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Health Risk Assessment of Air Pollutants Emitted from Municipal Solid-Waste Incinerators in Thailand

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Abstract

One of the recommended tools for estimating adverse health effects on people living near municipal solid-waste incinerators (MSWIs) is the health risk assessment (HRA). In this study, the emissions from MSWI stacks were estimated using the existing MSWI and Compilation of Air Emissions Factors by the U.S. EPA (AP-42). Ground-level concentrations of air pollutants emitted from MSWI were estimated using an air quality model AERMOD. Air pollutants include 1) The criteria air pollutants (CAPs) of Sulfur dioxide, Carbon monoxide, Particulate matter, Nitrogen oxide and Lead; 2) hazardous air pollutants (HAPs) such as As, Cd, Cr, Hg, Ni and tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans (CDD/CDF); and 3) HCl. Five study areas were selected as representative of the factors of size and location, namely, Lamphun, Khon Kaen, Rayong, Phra Nakhon Si Ayutthaya and Surat Thani. For HAPs, the estimated carcinogenic risks were compared with the acceptable level of E-06 as suggested by the U.S. EPA, while for non-carcinogenic risks, the value should be lower than 1. Result show that the multi-chemical cancer risk (CR) for the various sizes and locations of MSWIs are between 6.48E-07 and 2.51E-06. The CRs of the people living near some MSWIs are higher than the suggested value. The hazard index (HI) ranges from 1.60E-02 to 6.28E-02, which is within the U.S EPA acceptable limit of 1.

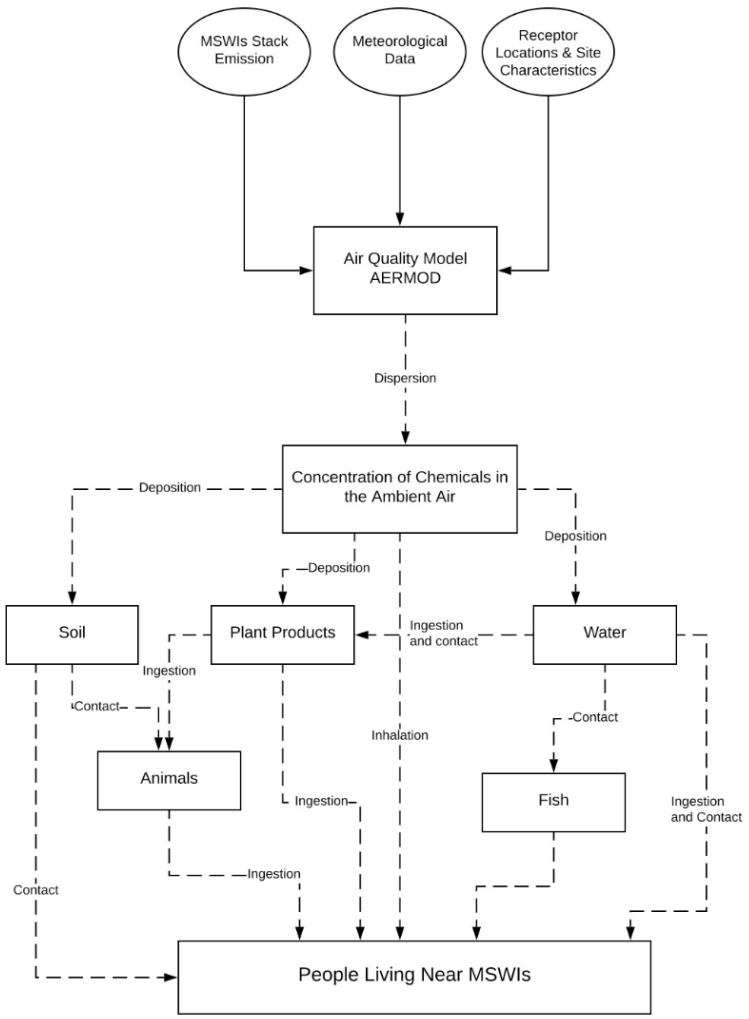
Keywords: Municipal solid-waste incinerator; Air quality modeling; Heavy metals; Organic pollutants; CAPs; HAPs; Health risk assessment; multiple pathways; Hazard index; Cancer risk

1. Introduction

In Thailand, waste incinerators have been used recently to reduce municipal waste and to produce electricity as a by-product using the waste-to-energy (WtE) concept (Tanakwang, 2010; PCD, 2015, 2016; Towprayoon, 2016). However, they also create health risks to the people living nearby because of the pollutants emitted from municipal solid-waste incinerators (MSWIs). According to the United States Environmental Protection Agency (U.S. EPA, 1996), hazardous pollutants emitted from refuse combustion include heavy metals like arsenic (As), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr) and mercury (Hg); chlorinated organic chemicals like tetra-through octa-chlorinated dibenzo-p-dioxin (CDD) and chlorinated dibenzofurans (CDF); and criteria air pollutants (CAPs) like particulate matter, sulfur dioxide, nitrogen oxides (NOx) and carbon monoxide. Polycyclic aromatic hydrocarbons (PAHs) and dioxins have been found to result from insufficiently controlled combustion processes (Ravindra *et al.,* 2008). Some chemicals such as arsenic, cadmium, lead, and dioxins and furans are classified as carcinogens, or as suspected carcinogens, by the International Agency for Research on Cancer (IARC, 2019).

