A STUDY OF AERMOD TIERING APPROACH FOR NITROGEN DIOXIDE PREDICTION IN MAPTAPHUT INDUSTRIAL AREA

SUPITCHAYA TUNLATHORNTHAM

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE
(ENVIRONMENTAL TECHNOLOGY)
FACULTY OF GRADUATE STUDIES
MAHIDOL UNIVERSITY
2015**

Thesis
entitled

A STUDY OF AERMOD TIERING APPROACH FOR NITROGEN DIOXIDE PREDICTION IN MAPTAPHUT INDUSTRIAL AREA

…………….………….…..………
Miss Supitchaya Tunlathorntham
Candidate

……………….….………….……
Asst. Prof. Sarawut Thepanondh,
Ph.D. (Atmospheric Science)
Major advisor

……………….….…………...…
Lect. Suphaphat Kwonpongsagoon,
Ph.D. (Environmental Engineering)
Co-advisor

……………….….…………...…
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochmistry)
Dean
Faculty of Graduate Studies
Mahidol University

……………….….…………..…
Assoc.Prof. Nipapun Kungskulniti,
Ph.D. (Environmental Health)
Program Director
Master of Science Program in
Environmental Technology
Faculty of Public Health
Mahidol University

Thesis
entitled

A STUDY OF AERMOD TIERING APPROACH FOR NITROGEN DIOXIDE PREDICTION IN MAPTAPHUT INDUSTRIAL AREA

was submitted to the Faculty of Graduate Studies, Mahidol University
for the degree of Master of Science (Environmental Technology)
on
May 22, 2015

……………….……….…..………
Miss Supitchaya Tunlathorntham
Candidate

…………………….…..………………
Asst. Prof. Chutarat Chompunth,
Ph.D. (Environmental Management)
Chair

…………………….…..……………..……
Asst. Prof. Sarawut Thepanondh,
Ph.D. (Atmospheric Science)
Member

…………………….…..……………...…
Lect. Suphaphat Kwonpongsagoon,
Ph.D. (Environmental Engineering)
Member

…………………….…..……………...…	…………………….…..……………..…
Prof. Patcharee Lertrit,	Assoc.Prof. Prayoon Fongsatitkul,
M.D., Ph.D. (Biochmistry)	Ph.D. (Environmental Engineering)
Dean	Dean
Faculty of Graduate Studies	Faculty of Public Health
Mahidol University	Mahidol University

ACKNOWLEDGEMENTS

The success of this thesis can be succeeded by the attentive support and assistance from my advisor, Assist.Prof. Sarawut Thepanondh, for his valuable guidance, advice and assistance throughout the entire duration of this study. I also would like to express my appreciation to my co-advisor, Dr. Suphaphat Kwonpongsagoon and Assist.Prof. Chutarat Chompunth for their contribution to the examination of this thesis and providing suggestions for improvement.

I am grateful to all staff of the Department Sanitary Engineering, Faculty of Public Health, Mahidol University for their helpful support encouragement. I also would like to thank Faculty of Graduate Studies Mahidol University Educational Scholarship in Honor of “The 60th Year Supreme Reign of His Majesty King Bhumibol Adulyadej”. Graduate tutition free for the course under my degree program was granted by this scholarship.

I would like to thanks the Center of Excellence on Environmental Health and Toxicology (EHT) for supporting this study.

I wish to thank all my friends who are always nice and friendly, for their consolation and support given to me during my study.

I would like to express my deep sense of appreciation to my family for their understanding, moral support, financial support, entirely care and unconditional love and encouragement throughout. I dedicate to my father and my mother; Mr. Veerachart Tunlathorntham and Mrs. Anchalee Tunlathorntham who support that have enable me to succeed in my life.

Finally, I wish to thanks Office of Natural Resource and Environment Policy and Planning (ONEP), Pollution Control Department of Thailand, Industrial Estate Authority Of Thailand (IEAT) and the BLCP Power Plant, Maptaphut Rayong for providing data for analysis in this research.

Supitchaya Tunlathorntham

A STUDY OF AERMOD TIERING APPROACH FOR NITROGEN DIOXIDE PREDICTION IN MAPTAPHUT INDUSTRIAL AREA

SUPITCHAYA TUNLATHORNTHAM 5636766 PHET/M

M.Sc. (ENVIRONMENTAL TECHNOLOGY)

THESIS ADVISORY COMMITTEE: SARAWUT THEPANONDH, Ph.D. (ATMOSPHERIC SCIENCE), SUPHAPHAT KWONPONGSAGOON, Ph.D. (CIVIL & ENV.ENG)

ABSTRACT

The Maptaphut industrial area, Rayong Province is the largest industrial complex in Thailand. There has been concern about many air pollutants over this area. This study presents the methodologies and results of an application of the AERMOD model to predict the air quality impacts of NO_2 emitted by industrial emission sources in Maptaphut Industrial Estate. These emissions are typically composed of a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2), an oxide of nitrogen (NOx). NO is subsequently oxidized to NO_2, which is an air pollutant found in the environment. Taking into consideration the chemistry of NOx and characteristics of the conversion of NO to NO_2, three different tiers, recommended by the USEPA are tested and evaluated for their ability in predicting NO_2 ambient concentration in the study area.

The performance evaluation of the AERMOD dispersion model in predicting 1-hour average concentrations in the vicinity of the Maptaphut industrial complex was conducted for the years 2012 and 2013 (1 January, 2012 to 31 December, 2013). Measured data from 10 ambient air monitoring stations were used to compare with those modeled results. The results from the model indicated that Tier 1 (100% conversion of NO_x to NO_2) provided less bias with those measured data as compared with other tiers. It also performed very well in predicting the extreme end of NO_2 concentrations.

