.95	0	0.50
2008	4.97	1.07	0	0.17
2009	8.67	1.77	0	0.29
2010	6.10	2.1	0	0.20
2011	3.22	0.78	0	0.11
2012	**11.13**	5.33	0	0.37
2013	**12.76**	2.95	0	0.43
2014	**8.02***	2.12	0	0.27

*Total monthly rainfall accumulation (June 2014) of 8.02 inches did not exceed "fences" in Table 49.

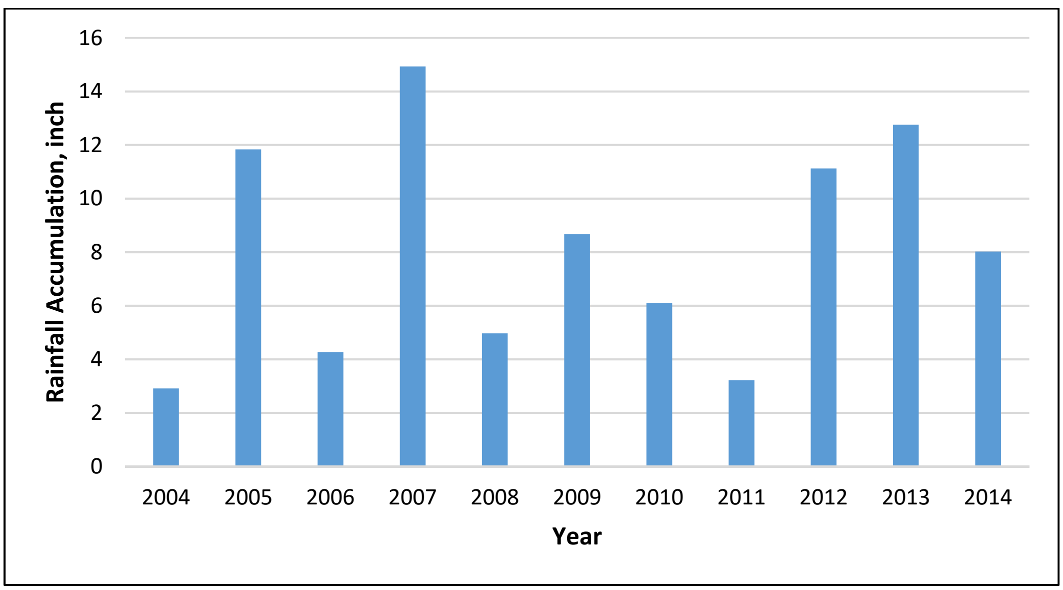


Figure 71. Monthly Rainfall Distribution for Month of June, Time Period from 2004-2014

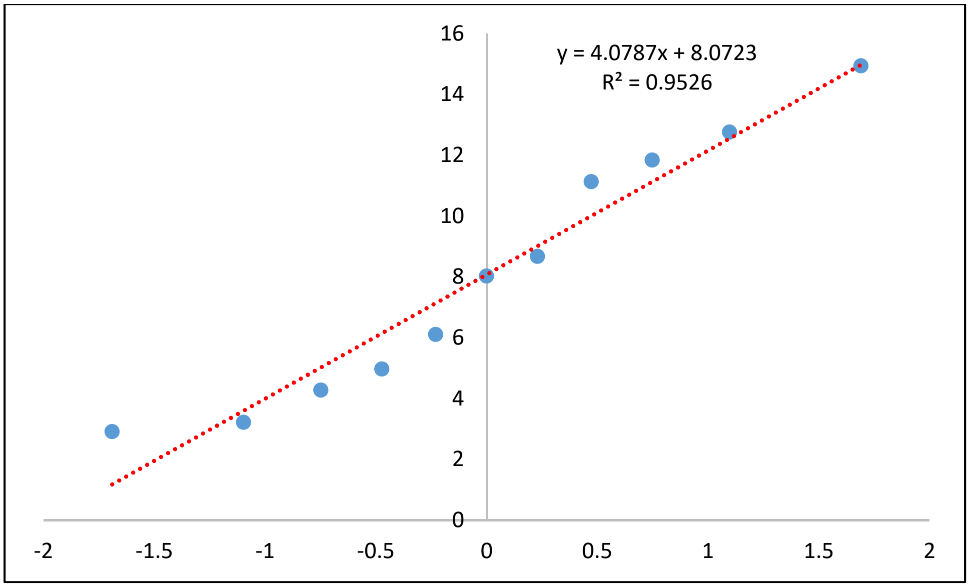


Figure 72. Normal Probability Plot: Rainfall Accumulation for Month of June (2004-2014) based on Calculated Standard Normal Scores (Values) Revealing Normal Distribution

Table 47. Summary Statistics for Rainfall Accumulation for Month of June (2004-2014): Normal Distribution (Mean and Median values very close to each other; Skewness value close to 0)

