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Impact of Methane Emission Reduction Measures in a Tropical Landfill to Methane Ambient Air Quality

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Abstract

Anaerobic process occurred in landfills emits substantial amount of methane (CH4) to the atmosphere. Methane is a strong greenhouse gas (GHG) as well as an ozone precursor therefore reduction of the emission would provide co-benefits on reduced climate forcing and improved air quality. Emission inventory for the base year of 2019 where the activity data were available was done using both Intergovernmental Panel on Climate Change (IPCC) and Landfill Gas Emissions Model (LandGEM) models. Emission results were compared with the flux rate measurement using close flux chamber at the landfill but for limited period. Two selected measures were proposed: biocover (biosolid) and pipe-flaring system and emission reductions were calculated. Dispersion analysis of base year methane emission was done using the Aermic Model (AERMOD) model with grids size of 0.5 x 0.5 km with a radius of 5 km from the landfill for maximum hourly, daily maximum, and annual average periods. The results of the model analysis showed that the locations exposed to the maximum concentration were within a radius of up to 1 km from the landfill to the eastern part of domain which is dominated by rice fields and residential area. High concentrations of methane over the residential areas potentially triggered the ozone formation as other local ozone precursors such as NOx and CO were potentially emitted. Meteorological factors, especially wind patterns, greatly affected the distribution pattern of CH4 in the study area. Simulations of two measures of bio-cover and pipe-flaring system were also done to investigate the impact on the methane air quality. Emission reduction of the pipe-flaring system yielded higher value as compared to the biocover therefore simulated methane also showed lower concentrations over the domain. In the near future, it is recommended that the pipe-flaring system to be installed in the landfill.

Keywords: Landfill; Methane; IPCC; LandGEM; AERMOD

1. Introduction

Landfill is generally known as the final processing of the solid waste therefore anaerobic degradation process occurs which can generate methane gas (Chiemchaisri *et al.,* 2007). Methane is generally known as a Greenhouse Gas (GHG) and it is also involved in the atmospheric photochemistry as ozone precursor despite of its low reacivity rate (Permadi and Kim Oanh, 2008). It is worth noted that methane absorbs more energy than CO_2 and it has global warming potential (GWP) of 27 - 30 over 100 years' time span (Costa *et al.,* 2021). Methane is also known as strong short-lived climate forcing pollutant (SLCP) which has role to change radiative budget of the earth thus creating climate change (Shindell *et al.,* 2017). In addition, methane gas that accumulates in piles of waste has the potential to cause explosions at the landfills. High rate of urbanization in developing countries like Indonesia generated the total amount of solid waste of about

170 – 180 tons/day in which 69% were piled up in landfills (Chaerul *et al.,* 2006; MoEF, 2015). Most landfills are operated as open dumping rather than the controlled one. This yielded the national methane emissions from landfill in 2010 of about 8.2 Gg/year using the Intergovernmental Panel on Climate Change (IPCC) method (Permadi *et al.,* 2018).

Emission inventory of methane gas emissions from landfill can be done using several approaches: i) the Intergovernmental Panel on Climate Change (IPCC) method, ii) emission model of landGEM, and ii) measuring methane flux in the field with a close flux chamber. The IPCC and LandGEM models use the first-order reaction kinetics of methane formation. They both require data on volume, organic content of degradable waste, condition of the landfill, to feed in the equations to calculate methane emission. Close flux chamber (CFC) was used to determine the actual methane emission rate from disposal sites utilizing the time varying measurement of methane inside chamber and the size of the chamber. This method is known to produce satisfactory results for monitoring local emissions and comparable results to tracer gas methods (Tregoures *et al.,* 1999; Chiemchaisri *et al.,* 2007). Note that, existing landfill methane gas estimation in Indonesia relies on only one method either IPCC or LandGEM without field measurement (Permadi dan Kim Oanh, 2008; Wijaya *et al.,* 2021). The IPCC and LandGEM methods are also useful to quantify impact of various mitigation options on emission reduction.