According to the Pollution Control Department (PCD, 2015) of Thailand, sizes of MSWIs are classified into "clusters" according to waste input as determined by the Waste and Hazardous Substances Management Bureau

(WHSMB) (Waste and Hazardous Substances Management Bureau, 2014). While these clusters are sub-classified into 6 sizes, only 3 sizes were proposed for development because of worthiness for construction by WtE because of the amount of waste input involved. They were chosen to be included in this study according to these descriptions: 1) large cluster 1 (L1), which operates 24 hours continuously working over 6,000 hours per year, processing over 700 tons of waste per day and servicing an area of waste collection within a 50 kilometers radius; 2) large cluster 2 (L2), which operates 24 hours continuously and shuts down only for maintenance, processing 300 - 700 tons of waste per day and servicing an area of waste collection not over 50 kilometers radius; and lastly, 3) medium cluster 1 (M1), which operates 24 hours for waste incineration and electricity generation, processing 100 - 300 tons of waste per day and servicing an area of waste collection not over 50 kilometers radius. Communities located near incinerators are potentially exposed to hazardous substances in multi-exposure pathways (Franchini *et al.,* 2004) including 1) inhalation of contaminated air, 2) ingestion of contaminated foods and water, and 3) dermal contact with contaminated soil or water. Several studies show significant associations between waste incineration and lung cancer, urinary mutagens and blood-contamination levels from certain organic compounds and heavy metals



Source: Hu & Shy, 2001.

Figure 1. Conceptual framework of multi-exposure pathways from operation of MSWIs

The human health risk assessment (HHRA) is a recommended tool for assessing the health impact from exposure to multi-risk agents, such as chemical contaminants. The basic steps include: 1) Hazard identification: Examines the compounds of potential concern (COPCs) that can be harmful to people living near MSWIs. In this study, atmospheric dispersions and depositions of the emitted COPCs from MSWIs were considered. Dispersion of COPCs were estimated using the air quality model, AERMOD; 2) Dose-response assessment: Examines the relationship between exposure to pollutants and their effects; 3) Exposure assessment: Examines the frequency, duration and exposure levels that people come into contact with, as both a direct (inhalation) and an indirect (ingestion and dermal contact) pathway with the COPCs; and 4) Risk characterization: Concludes the HRA for all COPCs (U.S. EPA, 2017). In Figure 1, direct exposure to COPCs via an inhalation pathway was evaluated for receptors. For indirect exposure, COPC deposition, and then contamination to water, soil, plants and animals via either dermal contact or ingestion, were also evaluated (Office of Solid Waste, 2005).

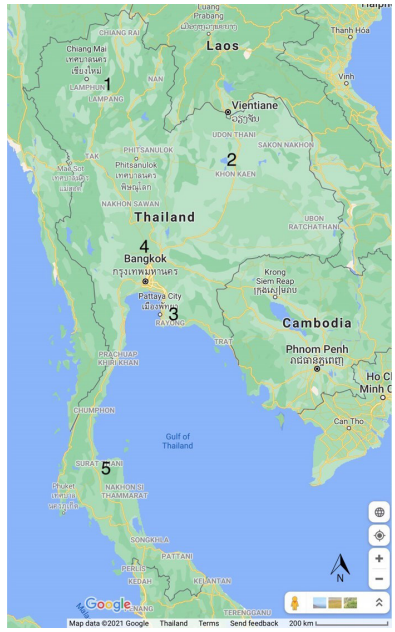
2. Material and Methods

2.1 Study Area

PCD proposed 53 locations for developing MSWI projects in Thailand (PCD, 2015), and this study selected 5 sites as representatives of the five Regions of Thailand, namely, Lamphun for the Northern region, Khon Kaen for the Northeastern Region, Phra Nakhon Si Ayutthaya for the Central region, Rayong for the Eastern Region and Surat Thani for the Southern Region, as shown in Figure 2. It was proposed that the Lamphun MSWI (LP MSWI) be located in the Mae-Tha District. The city occupies 751.60 square kilometers. In 2017, the city had a population of 39,231 and a population density of 52.19 people per square kilometer. It was proposed that the Khon Kaen MSWI (KK MSWI) be located in the Muang District of Khon Kaen. The city occupies 963.39 square kilometers and has a population of 219,821 with a population density of 228.17 people per square kilometer. It was proposed that the Phra Nakhon Si Ayutthaya MSWI (AY MSWI) be located in the Bang Ban District. The city occupies 135.305 square kilometers and had a population of 34,435 with a population density of 135 people per square kilometer. It was proposed that the Rayong MSWI (RY MSWI) be located in the Muang District of Rayong. The city occupies 514 square kilometers and had a population of 546,586 with a population density of 1,063.4 people per square kilometer. Lastly, it was proposed that the Surat Thani MSWI (SR MSWI) be located in the Phunphin District. The city occupies 1,205.5 square kilometers, and has a population of 89,901with the population density of 76 people per square kilometer (Department of Provincial Administration, 2017).