Therefore, Tier 1 may be considered as appropriate for prediction of the annual average as well as in determining the maximum ground level concentration of NO_2 in the Maptaphut industrial area.

KEY WORDS: AERMOD/ NITROGEN DIOXIDE/ MAPTAPHUT/ OLM/ PVMRM

79 pages

การศึกษาแนวทางการประยุกต์ใช้แบบจำลอง AERMOD ในการคาดการณ์ระดับความเข้มข้นของไนโตรเจนไดออกไซด์ในพื้นที่อุตสาหกรรมมาบตาพุด

A STUDY OF AERMOD TIERING APPROACH FOR NITROGEN DIOXIDE PREDICTION IN MAPTAPHUT INDUSTRIAL AREA

สุพิชญา ตุลธรธรรม 5636766 PHET/M

วท.ม. (เทคโนโลยีสิ่งแวดล้อม)

คณะกรรมการที่ปรึกษาวิทยานิพนธ์ : สราวุธ เทพานนท์, Ph.D. (ATMOSPHERIC SCIENCE),
สุพพัต ควรพงษากุล, Ph.D. (CIVIL & ENV.ENG.)

บทคัดย่อ

พื้นที่อุตสาหกรรมมาบตาพุด จังหวัดระยอง ตั้งอยู่ในพื้นที่ภาคตะวันออกของประเทศไทยเป็นเขตอุตสาหกรรมที่ใหญ่ที่สุดของประเทศ ทำให้พื้นที่นี้มีปัญหาทางด้านมลพิษทางอากาศ การศึกษานี้ได้นำเสนอวิธีการในการศึกษาแนวทางการประยุกต์ใช้แบบจำลอง AERMOD ในการคาดการณ์ความเข้มข้นของไนโตรเจนไดออกไซด์ที่ระบายจากแหล่งกำเนิดจำพวกอุตสาหกรรมในนิคมอุตสาหกรรมมาบตาพุด โดยมลพิษที่ระบายจะอยู่ในรูปของไนตริกออกไซด์ (NO) และไนโตรเจนไดออกไซด์ (NO_2) ซึ่งรวมเรียกสารประกอบดังกล่าวว่าออกไซด์ของไนโตรเจน (NOx) โดยไนตริกออกไซด์จะถูกออกซิไดซ์เปลี่ยนรูปเป็นไนโตรเจนไดออกไซด์ จากคุณลักษณะและกระบวนการทางเคมีในการเปลี่ยนรูปของ NO ไปเป็น NO_2 ดังกล่าวนำมาซึ่งการศึกษาเพื่อทดสอบและประเมินความสามารถของวิธีการ 3 แบบ ซึ่งแนะนำโดย US. EPA. ในการประเมินระดับความเข้มข้นของไนโตรเจนไดออกไซด์ในพื้นที่ที่ศึกษา

การแปรผลข้อมูลของแบบจำลอง AERMOD ในการคาดการณ์ความเข้มข้นเฉลี่ยของไนโตรเจนไดออกไซด์ที่เวลา 1 ชั่วโมงในพื้นที่อุตสาหกรรมมาบตาพุดในปี 2012 ถึงปี 2013 (1 มกราคม 2555 ถึง 31 ธันวาคม 2556) โดยใช้ข้อมูลตรวจวัดจากสถานีตรวจวัดคุณภาพอากาศทั้ง 10 สถานี เพื่อนำมาเปรียบเทียบกับข้อมูลที่ได้จากแบบจำลอง AERMOD ผลการศึกษาพบว่า Tier 1 (100% ออกไซด์ของไนโตรเจนเปลี่ยนรูปเป็นไนโตรเจนไดออกไซด์ทั้งหมด) ให้ค่าเบี่ยงเบนจากค่าที่ตรวจวัดน้อยที่สุดเมื่อเทียบกับ Tier อื่นๆ รวมทั้งสามารถคาดการณ์ความเข้มข้นของไนโตรเจนไดออกไซด์ที่ระดับความเข้มข้นสูงได้ใกล้เคียงกับข้อมูลตรวจวัดมากที่สุด

ดังนั้น Tier 1 จึงมีความเหมาะสมในการคาดการณ์ความเข้มข้นของไนโตรเจนไดออกไซด์เฉลี่ยรายปีได้ดี รวมถึงมีความเหมาะสมในการคาดการณ์ปริมาณความเข้มข้นสูงสุดของไนโตรเจนไดออกไซด์ที่ระดับพื้นในพื้นที่อุตสาหกรรมมาบตาพุด

79 หน้า

CONTENTS

CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AERMOD	American Meteorological Society Regulatory Model
AERMAP	American Meteorological Society Regulatory Model terrain Preprocessor
AERMIC	American Meteorological Society Regulatory Model Improvement Committee
AERMET	American Meteorological Society Regulatory Model Meteorological reprocessor
AMS	American Meteorological Society
IEAT	Industrial Estate Authority Of Thailand
BLCP	BLCP Power Maptaphut sub-district, Rayong province
CBL	Convective Boundary Layer
EPA	Environmental Protection Agency
IEAT	Industrial Estate Authority of Thailand
MIE	Map Ta Phut Industrial Estate
NAAQS	National Ambient Air Quality Standards
NWS	National Weather Service
ONEP	Office of Natural Resources and Environmental Policy and Planning
OLM	Ozone Limited Method
PBL	Planetary Boundary Layer
PM	Particulate Matter
PCD	Pollution Control Department
PVMRM	Plume Volume Molar Ratio Method
US.EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds
HMTP	Health Promotion Hospital Maptaphut
FCRC	Field Crops Research Center

LIST OF ABBREVIATIONS (cont.)