Once emitted, pollutant may undergo dispersion process in the atmosphere and at certain distance from the source, it can impact human. Air quality dispersion model (AQM) is able to predict concentration of harmful pollutants in the air which can be done at low cost. The correlation between several sources of pollutant emission in an area and the concentration of pollutants under the influence of meteorological parameters in the atmosphere is the basis of AQM. American Meteorological Society (AMS) Environmental Protection Agency (EPA) (AERMOD) model version 11.1 by Lakes Environment has been used world-wide in predicting the pollutant transport process for the purposes of evaluating the impact of emission which is recommended by the United States EPA (US EPA, 2004). This model has capability to simulate impacts of various emission reduction measures from certain sources to the ambient air quality. Dispersion of methane emission in the ambient air has been widely done using AERMOD model due to low reactivity rate thus the result is less uncertain (Hanna *et al.,* 2004; Ravikumar *et al.,* 2016).

To date, an integrated approach of emission – modeling – measures (EMM) has been never done for any landfill in Indonesia despite of its importance for planning purpose. In this research, this approach was demonstrated in one landfill namely Jalupang which receives solid waste from an industrial city of Karawang, Indonesia. Emission inventories were done using the IPCC and LandGEM and the results were evaluated using the CFC measurement (only for wet season). Two possible emission reduction scenarios of bio-cover and pipe flaring system were assessed. Dispersion modeling was done using AERMOD to simulate ambient methane concentrations for base year of 2018 and the two emission reduction scenarios. Framework and results of this study serve as science-based evidence for local authority to compile the emission inventory data and to formulate action plan of emission reduction measures. This is an important issue for landfill management because even after the closure of the landfill, methane gas will be still emitted.

2. Methodology

2.1 Study area and brief description of landfill

An open dumping landfill, Jalupang, which is located in the Karawang District, West Java, Indonesia (Figure 1) was selected as the study area. This landfill receives municipal solid waste that represents typical landfill operation in Indonesia. There has been quite good database for this landfill in-hand therefore this study was carried out. The landfill has been operating since 2003 with a service period up to 2025 (Pudyastuti, 2015) with a land area of 4.7 Ha. Its waste storage capacity reaches 400,000 m^3. Jalupang landfill consists of three zones in which two zones are inactive, while only one zone is still active. The height of the landfill in the inactive zone is 17 meters, while the height of the waste in the active zone has reached 10 meters. The effective service area of the landfill is 4.7 ha which is divided into an active zone area of 1.3 ha and while the inactive zone has a total area of 3.4 ha.

Previous survey in this landfill found out that the existing weight of waste in the year of 2019 was 177,502 ton/year (Adnan, 2019). The survey was conducted using Global Positioning System (GPS) tracking and the results were then supplied to the software developed by the Department of Natural Resources Global Positioning System (DNRGPS). The output was the existing volume of waste, altitude contour, and the slope. Density of waste was previously measured at the landfill by referring to the American Standard Testing and Material (ASTM) No. E1109 – 86 for determining the Bulk Density of Solid Waste Fractions. Further the estimation of the existing weight of waste was calculated and the result is presented in Table 1.