Mean	8.07227273*
Standard Error	1.2469529
Median	8.02*
Mode	#N/A
Standard Deviation	4.13567489
Sample Variance	17.1038068
Kurtosis	-1.3063668*
Skewness	0.28045852*

* Mean and Median values very close to each other; Skewness value close to 0

Table 48. Minimum Value, Lower Quartile, Median, Upper Quartile and Maximum Value for Total Monthly Rainfall Accumulation for June, Time Period from 2004-2014

		Differences
Min	2.91	2.91
Q1	4.6175	1.7075
Med	8.02	3.4025
Q3	11.48	3.46
Max	**14.93**	3.45

Table 49. Calculated "Fence" Values to Identify an "Extreme Outlier" for the Month of June, Time Period from 2004-2014: No outlier recognized

Interquartile Range	6.8625
Lower Inner Fence	-5.67625
Upper Inner Fence	21.77375
Lower Outer Fence	**-15.97**
Upper Outer Fence	**32.0675**

Appendix D: Descriptive Statistics of Meteorological Data used for Analysis of Isolated Days and Days with No Complaints with Similar Weather Patterns

Value zero next to the name of the parameters represents the days when odor complaints did not occur.

Tables 50-51 reveal how all the meteorological parameters, except precipitation accumulation, have good consistency between the values weather odor complaints occurred or no. Precipitation differs and it can be observed that higher rainfall (Urban Site 1: 12.54 inches; Urban Site 2: 13.87 inches) could potentially lead to higher number of odor complaints.

Table 50. Summary Statistics of Meteorological Parameters of Interest: Temperature, Humidity, Pressure, Wind Speed and Precipitation Accumulation, Urban Site 1

	AvgT	*Avg T0*	*AvgH*	*Avg H0*	*Avg P*	*Avg P0*	*Avg ws*	*Avg Ws0*	*Accum*	*Accum 0*
Mean	76.98	77.17	73.94	73.54	30.02	30.03	8.28	7.85	0.24	0.14
St Err	1.07	0.96	1.04	1.04	0.02	0.01	0.47	0.36	0.07	0.04
Median	79.00	79.50	75.00	74.50	29.99	30.03	7.00	8.00	0.01	0.00
Mode	78.00	81.00	81.00	69.00	29.99	30.03	7.00	8.00	0.00	0.00
St Dev	7.75	7.08	7.57	7.63	0.11	0.09	3.40	2.65	0.49	0.26
Sample Var	60.13	50.14	57.25	58.22	0.01	0.01	11.59	7.00	0.24	0.07
Kurtosis	4.05	6.33	0.96	2.11	0.17	2.01	-0.26	0.04	15.50	9.98
Skewnes	-1.87	-2.18	-0.83	-1.35	0.33	0.77	0.67	0.68	3.48	2.85
Range	39.00	37.00	37.00	36.00	0.52	0.45	14.00	11.00	2.84	1.40
Min	48.00	48.00	50.00	49.00	29.76	29.84	3.00	3.00	0.00	0.00
Max	87.00	85.00	87.00	85.00	30.28	30.29	17.00	14.00	2.84	1.40
Sum	4080.00	4167.00	3919.00	3971.00	1591.20	1621.62	439.00	424.00	12.54	7.45
Count	53.00	54.00	53.00	54.00	53.00	54.00	53.00	54.00	53.00	54.00
Conf Level(95.0%)	2.14	1.93	2.09	2.08	0.03	0.02	0.94	0.72	0.13	0.07

Table 51. Summary Statistics of Meteorological Parameters of Interest: Temperature, Humidity, Pressure, Wind Speed and Precipitation Accumulation, Urban Site 2

	Av T	Av T0	Av H	Av H0	Av P	Av P0	Av Ws	Av Ws0	Precip. (in)	Precip. (in)0
Mean	75.32	76.26	76.10	76.62	30.07	30.03	9.42	9.88	0.45	0.21
St Err	1.20	1.00	2.12	1.81	0.02	0.02	0.71	0.60	0.17	0.11
Median	75.00	76.00	77.00	76.50	30.09	30.03	9.00	10.00	0.00	0.00
Mode	76.00	80.00	81.00	77.00	30.10	30.04	8.00	8.00	0.00	0.00
St Dev	6.67	5.82	11.83	10.53	0.09	0.13	3.96	3.50	0.96	0.62
Sample Var	44.49	33.84	139.96	110.91	0.01	0.02	15.72	12.23	0.93	0.38
Kurtosis	-0.05	-0.32	-0.48	-0.26	1.03	-0.41	-0.46	-0.33	5.28	19.15
Skewness	-0.27	-0.52	-0.27	-0.36	-0.74	0.24	0.36	0.40	2.40	4.25
Range	28.00	24.00	43.00	41.00	0.38	0.46	15.00	14.00	3.85	3.25
Min	60.00	62.00	53.00	53.00	29.85	29.81	3.00	4.00	0.00	0.00
Max	88.00	86.00	96.00	94.00	30.23	30.27	18.00	18.00	3.85	3.25
Sum	2335.00	2593.00	2359.00	2605.00	932.25	1020.97	292.00	336.00	13.87	7.08
Count	31.00	34.00	31.00	34.00	31.00	34.00	31.00	34.00	31.00	34.00
Conf Level(95.0 %)	2.45	2.03	4.34	3.67457	0.03	0.04	1.45	1.22	0.35	0.22