BTKH	Ban Ta Kuan Public Health Center
WNFS	Wat Nong Fap School
MMTP	Muang Mai Maptaphut
KKYC	Krok Yai Cha
MCLT	Map Chalut Temple
TKTP	Ta Kuan Temple
HBGD	Herbal Garden
CCIL	Chum Chon Islam

CHAPTER I
INTRODUCTION

1.1 Rationale and Justification

Maptaphut industrial area (MA), Rayong province in the eastern region is the largest industrial complex in Thailand. Main industries found in the MA are petrochemical industry (48%), metal processing (10%), oil refining (2%), gas separation (10%), electricity generation (5%), chemical product (17%) and other industries (9%) (MTPIE, 2013). This area has been concern in Thailand in terms of air pollution problems including sulfur dioxide (SO_2), particulate matter (PM), volatile organic compounds (VOC) especially nitrogen dioxide (NO_2) are mainly pollutants over this area (Chusai *et al.*, 2012).

NOx gases are usually emitted by fuel combustion sources in the form of nitric oxide (NO), and in smaller quantities as NO_2 gas (US. EPA, 2008). NO gases in the emission plume mixes with the atmosphere and reacts with ozone and other oxidants to oxidize a portion of the NO to NO_2. There are numerous other atmospheric reactions of NOx species; these include further oxidation of NO_2 to nitrate radical (NO_3) and nitric acid (HNO_3), as well as photo-dissociation of NO_2 back to NO through the absorption of UV radiation during the daytime (Rethinking the Ozone Prob, 1991). However, during the early stages of the dispersion of a NOx emission plume (i.e., at distances ranging from approximately 0.1 to 10 km over time intervals of 10e300 min), the principal NOx reaction is NO oxidation by ozone to form NO_2 (Karamchandani *et al.*, 1998; Podrez, 2015).

Air dispersion modeling has been recognized as a promising approach to predicting outdoor spatial and temporal variations of pollutants and the 'behaviors' of these pollutants through mathematical algorithms that take into account atmospheric dispersion, chemical, and physical processes in an attempt to approximate concentrations of pollutants (Holmes and Morawska, 2006). As a state-of-the-art dispersion model for regulatory applications, AERMOD (atmospheric dispersion modeling) is a kind of steady-state plume dispersion model for assessment of different ambient air pollutants concentrations from different emission sources (Cimorelli *et al.*, 2005). In AERMOD modeling processes, meteorological observation data of surface and upper air were obbligato required. It advanced in characterizing the fundamental boundary layer (FBL) parameters and vertical profile of the atmosphere along with better representation of plume buoyancy, penetration, and urban nighttime boundary layer (Perry *et al.*, 2005). AERMOD had concerned about simulating the air quality in the near future as the outcome of emission control policy by applying AERMOD (Ma *et al.*, 2013).

This study presents the methodologies and results of an application of the AERMOD model to predict the air quality impacts of nitrogen dioxide (NO_2) emitted by the Maptaphut industrial area, Rayong province. These emissions are typically composed of a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2). At ambient temperature and excess oxygen, NO is subsequently oxidized to NO_2 which is a precursor to nitric acid. NOx disperses widely and can react with O_3 and volatile organic compound (VOC) to secondary particulate matter (PM). There different tiers, recommended by US.EPA are tested and evaluated for their ability in predicting NO_2 ambient concentration in study area.

1.2 Research objectives

1.1.1 To investigate the concentration of nitrogen dioxide (NO_2) concentrations Maptaphut industrial area by using AERMOD model.

1.1.2 To evaluate performance of different tiers of AERMOD in predicting of NO_2 ambient concentration.

1.1.3 To study a sensitivity of Ozone (O_3) concentration to the concentration of NO_2, predicted by AERMOD model.

1.3 Scope of study

Data from ambient air quality monitoring station network in Maptaphut industrial area are used to evaluate predicted concentration with measured data ten monitoring stations, used in this study are as followed.

1. Health Promotion Hospital Maptaphut (HMTP)
2. Ban Ta Kuan Public Health (BTKH)
3. Wat Nong Fap School (WNFS)
4. Muang Mai Maptaphut (MMTP)
5. Map Chalut Temple (MCLT)
6. Ban Plong Community (BPLC)
7. Nop Pakate Village (NPKV)
8. Krok Yai Cha (KYC)
9. Dry Crops Reseach Center (DCRC)
10. Chum Chon Islam (CCI)

Emission characteristics are obtained from Office of Natural Resources and Environmental Policy and Planning (ONEP), Pollution Control Department (PCD), Industrial Estate Authority of Thailand (IEAT) and BLCP Power Plant.

Model period: January 2012 – December 2013

1.4 Expected outcome

This study will assist in evaluation of a suitable scenarios for predicting NO_2 ambient concentrations in Maptaphut industrial area.

1.5 Conceptual framework

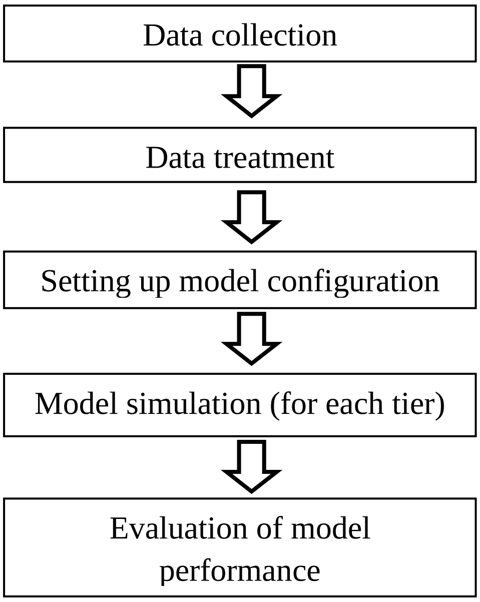


Figure 1.1 Conceptual Framework

1.6 Definition of keywords

AERMOD MODEL

The AERMOD system is a state-of-science steady-state plume dispersion modeling system developed under support of the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) (Cimorelli *et al.*, 2005; Perry *et al.*, 2005; US. EPA, 2004). It is a new regulatory dispersion model in place of its predecessor the Industrial Sources Complex Short Term (ISCST) model, and it has been used in environmental impact assessment (Huertas *et al.*, 2012; Perry *et al.*, 2005; Silverman and Tell, 2007; Venkatram *et al.*, 2001). The system consists of four main processors: AERMAP as the terrain processor, AERSURFACE as the surface property/ characteristic processor, AERMET as the meteorological processor, and AERMOD as the main dispersion model processor (Chusai *et al.*, 2012).