2.2 Air-Modeling Input Data

Risk assessment was conducted over an area of 10×10 km^2 (with grid resolution 200×200 m^2) around the MSWIs. The stack emissions of MSWIs were determined according to the AP-42 (U.S. EPA, 1996) and KK MSWI. Emission rates were directly adjusted according to waste input and corrected with the actual emissions of KK MSWI as monitored by the local municipalities. The characteristics of MSWIs for the model application included stack diameter, stack height, stack-gas velocity, flue-gas temperature and emission rates, as shown in Table 1.



(Map adapted from Google Map, 2021, were retrieved from https://www.google.com/maps/@14.0037609,102.0878303,6.34z?hl=en)

Figure 2. Locations of MSWIs in this study 1) Mae Tha District, Lamphun (516288, 2041580); 2) Mueng District, Khon Kaen (266366, 1836058); 3) Mueng District, Rayong (743006, 1410505); 4) Bang Ban District, Phra Nakorn Si Ayutthaya (661430, 1586128) ; and 5) Phunphin District, Surat Thani (517746, 1000476)

Table 1. Summary of source parameters for MSWIs

Source description		Value				
		LP	KK	RY	AY	SR
Location (UTM)	East	516288	266366	743006	661430	517746
	North	2041580	1836058	1410505	1586128	1000476
Size of MSWIs		L2	L2	L1	L1	M1
Waste input (tons/day)		313	490	1000	593	229
Stack height (m)		57.09	48.70	85.71	49.71	42.13
Flue-gas temperature (K)		469.60	440.73	610.00	353.80	418.13
Exit velocity (m/s)		9.87	8.42	19.57	11.35	7.28
Stack diameter (m)		2.70	2.30	2.71	1.57	1.99
Emission rate (g/s)						
SO_2		2.89E-01	4.00E-01	9.23E-01	5.35E-01	2.13E-01
NOx		3.06E-01	3.90E-02	9.76E-01	5.66E-01	2.25E-01
TSP		2.10 E+00	1.51 E+00	6.27 E+00	3.90 E+00	1.55 E+00
CO		3.87E-02	5.58E-02	1.24E-01	7.18E-01	2.86E-02
As		3.57E-04	1.74E-04	1.14E-03	6.62E-04	2.64E-04
Cd		9.10E-04	1.29E-03	2.91E-03	1.69E-03	6.71E-04
Cr		7.50E-04	3.66E-04	2.39E-03	1.39E-03	5.48E-04
Hg		4.67E-04	1.38E-04	1.49E-03	8.66E-03	3.45E-04
Ni		6.56E-04	3.20E-04	2.10E-03	1.22E-03	4.35E-04
Pb		1.79E-02	8.72E-03	5.71E-02	3.31E-02	1.32E-02
HCl		5.34E-01	3.69E-01	1.71E+00	9.90E-01	3.94E-01
CDD/CDF		1.39E-07	1.29E-07	4.45E-07	2.58E-07	1.03E-07

The local meteorological data (MET) during 2014-2016 were retrieved from the Thai Meteorological Department (TMD). The MET were arranged to conform to the SCRAM (Support Center for Regulatory Atmospheric Modeling) format for surface data and FSL (Forecast Systems Laboratory) format for the upper-air data. From the surface and the upper-air data files, AERMET (a MET preprocessor) was applied to create an hourly MET file as input to the air quality model AERMOD (Lake Environment version 6.6.0). The terrain data were retrieved from http://www.webgis.com/srtm3.html. The site characteristics were determined from a local land-use map. Ground-level concentrations (GLCs) of contaminants or COPCs ($\mu g/m^3$) were predicted by an air quality model as recommended by the U.S. EPA (Office of Solid Waste, 2005). The result of this study is presented as contour lines of unit risk overlaid onto geographical maps. The results were interpreted, as well as estimated, to ascertain total risk.

2.3 The HHRA Protocol

2.3.1 Identification COPCs

This study considered 3 groups of pollutants emitted from the MSWIs stacks: 1. CAPs, including SO2, CO, TSP, NOx and Pb; 2) hazardous air pollutants (HAPs), including As, Cd, Cr, Hg, Ni, PCDD and PCDF; and 3) HCl. All COPCs emission factors, with the exception of KK MSWI, were applied from AP-42 (U.S. EPA, 1996), depending on the characteristics of the waste and MSWIs condition.

