Simulation of Odor Transport and Dispersion from a Waste Water Treatment Plant: A case study of Kahawa Ward Nairobi County

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ABSTRACT

Increasing evidence alludes that the developing countries are slowly losing their natural beauty and a clean environment to the different forms of hazardous waste among them waste water pollution. Waste water treatment plants emit odor that is considered a significant source of environmental pollution in Kenya. This is a crucial issue owing to the potential health impacts on the surrounding population and its significance to climate change. In this study, the seasonal distribution of odor was analyzed by use of Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT) and dispersion analysis. The study utilized archived meteorological data (daily wind speed and direction, temperature and humidity) as model input. Time series analysis was used to determine the temporal evolution of boundary layer depth, vertical mixing coefficient and atmospheric stability. Moreover, Computed odor concentration levels were compared to the national ambient air quality standards as a measure of possible health and environmental effects. The results showed that the predominant wind directions were easterly and south easterly with odor concentration reducing away from the source due to the resultant atmospheric dilution. Similarly, odor concentration depicted seasonal variations with the highest concentration levels being recorded during December January February season, while September October November season had the least values of odor concentration. Moderate odor concentration levels were observed during the March April May and June July August seasons. In conclusion, the variation of wind speed and direction influences depth of the boundary layer, vertical mixing coefficient and atmospheric stability. This in turn influences the transport and dispersion of odor. The findings from the study will prove useful in predicting odor occurrences in the area of study and hence develop solutions for effective management of wastewater plants.

Keywords: odor, wastewater treatment plants, mixing coefficient, boundary layer depth, atmospheric stability

1. Introduction

Air pollution represents a major global public health risk. Its affects people world over irrespective of their settings, socio economic status and age groups. While exposure to air pollution results to increased morbidity and mortality worldwide, low and middle income countries such as Africa, Asia and Middle East disproportionately experience the burden according to a World Health Organization (WHO) report on Ambient Air Pollution, 2016. Increased premature deaths have also been attributed to deteriorating air quality (WHO, 2014; World Bank, 2016). WHO, 2014 reported 3.7 Million premature deaths worldwide in 2012 resulting from exposure to small particulate matter with a diameter of 10 microns or less (PM$_{10}$). Similarly, the Economic Survey of 2014 reported an increased trend in reported cases of respiratory diseases from 34% in 2013 to 36.2% in 2014 owing to deteriorated state of air quality over years. The report further revealed that respiratory diseases accounted for the highest number of ailments in Kenya; with 17 million attributions out of 47 million cases reported in 2013.

Deterioration of ambient air quality can be as a result of emission from both natural occurrences and anthropogenic activities. A significant source of environmental pollution due to anthropogenic activities is the Waste Water Treatment Plants (WWTPs). Waste water treatment plants emit odor which contains two common highly toxic components, i.e., hydrogen sulphides and ammonia. Other components include; carbon dioxide, Sulphur dioxide, nitrous oxides and biological agents. In addition to odors and aerosols, wastewater treating generates methane (Sneller, 2010).

These substances pose numerous threats not only to the health of the surrounding residents but also to the future climate as some of these pollutants could modify the climate to a considerable extent. Consequently, air quality in the vicinity of WWTPs has been found to have a great deal of interest globally due to its relative risks to the welfare of the surrounding residents and its significance to climate change. Among those near the WWTPs, odor annoyance is regarded as the most perceived response, and thus, a certain association exists between the proximity and odor annoyance (Aatamila et al., 2011; Che et al., 2013). The intensity of odor incidents and the range of the affected area depend on the nature of initial waste water components, treatment method, exposure of the products to the atmosphere, wind direction and the prevailing weather conditions.

Although human response to odor is considered subjective depending on numerous factors (Stuetz and Frenchen, 2001), which may affect the number and the extent of the reported complaints; several studies have found a significant relationship between odor and certain respiratory and pulmonary related diseases (Watt and Seaton, 1997; Eilsten, 2010; Elkadhi and Hamida, 2014). Despite the potentially deadly health effects of air pollution, very few studies have been carried out on the status of air quality in Kenya. Additionally, there’s no national monitoring program for ambient air quality levels. In their study, Mulaku and Kariuki (2001) noted that the total suspended particles over Nairobi were beyond World Health Organization acceptable level. However, the study did not ascertain the sources of existing total suspended particles.