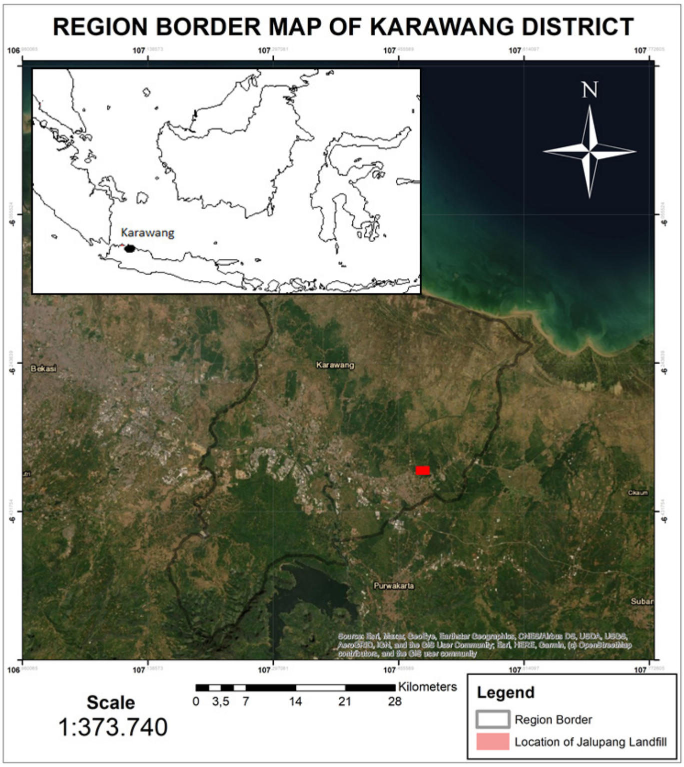


Figure 1. Study area of Jalupang Landfill, Karawang, Indonesia

Table 1. Existing and projected waste received at the landfill

Year	Weight (Tons/year)		
	Non-active	Active	Total
2019	111,402	66,100	177,502
2020		66,894	178,296
2021		67,696	179,098
2022		68,514	179,916
2023		69,331	180,733
2024		70,163	181,565
2025		70,960	182,362

Source: Adanan (2019)

2.2 Emission inventory and evaluation

Emission inventory of CH_4 was done based on the First Order Decay (FOD) method using the 2006 IPCC spreadsheet and the First Order Decomposition Rate Equation method using the USEPA (Landfill Gas Emission Model [LandGEM] version 3.03 spreadsheet). Calculations with the IPCC model used bulk waste and tier 2, which means that the parameters used are a combination of the default parameters and secondary data from previous studies. The data used were the generation of waste that goes to the landfill, the weight of the existing waste in every zone of landfill, *Degradable Organic Carbon* (DOC), and methane correction factor (MCF). For the parameters of DOC, DOCf, and F were taken from the previous research in landfill in Java Island, Indonesia (Chaerul *et al.,* 2020). Parameter *k* was selected using Tropical Dry for dry months and Tropical Wet for wet months. The MCF parameter used a value of 0.8 because the landfill has been operated as the open dumping and the embankment height is > 5 m. The OX parameter used 0 value due to the same reason. IPCC 2006 and LandGEM model have the same approach of using the FOD but the provided values were somehow different. The landfill area was divided based on the active and inactive zones and the weather class of dry and wet months. The later affected the selection of parameters for example IPCC dry or wet tropical and the LandGEM conventional or arid area. The results were differentiated for different zones and different season of dry and wet months. Year of 2018 was used as the initialization required by the IPCC and LandGEM for the FOD calculation, therefore the emission will be zero in that particular year. Basic principles of calculation for both approaches are presented in Table 2.

Table 2. Basic principles for emission calculation for IPCC and LandGEM methods

IPCC[a]	LandGEM[b]
$DDOC_{m(deposited)} = W_{T-1}\ x\ DOC\ x\ DOC_f\ x\ MCF$ $DOC_{m(accumulated\,T-1)} = DDOC_{m(deposited)} + (DDOC_{m(accumulated\,T-2)}\ x\ e^{-k})$ $DDOC_m = DDOC_{m(accumulated\,T-1)}\ x\ (1-e^{-k})$ $CH_4\ generated_{x,T} = DDOC_m\ x\ \frac{16}{12}\ x\ F$ $CH_4\ emission\ for\ year\ T, Ggram = [\sum_x CH_4\ generated_{x,T} - R_T]\ x\ (1-OX_T)$ $CH_4\ emission = [\sum_x CH_4\ generated_{x,T} - R_T]\ x\ (1-OX_T)$ Where, $DDOC_m$ = Decomposable Degradable Organic Carbon, (Gg) W = Mass of collected waste, (Gg) DOC = Degradable organic carbon, (Gg C/Gg waste) K = Methane formation reaction rate (second^{-1}) DOC_f = Fraction of decomposed DOC MCF = Methane correction factor for aerobic decomposition T = Inventory year X = Type of solid waste R_T = Amount of recovered or flared CH_4 for year T, Gg OX_T = Oxidation factor for year T.	$L_o = 493\ DOC$ $Q_{CH_4} = \sum_{i=1}^{n}\sum_{j=0,1}^{1} kL_o\left(\frac{M_i}{10}\right)e^{-kt_{i}}$ Where, Q = Volume methane generation (m^3/year) DOC = Degradable organic carbon (Ton C/Ton of waste) L_o = Methane generation potential (m^3/Ton) M_i = Annual amount of waste delivered to landfill (Ton/year) k = Methane formation reaction rate (year^{-1}) t_{ij} = Age j of M_i waste type included in year i i = Incremental age of 1 year j = Incremental age of 0,1 year n = calculation year – year of operational of landfill.