2.3.2 Dose-Response Assessment

The GLC of air pollutants were calculated by the air quality model, as mentioned earlier. The next assessment was to describe the likelihood and severity of adverse health effects related to COPC exposure. First, the intake (I) of COPC receptors from COPCs deposits into the media of water, soil and food through these three pathways (i.e. by direct and indirect inhalation and from ingestion and contact). In order to compare the deposit levels with the acceptable levels, Reference dose or reference concentration (RfD or RfC) was applied to determine the individual hazard quotient (HQ), where the hazard index (HI) is the sum of HQ's for all pathways (Equation 1). For carcinogenic substances, inhalation unit risk (IUR) and oral slope factor (OSF) were applied for individual cancer risk (ICR), and the total cancer risk is the sum of CR for all pathways (Equation 2). The characterization of risk associated with exposure was carried out by the HQ of those toxic substances. For carcinogens, the ICR was the reference to establish the probability of a human to develop cancer (U.S. EPA, 2017).

$$HQ = \frac{I}{RfD \text{ or } RfC} \quad ; \quad HI = \sum_1^i HQ \qquad (1)$$

$$ICR = I \times OSF \text{ or } IUR; \quad TCR = \sum_1^i ICR \qquad (2)$$

Where HQ = Hazard quotients (dimensionless)
I = Intake of COPCs from medias (mg/kg or $\mu g/m^3$)
HI = Hazard index (dimensionless)
RfD = Reference dose (mg/kg of BW-day)
RfC = Reference concentration ($\mu g/m^3$)
ICR = Individual cancer risk (dimensionless)
OSF = Oral slope factor (per mg/kg)
IUR = Inhalation unit risk (per $\mu g/m^3$)
TCR = Total cancer risk (dimensionless)

2.3.3 Exposure Assessment

The exposure assessment was accomplished in order to estimate the nature and probability of adverse health effects in those who were exposed to COPCs whenever the MSWIs are in operation. In this study, adult residents (above 15 years old) were assumed to be the representative scenario. Exposures to heavy-metal and organic matter from the MSWIs were considered significant, especially in rural areas (Sipter *et al.*, 2008). Major exposure pathways include ingestion (from food and water), dermal contact (water and soil) and inhalation.

The quantitative exposure was estimated as intake (I) (mg/kg/day) by using Equation 3. The value was calculated on the basis of multi-media pollutant concentration in the environment. The maximum annual average concentration (C) was calculated from a multi-pathway of both direct and indirect exposure. Average time (AT) is the period over which exposure is averaged to determine a lifetime expectancy of 75.3 years for the Thai population (World Bank, 2019). This value was used in the calculation of lifetime carcinogenic exposure. The average Thai adult bodyweight (BW) is 68 kilograms (SizeThailand, 2009). Exposure duration (ED) is estimated to be 30 years according to the break-even point of an MSWI project (Office of Solid Waste, 2005). Exposure frequency (EF) is the number of hours during which receptors are exposed to the chemicals during a year. IR is the total mass ingested, inhaled or absorbed. The ingestion rate (IR)of Thai people was taken from the report "Food Consumption Data of Thailand" (Ministry of Agriculture and Cooperatives, 2006).

$$I = \frac{C.IR.ED.EF}{BW.AT} \quad (3)$$

Where I = Intake of COPCs from medias (mg/kg or μg/m^3)
C = Maximum annual average concentration (μg/m^3)
IR = Ingestion rate (kg/day)
ED = Exposure duration (year)
EF = Exposure frequency (350 days/year)
BW = Body weight (kg)
AT = Averaging time (days)

2.3.4 Risk Characterization

Risk characterization is the final step of the risk assessment process. This evaluation is based on dose-response assessment of the COPCs and exposure assessment. This step addresses the risk to people living near the MSWIs because of the COPCs. In this study, risk characterization provides 2 types of quantitative evaluation of risk as follows:

1) Individual aggregate risk, the integrated risk caused by each COPC, which is broader for multiple exposure pathways. This value was calculated for each health risk, including HQ and CR.

2) Cumulative multi-chemical risk, the cumulative exposure of receptors to COPCs in the environment along all routes or pathways. The HQ and CR of each COPC were combined to be the HI and total CR respectively. The most adverse effect to health of the COPCs is the development of lung cancer.

3. Results and Discussion

3.1 Contaminant Distribution

An air quality modeling, AERMOD, was applied to calculate the annual GLC of each COPC. The maximum concentrations of each COPC in the area surrounding the MSWIs, as compared with air quality standards, are presented in Table 2. In terms of the predicted maximum annual concentrations given in Table 2, none of the COPC GLCs exceed the standard.

As determined from this study, the highest GLC for heavy metal was lead, which ranged from 0.00199 to 0.0228 μg/m^3. For the CAPs, the values ranged from 0.344 to 1.70 μg/m^3. The RY MSWI released the highest GLC, as compared to the others, since it had the highest-level waste input. Although the KK MSWI was not the smallest in size among all MSWIs, pollutants emitted from this MSWI were found to be the lowest in amount. Since the KK MSWI is an existing plant, the input data to AERMOD, namely, the emission rate, stack diameter, stack height, stack-gas temperature and stack-gas velocity, are the actual data.