Several studies have been conducted to quantify the contribution of waste water treatment plants to the ambient air while establishing if the individual pollutants violate the set standards on permissible levels. A study by Al-Mashaqbeh et al., (2015) on Al-Samra wastewater treatment facilities in Jordan by use of AERMOD dispersion Model, showed that concentrations of ambient hydrogen sulphide (H$_2$S), methane (CH$_4$) and ammonia (NH$_3$) in the vicinity of the facility were below national and international standards of ambient air quality. Similarly, a study on Zhengwangfen WWTP in Beijing found maximum concentration of NH$_3$ and H$_2$S under the worst weather conditions, that
is to say, moderate to extremely stable atmospheric conditions and slight breeze, to be 0.0043 and 0.059 mg/m$^3$, respectively (Zhang et al., 2015). Using the Gaussian point source diffusion model, the 200 meter setback distance for WWTPs dictated by their local regulation was found to be sufficient in usual operation and under normal weather conditions in the case of this plant in Beijing.

However, reviews of existing information suggest that there is very limited research on odor pollution in Kenya. Whereas concerns about air pollution are reflected in Sustainable Development Goals (SDGs) numbers three, seven, and eleven and thirteen (United Nations, 2015), reliable estimates of odor occurrences, pathways, distribution and concentration are crucial to understanding pollution levels, ascertain the accurate value of significance from odor pollution, as well as making informed decision on improving air quality. Therefore, the present study will make notable contribution.

2. Data and Methods

2.1 Area of Study

The wastewater treatment plant located in Kahawa Ward of Roysambu Constituency, Nairobi County is bounded by the longitudes E36° 54’ 38.88’’ and E36° 54’ 51.83’’ and latitudes S1° 11’ 29.76’’ and S1° 11’ 42.71’’. The plant is approximately 18, 115 square meters in area and its neighboring estates includes; Kahawa Garrison Barracks to the East through South-Eastern part of the plant and Githurai 44 to the South through South-West stretching to the Western part of the plant. Kongo Estate is to the North stretching North-Westward, while Kahawa Soweto is to the North-Eastern part of the treatment plant (Figure 1). The ward has a population of approximately 35,853 persons according to a census carried out by Kenya National Bureau of Statistics (KNBS, 2010) and is home to Farmer’s Choice Limited. Rainfall regime over the study area just like the entire Nairobi region is bimodal, with long rains received in the months of March April May (MAM) and short rains received during October November December (OND) season (Owiti and Zhu, 2012). The area experiences a cold season during the months of June July and August (JJA) and a hot season in December January February (DJF) season.

![Figure 1: Waste Water Treatment Plant in Kahawa ward (Source: modified from Digital Globe, 2016)](image)

2.2 Data

The study employed data on wind, temperature and humidity obtained from archived Global Data Assimilation System (GDAS), of National Centre for Environmental Prediction’s (NCEP), for the period between 2015 and 2016. The archived data files contain data in synoptic time series, i.e., 00, 06, 12 and 18 Universal Time Coordinated (UTC) and have no missing records. This data is at a resolution of 1 degree latitude-longitude, which is approximately equal to 111.11 km around the equator.

2.3 Methods

The daily wind roses, forward trajectory, concentration and distribution of odor were done using Hybrid Single Particle Integrated Lagrangian (HYSPLIT) Real-time Environmental Applications and Display sYstem (READY) model. According to Stein et al, 2015, HYSPLIT model is run interactively on the web and utilizes a hybrid calculation method between a moving frame of reference that follows air parcels as they move from their initial location for the simulation of advection, diffusion and deposition (Lagrangian) and a fixed three-dimensional grid
as a frame of reference to compute the pollutant air concentrations (Eulerian). The model calculates odor concentration and distribution using Gaussian dispersion Equation (1), usually found in standard statistical formulas:

\[ C_x = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} e^{-1/2 \left( \frac{y^2}{\sigma_y^2} \right)} e^{-1/2 \left( \frac{z^2}{\sigma_z^2} \right)} \] .............. (1)

Where, \( C_x \) represents ground level concentration at some distance \( x \) downwind (g/m^3), \( Q \) the average emission strength/rate (g/sec), \( \bar{u} \) the mean wind speed (m/sec), \( h \) the effective stack height (m), \( \sigma_y \) the standard deviation of wind direction in the horizontal (m), \( \sigma_z \) the standard deviation of wind direction in the vertical (m), \( y \) the off-center line distance (m) and \( e \) is the natural log equal to 2.71828.