Source: [a] IPCC (2006), and [b] US EPA (2005).

A half-day measurement of methane flux rate using close flux chamber was conducted following the method described in Chiemchaisri *et al.* (2007). The measurements were done for the morning (09:00-10:00), mid-day (12:00 – 13:00) and afternoon (15:00 – 16:00) with the reading interval of every 1 minute. Methane sensor used the waysear brand and the CFC used the acrylics material for the chamber. Estimation of CFC flux rate measurement was compared to the results of the IPCC and LandGEM derived emissions in term of total emission in a year (ton/yr). Average daily flux rates for active zone were multiplied with the area as well as those measured for the non-active zone. Then, the daily emission was multiplied with 365 days to estimate the annual emission rate. Basic principle for flux rate calculation is expressed in the following equation.

$$J = \frac{v}{A}\frac{dC}{dt} \quad \text{(Equation 1)}$$

Where:
J : methane flux rate (mole/m^2.hour)
V : chamber volume (m^3)
A : surface area of the chamber (m^2)
dC/dt : methane concentration increasing rate measured in the chamber (mol/m^3.jam).

2.3 Development of emission reduction measures

Mitigation efforts are suggested to reduce CH_4 gas emissions by changing the value of variables that affect the emissions. In this research, two scenarios were considered based on the existing literature: 1) pipe-flaring system, and 2) biosolids/biocover. In the first option, pipe system is installed covering all zones in the landfill to convey CH_4 emissions to the flaring system therefore methane is oxidized to emit H_2O and CO_2. The efficiency of reducing CH_4 emissions by the pipe & flaring system method varies with a range of 50% to almost 100% depending on the type of overburden and the piping system that includes the landfill (Barlaz *et al.,* 2012). In this study, it is assumed to use a pipe-flaring system and final soil cover with an efficiency of 95% CH_4 emission reduction (SWICS, 2009). This efficiency data was then multiplied with the base case CH_4 emissions. The pipe-flaring system was assumed to start operating in 2025 because the landfill is planned to be closed in that year.

For the second option, waste heap in the landfill is covered using a biocover, therefore CH_4 emissions are oxidized by methanotrophic bacteria. The reported efficiency of CH_4 emission reduction would depend on the type of biocover used. It was reported that the associated efficiency values were: sawdust-mud of 33.9% - 63.3% and mud-soil waste of 65% - 70% (Borjesson *et al.,* 2007). In this study, the scenario was assumed to use a landfill mining compost biocover type with a typical efficiency of 66%, which was generated through field experiments. The percentage (%) efficiency data were then supplied again to the inventory model to estimate the emission reduction when the application of biocover by 2025 is targeted.

2.4 AERMOD simulation

The analysis of dispersion patterns used AERMOD model. The data used was the CH_4 emission rate, elevation map from Google Earth processed using Global Mapper, and meteorological data. Surface meteorological data (wind speed, wind direction, temperature, solar radiation, pressure, humidity, lowest cloud height, cloud cover, and rain intensity) were obtained from the National Bureau of Meteorology, Climatology and Geophysics (BMKG) while the upper-air data were taken from the National Oceanic and Atmospheric Administration (NOAA) database. Surface meteorological data was retrieved for Halim Perdanakusuma International Airport for the year of 2019 while the upper-air data was retrieved for Soekarno Hatta International Airport for the year of 2019. Grid arrangement for receptors was done within a 5 km radius from the landfill with a grid size for each of 0.5 x 0.5 km. AERMOD model simulation was done for 1 year in 2019 and two cases were considered:

- Base year simulation using 2019 emission data
- Scenario simulation using 2025 emission data assuming implementation of the two emission reduction measures discussed above.