3.2 Risk Distribution

There are three possible pathways for humans to be exposed to pollutants in the environment, namely, inhalation, ingestion and dermal contact. In this study, the exposure pathway of inhalation contributes to the highest intake of both carcinogens and non-carcinogens. The calculated HI values using the U.S. EPA method for the five areas for individual and multi pathways are presented in Table 3 for cancer risk and Table 4 for HQ.

Table 2. Highest annual average GLCs of air pollutants

Area/ COPC	Highest annual average GLC (µg/m^3)*					Standard (µg/m^3)	Reference
	LP	KK	RY	AY	SR		
CO	0.02	0.01	0.03	0.03	0.03	n/a	
SO_2	0.18	0.00	0.25	0.21	0.23	100	PCD[1]
NO_x	0.20	0.02	0.26	0.39	0.25	57	PCD[1]
TSP	1.34	0.34	1.70	1.56	1.70	10	PCD[1]
HCl	0.34	0.08	0.46	0.40	0.43	n/a	
As	0.0002	0.0000	0.0003	0.0003	0.0003	0.0055	NZ[2]
Cd	0.0006	0.0003	0.0008	0.0007	0.0007	0.04	EU[3]
Cr	0.0005	0.0001	0.0006	0.0006	0.0006	0.11	NZ[2]
Hg	0.0003	0.0000	0.0004	0.0003	0.0004	0.13	NZ[2]
Ni	0.0004	0.0001	0.0006	0.0005	0.0005	0.006	EU[3]
Pb	0.011	0.002	0.016	0.023	0.015	0.5	NZ[2]
CDD & CDF (pg/m^3)	0.0887	0.00294	0.12	0.115	0.113	1	CN[4]

* The GLC was not including background concentration values.
[1]Thai Ambient Air Quality Standards (PCD, 2010)
[2]NZ as Ministry for the Environment, New Zealand. (Ministry for the Environment, 2002)
[3]EU as Environmental Science for European Refining (CONCAWE, 1999)
[4]CN as Connecticut's Dioxin Ambient Air Quality Standard (Rao and Brown, 1991).

For cancer risk, the U.S. EPA recommends that the unit risk should be below E-06 (U.S. EPA, 2017). From the predicted values as shown in Table 3, the direct and indirect pathways for most of individual COPCs were found to be lower than the acceptable level issued in the Clean Air Act; E-06 (U.S. EPA, 1990). However, the most concerning of the COPCs is chromium, since its CRs were higher than the reference value and it has an effect on the total cancer risk. According to the IARC, mercury is classified as a carcinogen, but it has no inhalation unit risk (IUR) or oral-cancer slope-factor (CSF) values. Using the additive approach, the total multi-chemical cancer-risk values, from highest to lowest, were found to be 2.51E-06, 2.34E-06, 1.39E-06, 1.35E-06 and 6.84E-07 for Rayong, Lamphun, Phra Nakhon Sri Ayutthaya, Surat Thani and Khon Kaen, respectively. Those values exceed the acceptable levels, except for Khon Kaen, for which the input parameters are actual data.

The HI for non-carcinogenic risk from the presence of multi-chemicals for each of the 5 areas was found to be below the reference level (<1) (U.S. EPA, 1990).The values from highest to lowest were found to be 6.28E-02, 3.43E-02, 3.38E-02, 3.27E-02 and 1.60E-02 for Rayong, Phra Nakhon Sri Ayutthaya, Surat Thani, Lamphun and Khon Kaen (Table 4), respectively, indicating that COPCs are unconvincing causes of adverse non-cancer health effects after a lifetime exposure of receptors to these agents (U.S. EPA, 2021). Hence, the HI of all five areas was at an acceptable level, even for the individual chemical. It must be explained that the level of uncertainty of related parameter values used for calculating the estimated risk has an effect on the results. Nevertheless, it is worth noting that the risk assessment was based on the highest concentration from the air quality model, which was then followed by a calculation showing the highest

exposure for those scenarios (Office of Solid Waste, 2005). A comparison of the CDD&F with the results of a study by Sun *et al.* in 2017 showed that the CR of CDD/Fs in fly ash was within the range of 2.5E-05 to 3.58E-04, and that their HI values were in the range of 3.78E-01 to 6.95E+00. These figures were very different when compared to that same study of Sun *et al.* of 2017. The possible reason is that the International Toxic Equivalent (I-TEQ) of PCDD/Fs in the latter study was much different when compared to the present study, and our study did not consider the effect from the fly ash.

The maximum GLCs were located at 225.41, 376.94, 518.26, 389.32 and 260.99 meters from the source in Lamphun (in the East), Khon Kaen (in the Northeast), Rayong (in the East), Phra Nakhon Si Ayutthaya (Central) and Surat Thani (in the South), respectively (Figure 3-4). The cancer risk and hazard index that were calculated from the MSWIs pollutants were not as high as expected, since the CRs were slightly out of the reference level and the HI did not exceed it. The results show similar low risks, as do the other studies of risk assessment (Cangialosi *et al.,* 2008; Morselli *et al.,* 2010).