Ozone Limited Method (OLM)

The OLM involves an initial comparison of the estimated maximum NOx concentration and the ambient ozone concentration to determine which is the limiting factor to NO_2 formation. If the O_3 concentration is greater than $[NOx]_{max}$, then total conversion is assumed. If [NOx] is greater than the O_3 concentration concentration the formation of NO_2 is limited by the ambient O_3 concentration. The OLM method does not account for the molar ratio of NOx to ozone mixed into the plume (Hendrick *et al.*, 2013).

Plume Volume Molar Ratio Method (PVMRM)

The PVMRM determines the conversion rate for NOx to NO_2 based on a calculation of the NOx moles emitted into the plume, and the amount of O_3 moles contained within the volume of the plume between the source and receptor. (Bange *et al.,* 1991). The implementation of PVMRM in AERMOD is based on the use of relative dispersion coefficients to calculate the plume volume.

CHAPTER II
LITERATURE REVIEWS

2.1 Air pollutant

Air pollution occurs when the air contains gases, dust, fumes or odour in harmful amounts. That is, amounts which could be harmful to the health or comfort of humans and animals or which could cause damage to plants and materials. The substances that cause air pollution are called pollutants. Pollutants that are pumped into our atmosphere and directly pollute the air are called primary pollutants. Primary pollutant examples include carbon monoxide from car exhausts and sulfur dioxide from the combustion of coal. Further pollution can arise if primary pollutants in the atmosphere undergo chemical reactions. The resulting compounds are called secondary pollutants. Photochemical smog is an example of this (US. EPA, 2014).

2.1.1 Nitrogen Dioxides (NO_2)

2.1.1.1 Source of Nitrogen Dioxides (NO_2)

Nitrogen oxides occur naturally and also are produced by man's activities. In nature, they are a result of bacterial processes, biological growth and decay, lightning, and forest and grassland fires. The primary source of man-made nitrogen oxides is from the burning of fossil fuels (Clean Air Strategic Alliance, 2004).

Of the NO_2 emitted, most is nitric oxide (NO), some is nitrous oxide (N_2O) and less than 10 percent is NO_2. The amount of NO_2 emitted varies with the temperature of combustion; as temperature increases so does the level of NO_2. Agriculture also plays a role in nitrogen oxide emissions with the use of fertilizers contributing nitrous oxide to the atmosphere was as shown in Figure 2.1 (Ministry for the Environment Manatū Mō Te Taiao, 2009).

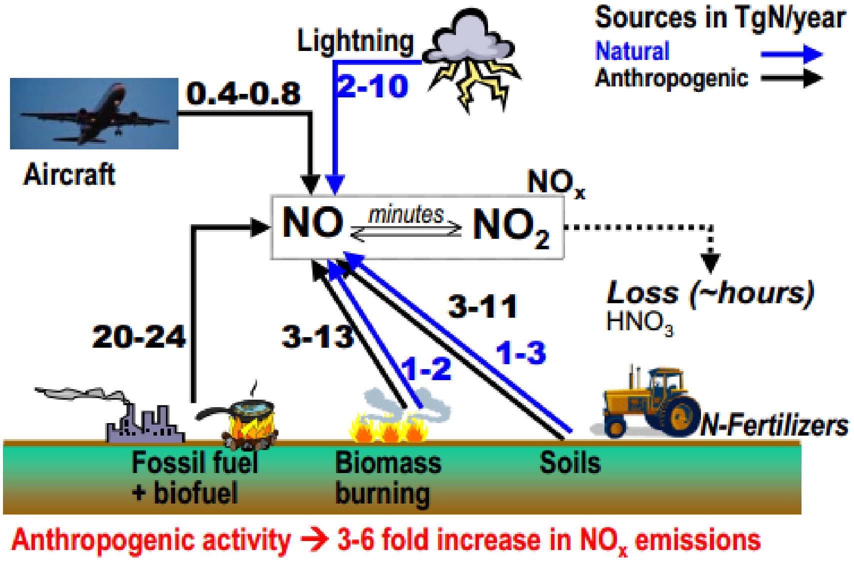


Figure 2.1 Global sources of NO_2 (Lyatt, 2008)

2.1.1.2 Formation of Nitrogen Dioxides (NO_2)

NO, is the collective name given to the oxides of nitrogen; these being nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). In general NO, is emitted from fossil fuel combustion in the form of NO, where upon it is oxidized to NO_2 in the atmosphere, although certain conditions can favour the production of NO_2 and N_2O leading to significant emissions (Miller and Bowman, 1989). Major sources of NOx formation during combustion have three recognized mechanism on NOx formation such as Thermal, Prompt and Fuel (Beltagui *et al.*, 2010).

1. Thermal NOx formation

Thermal NOx is produced by the reaction of atmospheric oxygen and nitrogen at elevated temperatures, and is reputed to contribute about 20% of the total NOx emission in pulverised coal firing, but is the dominant mechanism when the fuel contains little or no inherent nitrogen (i.e. gas firing). Where high air preheat temperatures are employed, for example in cement kilns, thermal NOx can also contribute considerably to the overall NOx emission.