3. Results and discussion

3.1 Emission inventory evaluation

The emission estimates generated by the IPCC, LandGEM and CFC measurement was compared for the base year of 2019 in the Table 3. Estimation by the IPCC method yielded nearly 3,000 ton/yr while LandGEM was only 672 ton/yr. The result of LandGEM was closer to that estimated using the CFC measurement. Though measurement was done only for wet season therefore emission estimation using CFC was also rough to provide alternative for the annual estimate.

Long-term simulated methane gas emission using both the IPCC and LandGEM is presented in Figure 2. The rate of methane gas emission occurred exponentially and reaches its peak in 2026 at 7,350 Mg/year (IPCC 2006) and 2,339 Mg/year (LandGEM v3.03). After 2026, the emission rate decreased because it was assumed that waste filling in landfills would be only until 2025 according to the planned operational time of the landfill. Therefore, there was an exponential reduction in methane emission after the year of 2025.

The results of the two methods produce numbers with significant differences. The results of the IPCC model were three times more than those of the LandGEM model. A similar study was conducted in India with the results of the IPCC model being much higher than the LandGEM model, according to the authors (Kaushal and Sharma, 2016). This was due to the different mathematical formulas and the different types of input data parameters used. IPCC used k and DOC parameters which were more adapted to many countries, while LandGEM used k and DOC parameters from research results in several landfills in the US. However, even without daily and monthly temporal variations, but rather average (conservative estimate), the result of CFC measurement was closer to LandGEM. These results are somehow consistent with Chiemchaisri *et al.* (2005) who conducted similar study for tropical landfill in Thailand. Their emission estimation showed that the result from the IPCC was higher than the LandGEM while the LandGEM result was also higher than that estimated using CFC.

Then, IPCC results were used to serve as input for AERMOD simulation in the next stage as well as for emission reduction. The consideration was to accommodate the worst condition due to high emission therefore worst effect on air quality could be anticipated. In fact, the LandGEM mainly relied on the data of sanitary landfill in the US and the reactivity rate (k) value was limited to 0.02 for rainfall intensity of less than 635 mm/year. In the tropical countries, the rainfall intensity was often observed higher than 2,000 mm/year.

3.2 Quantified emission reduction

The most efficient method of reducing methane emissions from the Jalupang Landfill was the pipe-flaring system with final soil cover, the maximum methane emission rate became 367 ton/year with an efficiency of 95% (Figure 3). The maximum CH_4 emission rate occurred in 2024 of 6,421 ton/year. Based on the landfill planning, the pipe-flaring system will be only installed by the year of 2025 thus the CH_4 emission was still peaking in 2024 (Pudyastuti, 2015).

Table 3. Comparison of emission estimates by the IPCC, LandGEM and CFC for the year of 2019

Emission estimation method	Methane emission in 2019 (Ton/year)
IPCC	2,976
LandGEM	672
CFC • Average flux rate: 780 mg/m^2/hr • Effective service area: 47,000 m^2	321

Note: CFC experiment was done only for wet season period

After the pipe-flaring system was implemented in 2025, then the maximum CH_4 emission rate occurred in 2026 of 367 ton/year. Note that this pipe-flaring system relies on the gas collection efficiency which was reported to vary from 10 to 90%. Oonk (2012) reported that collection efficiency depends on landfill types; i) landfills with state-of-the-art liners: 90 - 100%, ii) closed landfills: 10 - 90%; and iii) landfills in operation: 10 to 80%. Therefore, this factor should be considered for future study.