Table 3. Total cancer risk for human receptor

Area	COPCs	Cancer risk (dimensionless)						
		As	Cd	Cr	Ni	Pb	CDD	CDF
	IUR $(\mu g/m^3)^{-1}$	4.30E-03[1]	1.80E-03[1]	1.20E-02[1]	2.40E-04[1]	1.20E-05[2]	3.30E-01	3.80E-01[2]
	ORF $(mg/kg)^{-1}$	1.50E+00[1]	1.5E+01[2]	5.00E-01[3]	9.10E-01[2]	8.50E-03[2]	1.30E+05[3]	1.33E+05[3]
LP	Individual CR	6.80E-08	1.58E-07	1.04E-06	1.82E-08	9.92E-07	5.31E-09	6.12E-08
	Total CR of multi-chemicals	2.34E-06*						
KK	Individual CR	3.23E-08	8.35E-08	1.89E-07	3.31E-09	3.55E-07	1.84E-09	2.11E-08
	Total CR of multi-chemicals	6.84E-07						
RY	Individual CR	3.01E-07	2.68E-07	1.76E-06*	3.10E-08	4.21E-08	9.03E-09	2.51E-08
	Total CR of multi-chemicals	2.51E-06*						
AY	Individual CR	1.64E-07	1.46E-07	9.61E-07	1.69E-08	3.95E-08	5.46E-09	1.04E-07
	Total CR of multi-chemicals	1.39E-06*						
SR	Individual CR	1.64E-07	1.45E-07	9.47E-07	1.50E-08	2.28E-08	4.90E-09	5.64E-08
	Total CR of multi-chemicals	1.35E-06*						

* Exceed the reference level (E-06)

[1)] U.S. EPA. Integrated Risk Information System (IRIS) (U.S. EPA, 2019)

[2)] California Environmental Protection Agency (CalEPA) (CalEPA, 2015)

[3)] Regional Screening Levels (RSL) for Chemical Contaminants at Superfund Sites." (U.S.EPA, 1991)

[4)] Agency for Toxic Substances and Disease Registry (ATSDR, 2005)

Table 4. Total HI for human receptor

Area	COPCs	HQ (dimensionless)						
		As	Cd	Cr	Hg	Ni	CDD	CDF
	RfC (mg/m^3)	1.50E-05[2]	1.00E-05[4]	2.86E-05[1]	3.00E-04[1]	9.00E-05[4]	7.00E-10[3]	1.14E-08[3]
	RfD (mg/kg of BW-day)	3.00E-04[1]	5.00E-04[1]	3.00E-03[1]	3.00E-04[1]	2.00E-02[1]	4.00E-08[1]	1.00E-03[1]
LP	Individual HQ	2.64E-03	2.64E-02	4.36E-05	4.52E-04	2.12E-03	1.01E-03	3.96E-20
	HI of multi-chemicals	3.27E-02						
KK	Individual HQ	1.26E-03	1.40E-02	7.92E-06	4.98E-05	3.85E-04	3.49E-04	6.45E-21
	HI of multi-chemicals	1.60E-02						
RY	Individual HQ	1.17E-02	4.49E-02	7.38E-05	7.66E-04	3.60E-03	1.72E-03	2.38E-19
	HI of multi-chemicals	6.28E-02						
AY	Individual HQ	6.38E-03	2.44E-02	4.02E-05	4.17E-04	1.96E-03	1.04E-03	1.00E-19
	HI of multi-chemicals	3.43E-02						
SR	Individual HQ	8.94E-03	2.43E-02	3.96E-05	4.16E-04	1.75E-03	9.31E-01	3.93E-20
	HI of multi-chemicals	3.38E-02						

[1)] U.S. EPA. Integrated Risk Information System (IRIS) (U.S. EPA, 2019)
[2)] California Environmental Protection Agency (CalEPA) (CalEPA, 2015)
[3)] Regional Screening Levels (RSL) for Chemical Contaminants at Superfund Sites." (U.S.EPA, 1991)
[4)] Agency for Toxic Substances and Disease Registry (ATSDR, 2005)

For the purpose quantitative risk assessment, the HI results are within an acceptable limit. The CRs of multi chemicals are slightly higher than the acceptable level (10^{-6}). A reason could be the use of worst-case scenarios in the assessment. As a result, the control measures should be implemented only after considering options to decrease the concentration of pollutants and risk levels. As recommended by (Quina *et. al.*, 2011), heavy metals could be converted into non-volatile oxides and deposited into the fly ash. The techniques that are used to remove particles from the exhaust gas can then be adapted to this process. Moreover, the PCDD/F can be controlled by applying a catalytic reaction or catalytically coated fabric filters, which are often used in Europe, or a semi-dry technology with lime, which is commonly used in China (Li *et al.*, 2016).