In the determination of atmospheric stability, text results of the HYSPLIT stability plots were obtained and time series analysis of boundary layer depth, vertical mixing coefficient and Pasquill stability classes done using R software. The 15th day of the second month of every season was chosen based on previous studies as a representative of each season, with each giving a good representation of the respective season (Ongoma et al., 2014). The seasons selected were; December January February (DJF), March April May (MAM), June July August (JJA) and September October November (SON).

The limitations of the model are such that it is available at relatively coarse spatial resolution (1 degree latitude-longitude) and temporal resolution (1-6hours) which can result to errors for rapidly changing conditions. Moreover, the HYSPLIT interface does not incorporate the effects of dense gases, chemical reactions and complex terrain (Stein et al., 2015).

3. Results and Discussion

3.1 Seasonal Wind Analysis

Seasonal wind was analyzed using wind rose to give the following results.

Figure 2 showed ENE and southerly winds with wind speeds varying between 1-3 m/s depicting 10-15% frequency for the DJF season. Easterly and SSE wind speeds varied between 1-3 m/s at 20-25% frequency. Calm conditions also prevailed in the season. The easterly and southerly winds were the most predominant. Relatively low wind speeds and frequencies were observed during the DJF season. This is contrary to what is usually observed during the hot and dry season. However, this may be attributed to the cold conditions resulting from enhanced El Nino rains especially in the month of January 2016 coupled with other local features such as small pressure gradients resulting from little differential heating.

Figure 3 showed that the winds were mainly easterly and south easterly over the study area during the MAM season. South easterly wind depicted the highest frequency of 40-50%, with wind speed varying from 1-3 m/s to 4-6 m/s. Easterly and ESE winds were shown to have wind speeds of 1-3 m/s in magnitude and same frequency of more than 20%. SES winds were also observed with wind speeds of 1-3 m/s in magnitude and frequency of slightly more than 10%.

During this season, winds were observed to be blowing at a relatively higher speed compared to DJF season. This may be due to the presence of overhead sun (equinox phenomena) during the month of March. Consequently, maximum temperatures are observed during the month of April, causing relatively steep pressure gradients. Easterly and south easterly winds were observed to be dominant during the JJA season (Figure 4). Wind speed varied between 1-3 m/s and 4-6 m/s respectively. Easterly wind component depicted the most frequent wind at 40-50% followed by south easterly at 30-40%. ENE and ESE winds with same frequencies of above 10% and wind speeds of 1-3 m/s and 4-6 m/s respectively were also observed.
Wind orientation for SON season, illustrated by Figure 5, depicted the most frequent winds during the entire period of study of between 48% and 60%. This was observed to be ESE wind component with wind speeds varying from 1-3 m/s to 4-6 m/s. Easterly component showed wind speeds varying between 1-3 m/s and frequencies of between 24-36%. South easterly with frequency of about 12% blowing with wind speeds of between 4-6 m/s was also observed. The predominant winds over the waste water treatment plant were found to be easterly and south easterly. The results are in agreement with previous study by Ongoma et al., (2014), that showed the predominant wind direction over the Nairobi city to be generally easterly; with the direction ranging from north easterly in DJF to south easterly in JJA.

3.2 Time series analysis of Atmospheric Stability

This method was employed to determine temporal evolution of the planetary boundary layer depth, vertical mixing coefficient and the Pasquil stability classes. This would inform the extent to which pollutants would be dispersed in different atmospheric state of stability as well as their concentration. Season of SON presented the deepest boundary layer, largest vertical mixing coefficient and extremely unstable conditions, with values of 1200m, 1400m²/s and Pasquil stability class A respectively (Figure 6). The results were
attributed to strong insolation, hence strong prevailing wind speeds over the area. As previously stated, the most frequent wind with speeds of up to 6 ms\(^{-1}\) during the study period were observed during this season (Figure 5). Consequently, there was enhanced thermally and mechanically generated eddies resulting to an extremely unstable state of the atmosphere. The Pasquill stability classes varied from very unstable conditions (B) to extremely unstable conditions (A) from 0900 to 1200 hours Universal Time Coordinated (UTC) respectively during the same season. Worthwhile noting, the season recorded the maximum unstable conditions throughout the study period.