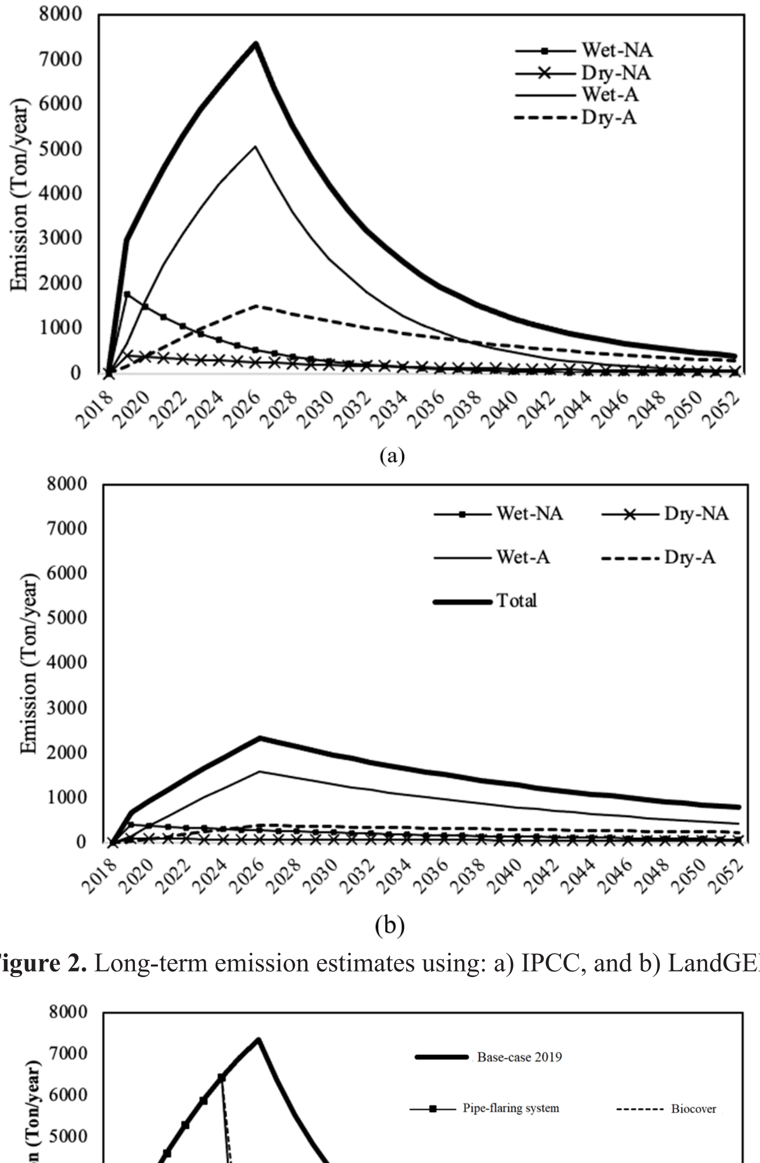


Figure 2. Long-term emission estimates using: a) IPCC, and b) LandGEM

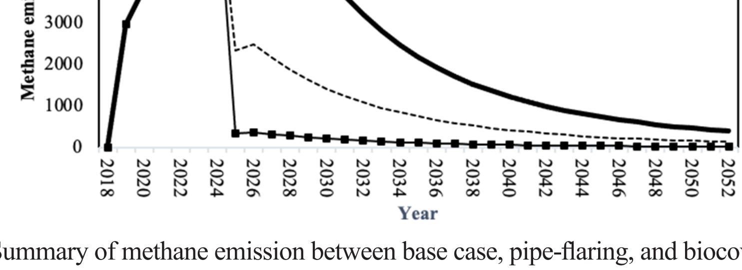
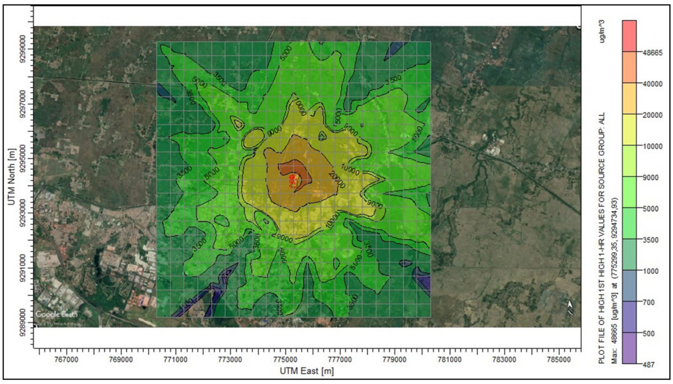