The total cancer risk from multi-chemicals can be plotted in terms of isopleths to explain the distribution of cancer risk in each area of $10\times10\ km^2$. Four of those areas: Khon Kaen, Rayong, Phra Nakhon Si Ayutthaya and Surat Thani are relatively flat terrain. As seen in Figure 3, the contours seem to be simple. On the contrary, in Lamphun, which is mostly complex terrain, the contours are rather complex. A high-altitude area potentially restricts dispersion of air pollution that would result in a higher cancer risk. Like cancer risk, the contour lines of the hazard indices (Figure 4) were also different between the flat and complex terrains. With these results, the geographical data could affect both the risk and HI (Jose, 2002; Nouwen *et al.,* 2001). The lowest risks are shown in the KK MSWI, as compared with the others, since the lowest stack emissions were taken from the actual monitoring and presence of the control device, while the others, which were predicted from AP-42, were uncontrolled.

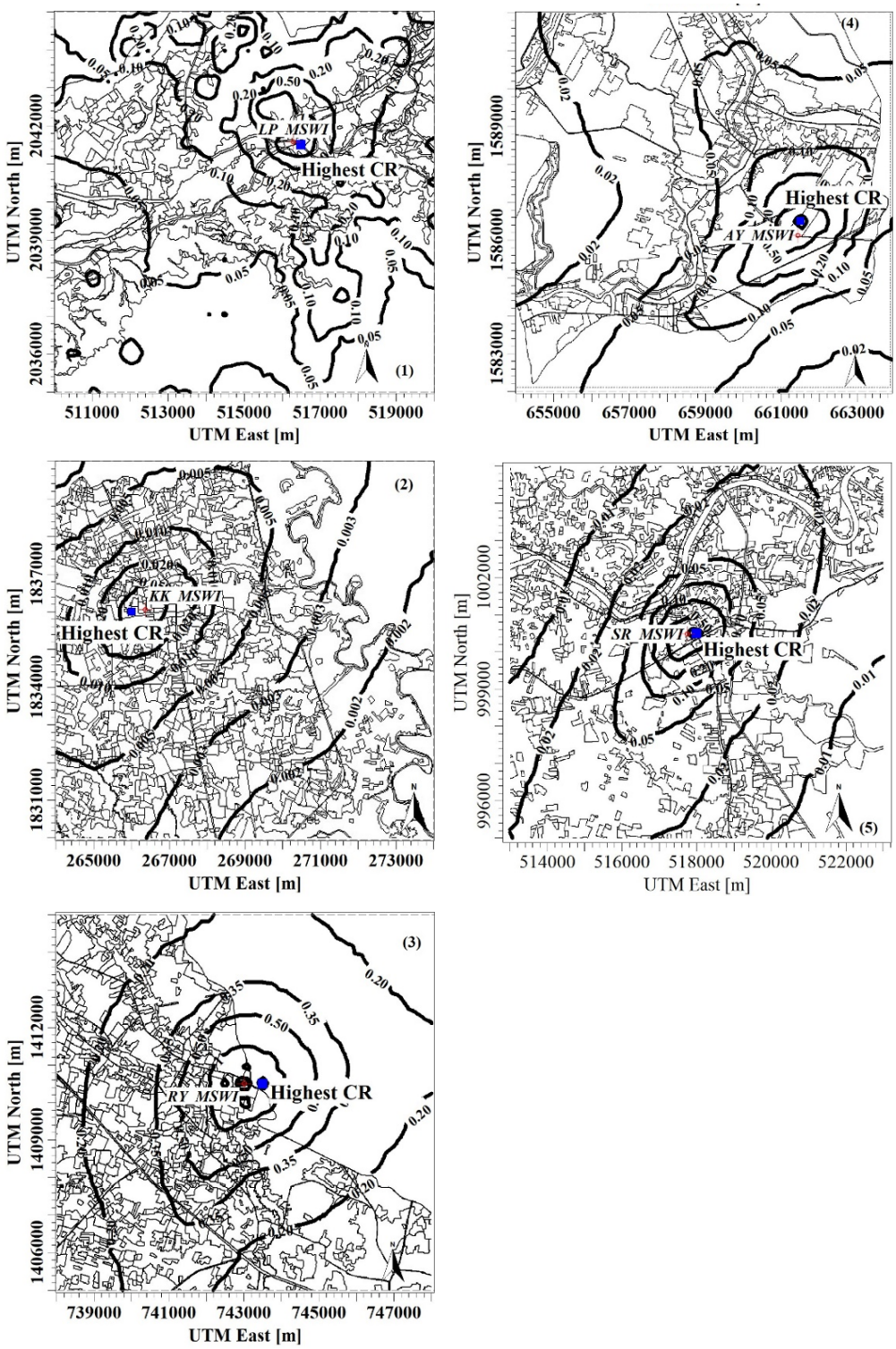


Figure 3. Risk distribution for carcinogenic COPCs from the various MSWI stack: (1) Lamphun, (2) Khon Kaen, (3) Rayong, (4) Phra Nakhon Si Ayutthaya, (5) Surat Thani; E-06