2. Prompt NOx formation

During the first part of combustion, the carbon-bearing radicals from the fuel react with nitrogen. Prompt NOx was formed by the reaction of hydrocarbon radicals with atmospheric nitrogen to produce HCN and hence NOx via a complex series of gas phase reactions. The contribution of the prompt NOx to the total emission in pulverised coal combustion is small (about 5%). Measures, which are effective in minimising thermal and fuel NOx, are also effective in minimising prompt NOx (Hesselmann and Rivas, 2010).

There are many hydrocarbon radicals in flame (CH, CH_2, CH_3, C_2H_4, C_2H_5, C_3H_7, C, C_2...), which can react with molecular nitrogen (N_2) (Wroclawska, n.d.).

$$CH_2 + N_2 \xrightarrow[\Delta]{} HCN + NH \qquad (1)$$

$$CH + N_2 \xrightarrow[\Delta]{} HCN + N \qquad (2)$$

$$C + N_2 \xrightarrow[\Delta]{} CN + N \qquad (3)$$

General:

$$CHx + N_2 \xrightarrow[\Delta]{} HCN \text{ and other radicals } (CN, NH, N...) \qquad (4)$$

As a result: HCN, NH i CN are easily oxidized to NO in flame.

3. Fuel NOx formation

Fuel NOx arises from the reaction of the organically bound nitrogen in the fuel with oxygen. The process is complex (reaction schemes typically consider of the order of 50 intermediate species and several hundred separate reversible reactions, and there is still considerable uncertainty as to the true value of the various rate constants, etc.) (Hesselmann and Rivas, 2010).

2.1.2 Ozone (O_3)

The main sources of background ozone include natural emissions of ozone precursors (e.g., biogenic methane and volatile organic compound (VOC), as well as oxides of nitrogen (NOx) from lightning and other natural processes), wildfires, transport of naturally occurring ozone from the stratosphere to the troposphere, and transport of anthropogenic ozone and ozone precursors from upwind regional and/or international locations. The first step in implementing an efficient plan for improving air quality is to develop a conceptual model of all the processes that lead to high concentrations of atmospheric pollutants within an airshed. As such, accurate estimates of the relative contribution of background ozone to observed ozone levels will be a key element in the development of air quality management plans for attainment of the ozone National Ambient Air Quality Standards (NAAQS) (Dolwick *et al.*, 2015).

2.1.3 Reactions in the atmosphere

NO is a colorless gas that has some harmful effects on health, but these effects are substantially less than those of an equivalent amount of NO_2. In the atmosphere and industrial devices NO reacts with O_2 to from NO_2, a brown gas that is a serious respiratory irritant. Its color is strong enough that it is often possible to see a distinct brown color emerging from a power plant stack or from the vent of any process using nitric acid, which releases NO_2. NO and NO_2 are often treated together as one problem or as a quasi species, and written NOx. Most regulations for NOx emissions base all numerical values on the assumption that all of the NO is converted to NO_2. One sees this written as “NOx expressed as NO_2.”

There is an NAAQS for NO_2 to protect human health, which was sometimes exceeded in the 1980s, but now is never exceed in the United States. Our principal concern with NOx is that nitrogen oxides contribute to the formation of ozone, O_3, which is a strong respiratory irritant and one of the principal constituents of urban summer eye- and nose-irritating smog. The overall reaction is shown in equation 5 (Glandt *et al.*, 1995).

$$NO + HC + O_2 + \text{sunlight} \longrightarrow NO_2 + O_3 \qquad (5)$$

In the troposphere

Ozone (O_3) is also formed by the splitting of molecules by sunlight. But in the lower atmosphere sunlight also splits nitrogen dioxide (NO_2) into nitric oxide (NO) and an oxygen atom. Therefore nitrogen dioxide provides the molecular oxygen needed for ozone formation (Allen, 2002).

$$NO_2 + \text{sunlight} \longrightarrow NO + O \qquad (6)$$

$$O + O_2 \longrightarrow O_3 \qquad (7)$$

Then ozone reacts with nitric oxide to create nitrogen dioxide and oxygen. This process occurs naturally and does not result in a net gain of ozone.

$$NO + O_3 \longrightarrow NO_2 + O_2 \qquad (8)$$

However, the human induced production of ozone precursors, NO, NO_2, and volatile organic compound (VOC) has altered the atmospheric chemistry which contributes to elevated levels of ozone in the lower atmosphere.

$$NOx + VOC + \text{sunlight} \longrightarrow O_3 \text{ (and other products)} \qquad (9)$$

Tropospheric, or ground level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compound (VOC). Ozone is likely to reach unhealthy levels on hot sunny days in urban environments. Ozone can also be transported long distances by wind. For this reason, even rural areas can experience high ozone levels (US. EPA, 2013). The photochemical reactions of ozone formation are shown in equation 10-13.

$$OH + VOCs\ (+O_2) \longrightarrow RO_2 \qquad (10)$$

$$RO_2 + NO \longrightarrow RO + NO_2 \qquad (11)$$

$$NO_2 + h\nu \longrightarrow NO + O \qquad (12)$$

$$O + O_2 \longrightarrow O_3 \qquad (13)$$

During the daytime, photochemical oxidation of VOCs initiated by hydroxyl radicals OH produces organic peroxy radicals (RO_2), facilitating cycling of NO to NO_2 and formation of tropospheric ozone (Zhang *et al.*, 2004).

2.1.4 Overview of the scientific assumptions of PVMRM and OLM

2.1.4.1 Basic OLM chemistry

To provide some background, the following is a simplified explanation of the basic chemistry relevant to the OLM. First, the relatively high temperatures typical of most combustion sources promote the formation of NO_2 by the following thermal reaction:

$2NO + O_2 \quad ==> \quad 2NO_2$ In-stack formation of NO_2

OLM assumes a default 10% of the NOx in the exhaust is converted to NO2 by this reaction, and no further conversion by this reaction occurs once the exhaust leaves the stack. Please Note: The District has compiled a list of NO_2/NOx ratios that can be used as default in-stack NO_2/NOx ratios until source test data become available. The remaining percentage of the NOx emissions is assumed to be nitric oxide (NO).