Figure 3. Summary of methane emission between base case, pipe-flaring, and biocover scenarios

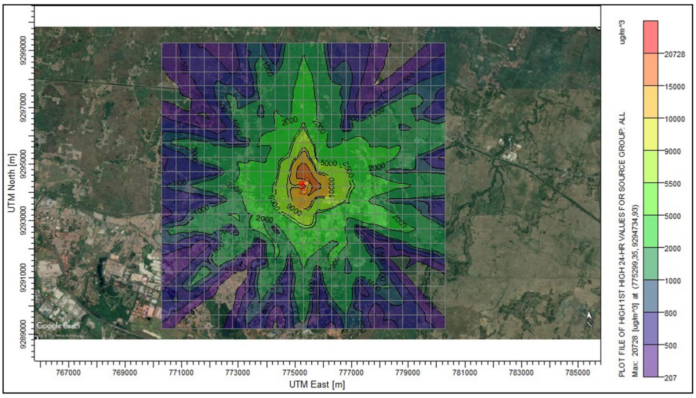
3.3 Simulation results

3.3.1 Base case

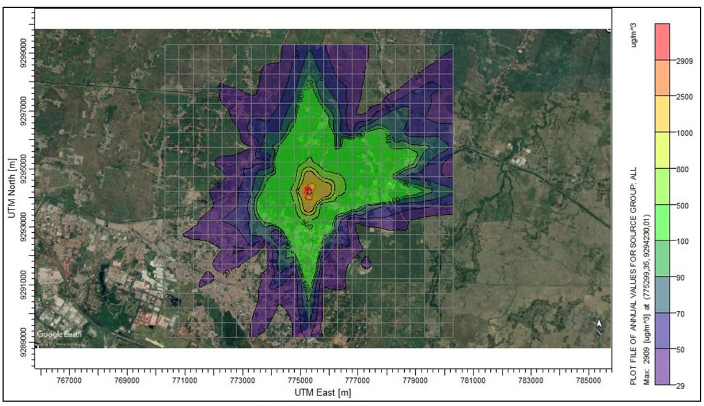
The maximum methane concentrations for the dispersion time of max. hourly, daily, and annual averages were 48,665 μg/m³, 20,728 μg/m³, and 2,909 μg/m³ (Figure 4a – 4c) with the distribution was more dominant towards the east or residential area. Locations potentially exposed to maximum methane concentrations were within a radius of up to 1 km from the Jalupang Landfill. In residential areas (west-south) methane concentrations were simulated of 0 μg/m³ - 20,000 μg/m³ (max. hourly), 0 μg/m³ – 5,000 μg/m³ (daily max.), and 0 μg/m³ - 500 μg/m³ (annual average). Apart from being a GHG, methane in the atmosphere could react (photoreaction) with NOx and CO to form ozone which can cause photochemical smog which is harmful to the respiratory system of living things (Permadi and Oanh, 2008).