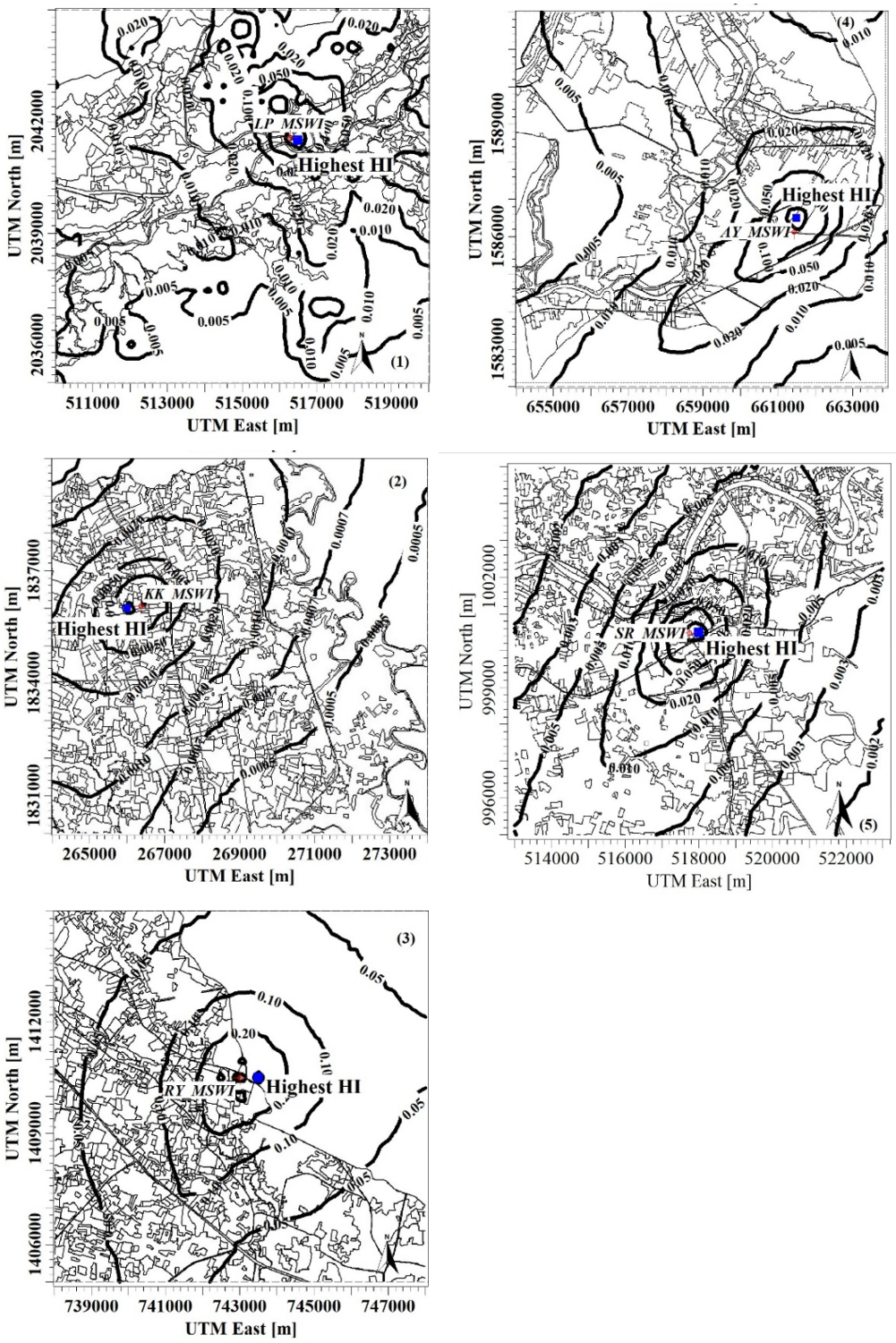


Figure 4. Risk distribution for non-carcinogenic COPCs from various MSWI stacks: (1) Lamphun, (2) Khon Kaen, (3) Rayong, (4) Phra Nakhon Si Ayutthaya, (5) Surat Thani; E-01

4. Conclusion

In this study, risk assessment was conducted in terms of the cancer risk and HI to determine the level of adverse human health effects caused by pollutants being emitted from the MISWIs. AERMOD was applied to predict pollutant concentration in each representative area within a 10×10 km^2 area, where the MSWIs are located at the approximate center. The annual maximum concentrations of the criteria and hazardous pollutants are below the ambient air quality standards. The calculated CR of a multi-chemical presence (i.e., As, Cd, Cr, Ni, Pb, Dioxins and Furans), which is used to evaluate long-term health effect over a long life time, shows high risk ($>10^{-6}$). However, the HI of a multi-chemical presence (i.e. As, Cd, Cr, Hg, Ni, Dioxins and Furans), which is used to evaluate health effects, shows a low risk for the people living around the MSWIs.

This study could be adopted to assess the HRA in Thailand for the development of the MSWI project in order to deal with the problem of overflowing waste. The results provide useful information for decision-makers in developing effective policies to counter the impact of the MSWIs on public health.

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