As the exhaust leaves the stack and mixes with the ambient air, the NO reacts with ambient ozone (O_3) to form NO_2 and molecular oxygen (O_2):

$NO + O_3 \quad ==> \quad NO_2 + O_2$ Oxidation of NO by ambient O_3

The OLM assumes that at any given receptor location, the amount of NO that is converted to NO_2 by this reaction is proportional to the ambient O_3 concentration. If the O_3 concentration is less than the NO concentration, the amount of NO_2 formed by this reaction is limited. If the O_3 concentration is greater than or equal to the NO concentration, all of the NO is assumed to be converted to NO_2. In the presence of radiation from the sun, ambient NO_2 can be destroyed:

NO_2 + sunlight $==>$ NO + O Photo-dissociation of NO_2

As a conservative assumption, the OLM ignores this reaction. Another reaction that can form NO_2 in the atmosphere is the reaction of NO with reactive hydrocarbons (HC):

$NO + HC \Rightarrow NO_2 + HC'$ Oxidation of NO by reactive HC

The OLM also ignores this reaction. This may be a non-conservative assumption with respect to NO_2 formation in urban industrial areas with relatively large amounts of reactive HC emissions.

2.1.4.1 Basic PVMRM chemistry

Building on the basic OLM chemistry, the PVMRM determines the conversion rate for NOx to NO_2 based on a calculation of the NOx moles emitted into the plume, and the amount of O_3 moles contained within the volume of the plume between the source and receptor. The dispersion algorithms in AERMOD and other steady state plume models are based on the use of total dispersion coefficients, which are formulated to represent the time-averaged spread of the plume. A more appropriate definition of the volume of the plume for purposes of determining the ozone moles available for conversion of NOx is based on the instantaneous volume of the plume, which is represented by the use of relative dispersion coefficients, (Bange *et al.*, 1991). The implementation of PVMRM in AERMOD is based on the use of relative dispersion coefficients to calculate the plume volume.

2.2 Effect of Nitrogen Dioxides (NO_2)

2.2.1 Health and environmental effects on NO_2

Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infections such as influenza. The effects of short-term exposure are still unclear, but continued or frequent exposure to concentrations that are typically much higher than those normally found in the ambient air may cause increased incidence of acute respiratory illness in children. EPA's health-based national air quality standard for NO_2 is 0.053 ppm (measured as an annual arithmetic mean concentration). Nitrogen oxides contribute to ozone formation and can have adverse effects on both terrestrial and aquatic ecosystems. Nitrogen oxides in the air can significantly contribute to a number of environmental effects such as acid rain and eutrophication in coastal waters like the Chesapeake Bay. Eutrophication occurs when a body of water suffers an increase in nutrients that leads to a reduction in the amount of oxygen in the water, producing an environment that is destructive to fish and other animal life (US. EPA, 2012).

2.2.2 Effect of NO_2 on Ozone

On sunny days where NO_2 pollution from traffic is high, the concentration of ozone in the air can reach levels that are dangerous for plants and animals. The U.S. Environmental Protection Agency characterizes ozone levels as "unhealthful" when they exceed the National Ambient Air Quality Standard of 125 parts per billion (ppb). In the state of Wisconsin, an "ozone alert" is issued when the average concentration of ozone over a four hour period is over 100 ppb. An "ozone warning" is announced when the this level reaches 300 ppb. An ozone emergencyป is declared when it exceeds 350 ppb. In addition to posing a threat to health, ozone in the air also damages polymeric materials such as rubber and plastics, causing them to deteriorate prematurely.

In contrast to the harmful effects of ozone in the air we breathe, the effects of ozone in the upper atmosphere are essential to the survival of life on Earth. In the upper atmosphere (specifically, the stratosphere, 15-55 km above the Earth's surface), ozone filters harmful ultraviolet radiation from sunlight. This ultraviolet radiation is highly energetic and would damage both plants and animals exposed to it. Diatomic oxygen absorbs the highest-energy ultraviolet radiation from the sun, namely, all radiation with wavelengths shorter than 240 nm. However, there is a great deal of ultraviolet radiation between 240 nm and 290 nm that is not absorbed by O_2 molecules. This radiation is absorbed by ozone are shown in equation 14-17. (US. EPA, 2012).

$$O_3 \xrightarrow{\text{uv light}} O_2 + O \tag{14}$$

$$NO + O_3 \longrightarrow NO_2 + O_2 \tag{15}$$

$$NO_2 + O \longrightarrow NO + O_2 \tag{16}$$

$$\text{Net:} \quad 2\,O_3 \longrightarrow 3\,O_2 \tag{17}$$

Because NO is regenerated in the third step, a single molecule of NO can assist in the destruction of very many ozone molecules. Crutzen described how N_2O released from soil rises unchanged in the lower atmosphere until it is decomposed by UV radiation in the stratosphere. A fraction of the N_2O is converted to the NO that catalytically destroys ozone.

2.3 AERMOD Model

2.3.1 History of AERMOD

AERMOD, the successor to the Industrial Source Complex (ISC) generation of models was introduced by the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC) in 1991. As mentioned earlier, the intended purpose of AERMOD was to replace ISCST3. In 1998, performance evaluation of AERMOD was assessed in various types of environments for which it would be used, and its performance was compared with ISCST3 (Patel and Kumar, 1998). Minor revisions were being applied at these times, but still AERMOD's performance fit observed data better than ISCST3. Afterwards, AERMOD was proposed by EPA in April 2000 as a replacement for the ISCST3 model (Paine, 2003) was as shown in Figure 2.2.