a) Maximum hourly



b) Daily maximum

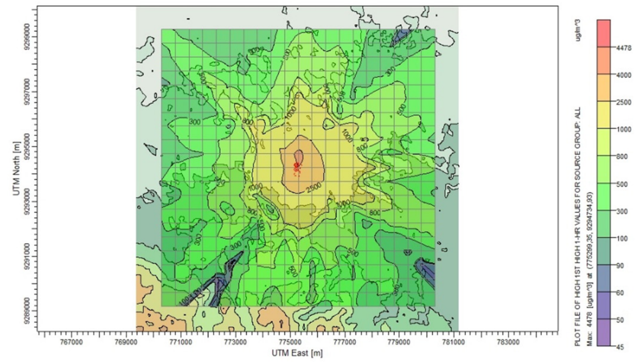


c) Annual average

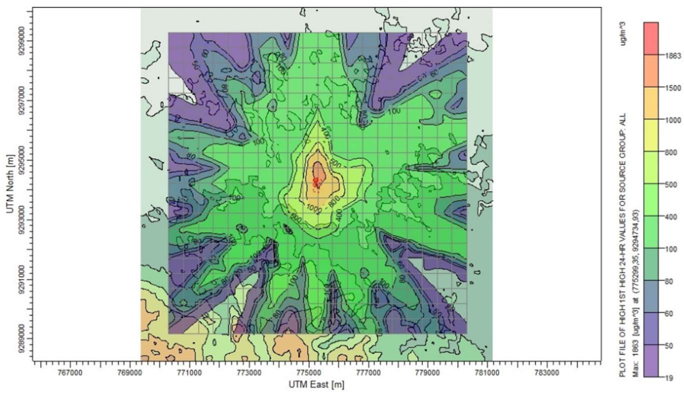
Figure 4. Spatial distribution of base case methane concentration

3.3.2 Emission reduction scenario

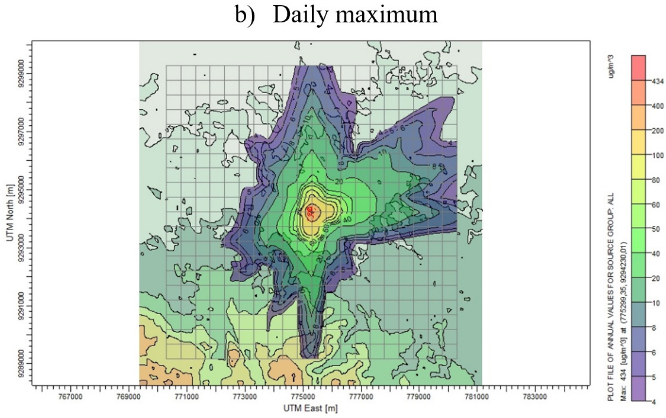
The results of the reduction in methane emissions (collectively both scenarios) were used for modeling the dispersion pattern to determine the concentration of methane in the atmosphere after the methane emission reduction scenarios were carried out. The maximum methane concentrations, after the methane emission reduction scenario for the dispersion time of max. hourly, daily, and annual averages were 2,433 μg/m³, 1,036 μg/m³, and 145 μg/m³ (Figure 5), with a more dominant distribution towards the east or rice fields. In residential areas, the concentrations of methane were simulated of 0 μg/m³ - 1,000 μg/m³ (max. hourly), 0 μg/m³ - 300 μg/m³ (daily max.), and 0 μg/m³ - 10 μg/m³ (annual average). Overall, compared to base case, concentrations of methane contributed by the Landfill after implementation of reduction measures could be reduced by nearly 95%.



a) Maximum hourly



b) Daily maximum



c) Annual average

Figure 5. Spatial distribution of methane concentrations after collective implementation of emission reduction measures

4. Conclusion

Emission inventory using the IPCC method resulted in the emission of 3,000 tons/year while LandGEM was only 672 tons/yr. This discrepancy is expected as the IPCC method estimates ultimate methane emission based on the exact amount of waste disposed in a particular year, while the LandGEM prediction is based on the remaining deposited waste in that year by assuming first-order decay rate from the starting year of site operation. The CFC measurement result was about 321 tons/year which was closer to the LandGEM result. Our results are consistent with another similar work conducted for tropical landfill showing the order of estimation magnitude of IPCC > LandGEM > CFC. As compared to bio-cover option, methane emission reduction measure of pipe-flaring system was more efficient which can bring down maximum emission from 367 tons/year to 6,421 tons/yr. The concentration of methane continued to decrease if the dispersion time was longer. The results of the spatial dispersion analysis showed that the maximum concentration of methane had the potential to occur within a radius of up to 1 km from the Landfill. The distribution pattern tends to be more dominant towards the east or residential area. Simulation of collective emission reduction measures of pipe-flaring systems and bio-cover could bring down atmospheric concentration of methane in the atmosphere by up to 95%. Measures tested through the emission inventory – modeling tools provided co-benefits in the potential reduction of ground-level ozone formation as well as the warming potential. This framework can be used to conduct quantitative prediction of the landfill activity impacts especially on the greenhouse gas emission inventory.

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