Planetary Boundary Layer depth and the vertical mixing coefficients were observed to have their peaks between 0900 and 1200 UTC, with a maximum at 1200 hours UTC corresponding to maximum solar radiation while 1200 hours UTC corresponded to maximum temperatures. Shallow boundary layer depth and small vertical mixing coefficients value were observed at night between 0000 hours and 0300 hours UTC. This translated to least activities or calm conditions being observed thus low stability classes. Likewise, the planetary boundary layer depth was presented to be directly proportional to the vertical mixing coefficients throughout the study period with minimal variation.

Noteworthy, the least vertical mixing coefficient value was observed during the DJF season. While the rest of the study period vertical mixing coefficient values were 1000m\(^2\)/s and above, DJF season had a value of 250m\(^2\)/s. This explains the variance in stability classes from neutral class (D) between 0900 and 1800 UTC, to extremely stable conditions (G) for the rest of the day. Similarly, a shallow boundary layer was observed during the MAM season, with a value of 700m. This affirms the results obtained after wind rose analysis during which low winds speeds and frequency were observed. Thus, planetary boundary layer is very important in the energetics and exchanges in the atmosphere.

![Figure 6: Diurnal variation of Atmospheric Stability, Boundary layer depth and vertical mixing coefficients over the study area for 15\textsuperscript{th} day of January 2016, April, July and October 2015](image)

### 3.3 Analysis of transport and dispersion of odor

a) **Odor transport analysis**

From the HYSPLIT trajectory analysis, odor was transported westward from the source during the DJF (Figure 7). The transport was to a distance of more than 8 km from the source. The transport of odor followed the direction of wind as was previously observed from the wind rose analysis for the same season.

Figure 8 depicts trajectory analysis for MAM season. The analysis presented transport of pollutants north westward 80 km from the source, to WNW direction beyond 80 km. This inferred that those residing in the above regions would be susceptible to odor effects.

Transport of odor during JJA season was to the west within 150 km from the source and then to the northwest direction from 150 to 300 km. Transport of odor was farthest during this season when compared to the other seasons (Figure 9).

Trajectory analysis for the month of October (Figure 10) depicted a westward transport of pollutant 100 km from the source, then WSW dispersion from 100 to almost 300 km. The season formerly represented the most frequent winds with average wind speeds of 1-6 m/s. In addition, SON season had the deepest boundary layer depth and largest vertical mixing coefficient. This confirms the faraway distances of odor transport during the season.
Trajectory analysis presented a general westward transport of odor from the treatment plant. MAM and JJA seasons depicted a northwest course, while in DJF and SON seasons the transport took a WSW course. Odor transport was in the same direction with the direction the wind was blowing. Thus, trajectory analysis could be used to assess those more exposed to odor pollution from the treatment plants by the relevant authorities towards appropriate action.

Figure 7: Forward trajectory for 15th of January 2016 over the study area

Figure 8: Forward trajectory for 15th of April 2015 over the study area

b) Odor dispersion analysis

HYSPLIT dispersion analysis showed spreading out of odor emanating from the treatment plant over a large area, reducing their concentration. From DJF season (Figure 11), the maximum concentration was observed to be 4.7E-12 mg/m$^3$ at the source and was found to be decreasing relatively fast downwind to 1.0E-12 mg/m$^3$, 1.0E-13 mg/m$^3$, 1.0E-14 mg/m$^3$ and 1.0E-15 mg/m$^3$ from the source to about 80 km. The observed minimum concentration was 3.2E-20 mg/m$^3$ over the plant. This season had the highest values of odor concentration for the entire study period mainly due to the least wind speeds and frequency as well as neutral atmospheric conditions that prevailed. Planetary boundary layer was observed to be very shallow and thus minimum activities took place. As a result, odor was dispersed the least possible distance throughout the entire study period.

Figure 9: Forward trajectory for 15th of July 2015 over the study area

Figure 10: Forward trajectory for 15th of October 2015 over the study area
Figure 12 presented dispersion analysis for the month of April. The maximum concentration was observed to be 2.1E-12 mg/m³. This concentration decreased directly downwind to 1.0E-12 mg/m³, 1.0E-13 mg/m³, 1.0E-14 mg/m³ and 1.0E-15 mg/m³ at 50 km, 100 km and beyond. The minimum concentration is observed to be 2.2E-19 mg/m³. In consistence with the trajectory, odor dispersal was observed to be in the north western direction of the treatment plant during the MAM season (Figure 8). Odor was shown to be dispersed a further distance as compared to DJF season due to an increase in wind speeds and frequency, as was evident from wind orientation from the wind rose analysis.