AERMOD is a near field steady state plume model based on planetary boundary layer (PBL) turbulence structure and scaling concepts, including treatment of both surface and elevated sources over simple and complex terrain (Holmes and Morawska, 2006). It is recommended by the US. EPA for examining the effects of sources on receptor that are generally within 50 km of the source (US. EPA, 2005). The AERMIC terrain preprocessor (AERMAP) both characterizes the terrain and generates receptor grids for the dispersion model (AERMOD) was as shown in figure 2.3 (US. EPA, 2004). For the stable boundary layer (SBL), AERMOD assumes the concentration distribution to be Gaussian in both vertical and horizontal. But in the convective boundary layer (CBL), the vertical distribution is described with a bi-Gaussian probability density function (PDF).

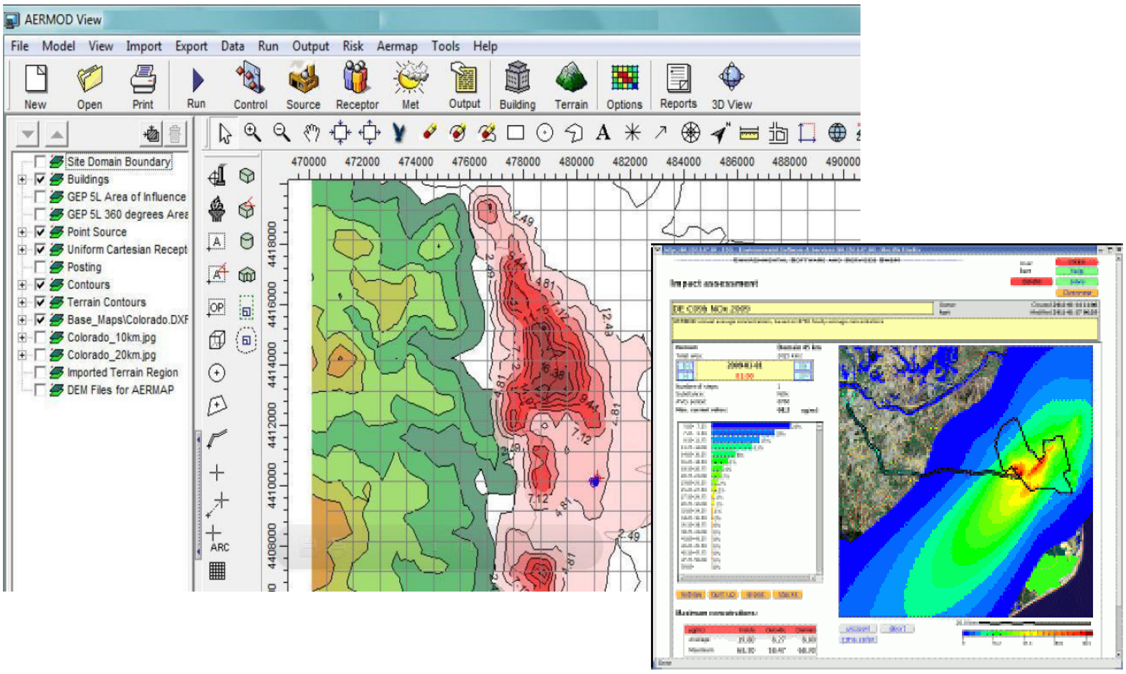


Figure 2.2 AERMOD View (Lakes Environmental Software, 2013)

The AMS/EPA Regulatory Model AERMOD

The general form of the expressions for concentration for both the CBL and SBL is given as:

$$C(x,y,z)=\frac{Q}{u}P_y\{y;x\}P_z\{z;x\} \tag{18}$$

where Q is the source emission rate, u is the effective wind speed, and P_y and P_z are the probability density functions (pdf) for the lateral and vertical concentration distributions, respectively. AERMOD assumes a traditional Gaussian pdf for both the lateral and vertical distributions in the SBL and for the lateral distribution in the CBL. The CBL’s vertical distribution of plume reflects the distinctly non-Gaussian distribution of the vertical velocity distribution in convectively mixed layers (US. EPA, 2004).

2.3.2 AERMOD modeling system

The modeling system consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP), are required in order to run AERMOD was as shown in figure 2.3. AERMAP is a terrain pre-processor which characterizes the terrain and generates receptor grids, discrete receptors, and elevation for AERMOD.

The major purpose of AERMET is to calculate boundary layer parameters for use by AERMOD. The meteorological INTERFACE, internal to AERMOD, uses these parameters to generate profiles of the needed meteorological variables. In addition, AERMET passes all meteorological observations to AERMOD (US.EPA, 2004). AERMAP is a terrain pre-processor which characterizes the terrain and generates receptor grids, discrete receptors, and elevation for AERMOD. Note that in AERMOD, when specifying discrete receptors, it is necessary to specify the position of a source relative to which the receptor is assigned (US. EPA, 2004a). Gridded terrain data are used to calculate a representative terrain-influenced height, associated with each receptor location, and are used to calculate the dividing streamline height (US. EPA, 2004a). The gridded data needed by AERMAP is selected from Digital Elevation Model (DEM) data. The elevation for each specified receptor is automatically assigned through AERMAP.

AERMET, the meteorological pre-processor, provides AERMOD with the information needed to characterize the boundary layer parameters and other meteorological data. Surface characteristics, such as Albedo, surface roughness, Bowen ratio (Paine, 1987), and other meteorological observations (wind speed, wind direction, temperature, cloud cover: usually available for nearby National Weather Service observations) are input data for AERMET for calculating Planetary Boundary Layer PBL parameters: friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux (US. EPA, 2004b).