Appendix E: Summary Statistics for the Data Used in Principal Component Analysis (PCA)

Table 52. Summary Statistics of Variables Included in Principal Component Analysis

Variable	Observations	Obs. with missing data	Obs. without missing data	Min	Max	Mean	Std. deviation
No of complaints	3910	0	3910	0	6	0.122	0.46
No of Comp (0 or 1)	3910	0	3910	0	1	0.089	0.284
compl t-1	3910	0	3910	0	6	0.122	0.459
compl t-2	3910	0	3910	0	6	0.122	0.459
compl t-3	3910	0	3910	0	6	0.122	0.459
Sat	3910	0	3910	0	1	0.143	0.35
Sun	3910	0	3910	0	1	0.143	0.35
Mon	3910	0	3910	0	1	0.143	0.35
Te	3910	0	3910	0	1	0.143	0.35
Wed	3910	0	3910	0	1	0.143	0.35
Th	3910	0	3910	0	1	0.143	0.35
Fr	3910	0	3910	0	1	0.143	0.35
Rain t-1	3910	0	3910	0	8.22	0.162	0.495
Rain t-2	3910	0	3910	0	8.22	0.162	0.495
Rain t-3	3910	0	3910	0	8.22	0.162	0.495
Temp t-1	3910	0	3910	50	99	83.52	6.944
Temp t-2	3910	0	3910	50	99	83.52	6.945
Temp t-3	3910	0	3910	50	99	83.52	6.946
low wind -1	3910	0	3910	1	31	9.119	3.581
low wind -2	3910	0	3910	1	31	9.118	3.581
low wind -3	3910	0	3910	1	31	9.118	3.582
Temp High	3910	0	3910	50	99	83.52	6.944
Temp Avg	3910	0	3910	41	90	76.37	7.852
Temp Low	3910	0	3910	32	85	68.79	9.367
Hum High	3910	0	3910	52	100	87.35	9.371
Hum Avg	3910	0	3910	31	97	70.99	8.347
Hum Low	3910	0	3910	9	93	54.09	10.788
P High	3910	0	3910	29.57	30.53	30.09	0.11
P Avg	3910	0	3910	29.28	30.47	30.03	0.111
P Low	3910	0	3910	28.8	30.43	29.98	0.117

Wind Speed Avg	3910	0	3910	6	83	19.22	5.085
Wind Speed Low	3910	0	3910	1	31	9.119	3.581
Precip	3910	0	3910	0	8.22	0.162	0.495

Table 53. Array of Loadings

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**
No of complaints	-0.048	-0.044	-0.056	-0.020	0.341	0.415	-0.603
Days -1	-0.048	-0.094	-0.031	-0.023	0.430	0.322	-0.163
Days -2	-0.009	-0.085	-0.007	0.008	0.555	-0.038	0.090
Days -3	0.010	-0.029	-0.040	0.011	0.450	0.140	0.729
Temp High	-0.341	0.352	-0.113	-0.155	0.005	0.066	0.052
Temp Chg	-0.035	0.162	-0.219	-0.182	-0.273	0.612	0.164
Temp Avg	-0.337	0.429	-0.093	-0.034	0.043	-0.020	0.015
Temp Low	-0.312	0.458	-0.072	0.055	0.068	-0.084	-0.013
Hum High	-0.266	-0.408	-0.243	0.055	-0.041	-0.014	0.067
Hum Chg	-0.133	-0.261	-0.250	0.067	-0.297	0.375	0.139
Hum Avg	-0.325	-0.199	-0.268	0.313	0.017	-0.124	-0.020
Hum Low	-0.269	0.051	-0.202	0.435	0.062	-0.179	-0.090
P High	0.365	0.111	-0.305	0.232	0.025	0.013	-0.013
P Avg	0.348	0.163	-0.358	0.208	0.027	0.000	-0.016
P Low	0.326	0.198	-0.391	0.182	0.021	-0.007	-0.011
Wind Speed Avg	-0.044	0.064	0.397	0.457	-0.043	0.307	0.066
Wind Speed Low	0.131	0.236	0.383	0.375	-0.033	0.174	0.046
Precip	-0.145	-0.152	0.087	0.405	-0.094	0.062	0.021

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