Odor dispersal during JJA season was to a relatively farther distance compared to the previous seasons. The maximum concentration over the region was observed to be 1.5E-12 mg/m³, while the minimum concentration was found to be 3.9E-20 mg/m³ at the source. The concentration decreased directly downwind to 1.0E-12 mg/m³, 1.0E-13 mg/m³, 1.0E-14 mg/m³ and 1.0E-15 mg/m³. Odor was transported beyond 160 km during the season. The observed dispersal was in agreement with trajectory of the cold season (Figure 9). JJA Dispersal analysis is as shown by Figure 13. The spread of odor was attributed to the comparatively high wind speeds observed over the area of study (Figure 4) and the dynamic atmospheric conditions that prevailed.

From SON season odor dispersion analysis, the maximum odor concentration was observed to be 1.8E-12 mg/m³ and decreased downwind to 1.0E-
12 mg/m$^3$, 1.0E-13 mg/m$^3$, 1.0E-14 mg/m$^3$ and 1.0E-15 mg/m$^3$ at 100 km, 200 km and beyond. The minimum concentration over the region was 1.5E-20 mg/m$^3$, as illustrated by Figure 14. SON season was noted to be the season during which odor was dispersed to the farthest distance away from the source. The season corresponded to that with the least pollutant concentration over the treatment plant. In addition, most unstable atmospheric condition as well as highest winds speeds and frequency were noted.

Odor was observed to be dispersed 70 km and beyond throughout the year of study. The dispersal was farthest during JJA and SON seasons and least during DJF and MAM seasons (Figure 11-14).

Enhanced odor concentration was observed during the DJF season, while the least odor concentration values were observed during the SON season. This showed that wind circulation patterns determine the transport and dilution of air pollutants, thus air quality. Residents on the far west and north western side of the treatment plant were less susceptible to the effects from the treatment plant, owing to high dilution of odor, compared to the population living approximately 5 km from the plant. Those residents to the eastern, north eastern side and southerly parts of the treatment plant were not affected by the presence of the waste water treatment plant as they are located upwind.

Similar results over Mui basin, Kitui County, showed that highest maximum pollutant concentration was observed during the DJF season, while minimum effects were expected during SON season. During MAM and JJA seasons, odor concentration values were moderate (Muthama et al., 2015)

It’s worth mentioning that although maximum odor concentration was observed during DJF season, maximum pollutant exposure would be pronounced during the JJA season. This is owed to incursions by cold south easterlies from southern hemisphere winter. As a result there are temperature inversions and thus a thermally stable atmosphere. Therefore, there is usually less mixing and thus the atmosphere suppresses odor to low levels, inhibiting dilution.

The contribution of odor pollution to air quality were compared with Air Quality Regulations on Ambient Air Quality Standards and emission standards for various sources in accordance with the provisions of the Environmental Management and Co-ordination Act (EMCA), 1999. Based on the Act, the daily national Ambient Air Quality Tolerance Limits for resident, rural and other areas as well as emission limits for controlled and non-controlled facilities specifically waste water treatment plants; the computed odor concentration levels were found to be below the permissible limit levels under the regulation for human health and safe environment. However, continuous monitoring of air pollutant sources and adoption of best environmental practices in waste management should be promoted

**Conclusion**

An attempt has been made to simulate the transport and dispersion odor characteristics over Nairobi for the first time. From this study, wind rose analysis depicted predominantly easterly and south easterly winds over the treatment plant for most times of the year. The generated trajectories confirmed that odor is transported westward and northwestward of the treatment plant. The typical range of wind speed over the study area was found to be 1-6 m/s.

Dispersion of odor from the treatment plant was observed to be driven by atmospheric stability that was influenced by insolation and wind patterns. This confirmed the key role of local atmospheric dynamics in the determination of dispersion of pollutants from any source. Unstable conditions enhanced dispersion while stable conditions inhibited dispersion. Pollution exhibited seasonality with high odor concentration during the DJF season and least pollutant concentrations during the SON season. It was also found out that there existed an association between odor concentration and the strategic position of the treatment plant described
by dilution aspect. Concentration decreased away from the source, deducing that the society in close proximity to the treatment plant is more exposed than those residing far away from the treatment plant.

The findings from the study will prove relevant to a number of disciplines, for instance, health and environment in determining possible threats on the population living in the neighborhood of wastewater treatment plants. Further studies should be carried out to establish the baseline ambient air quality levels, characterize odor and ascertain whether odor constituents from a given plant violates odor threshold values.

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