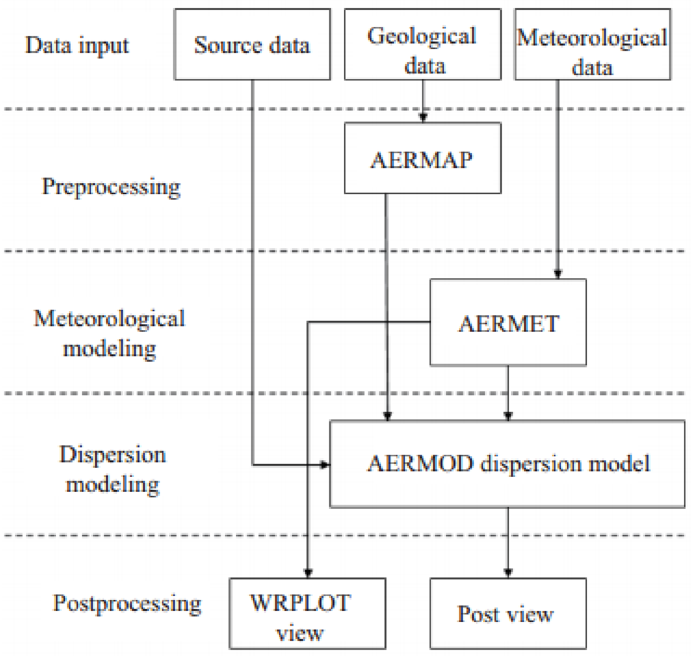


Figure 2.3 Data flow in the AERMOD modeling. (Seangkiatiyuth *et. al.*, 2011)

AERMOD is highly sensitive to the choice of the on-site meteorological monitor used in the AERMET modeling, as it uses only single values (rather than spatial distributions) for meteorological data (Paine, 2003, Faulkner *et al.*, 2008 and Long, 2004).

2.4 Tiering Options

Three – tier approaches were tested for their performance in predicting NO_2 ambient concentration. Assumptions of each tier were as follow:

Tier 1: which it is assumed that all modeled emissions of total NOx (NO plus NO_2 emissions) have been fully converted to NO_2. This is a very conservative method for estimating ambient NO_2 concentrations.

Tier 2: which applies an empirically derived conversion factor to the modeled NOx concentration. This factor is based on observed NO_2/NOx ratios of monitoring data, and EPA has recommended a fixed conversion factor of 0.8 for modeling 1-h NO_2 concentrations. In this study has used a default NO_2/NOx ratio of 0.60 (Ruangkawsakun and Thepanondh, 2014), the assumption is made that 60% of the NOx emitted from a source is converted to NO_2.

Tier 3: methods are the Ozone Limiting Method (OLM) and the Plume Volume Molar Ratio Method (PVMRM). Both of these methods assume that ozone in the atmosphere instantaneously reacts with the emitted NO in the plume to form NO_2. The OLM method assumes that atmospheric ozone is instantly mixed throughout the plume, while the PVMRM method considers the number of moles of atmospheric ozone that could be entrained into the NO emission plume based on the extent of the plume dispersion. These Tier 3 methods require the identification of representative ozone monitoring data for the study area, and data on the actual in-stack ratios of the emitted NO and NO_2 gaseous species (Podrez, 2015).

2.5 Related Research

Alen, 2004 studied results of a sensitivity analysis of the PVMRM and OLM options for NOx to NO_2 conversion in the AERMOD dispersion model. Several single source scenarios were examined as well as a multiple-source scenario. The average conversion ratios of NO_2/NOx for the PVMRM option tend to be lower than for the OLM option and for the Tier 2 option of 0.75 ARM. The sensitivity of the PVMRM and OLM options to emission rate, source parameters and modeling options appear to be reasonable and are as expected based on the formulations of the two methods. For a given NOx emission rate and ambient ozone concentration, the NO_2/NOx conversion ratio for PVMRM is primarily controlled by the volume of the plume, whereas the conversion ratio for OLM is primarily controlled by the ground-level NOx concentration.

Seangkiatiyuth *et al.,* 2011 studied application of the AERMOD modeling system for environmental impact assessment of NO_2 emissions from a cement complex. The dispersion of NO_2 from four cement plants within the selected cement complex were investigated both by measurement and AERMOD simulation in dry and wet seasons. Simulated values of NO_2 emissions were compared with those obtained during a 7-day continuous measurement and simulation were in good agreement, than at the receptors 5 km futher away from the reference point. The Quantile- Quantile plots of NO_2 concentrations in dry season were mostly fitted to the middle line compared to those in wet season. This can be attributed to high NO_2 wet deposition. The results show that for both the measurement and the simulation using the AERMOD, NO_2 concentrations do not exceed the NO_2 concentration limit set by the National Ambient Air Quality Standards (NAAQS) of Thailand. This study indicated that NO_2 emissions from the cement complex had no significant impact on nearby communities.

Schroeder, 2012 studied reviews 1-hour NO_2 concentrations predicted by AERMOD for a hypothetical source at four locations throughout the United States with hourly varying background ozone concentrations. The sensitivity of the model-predicted concentrations to the tier used (i.e., Tier 1 versus Tier 3) is presented based on distance from the source and evaluated on a 1-hour NO_2 NAAQS design concentration basis. All scenarios use hourly varying ambient ozone concentrations corresponding to the same time period as the meteorological data input to AERMOD. Also presented are results showing the sensitivity of AERMOD outputs to those inputs needed for the Tier 3 approach (e.g., in stack ratio of NO_2/NOx, ambient equilibrium ratio, and ambient ozone concentrations), to the relative magnitude of the emission rate modeled, and to the relative ambient ozone concentration.

Hendrick *et al*., 2013 evaluated NO_2 concentrations by the plume volume molar ratio method (PVMRM) and ozone limiting method (OLM) in AERMOD using new field observations. The U.S. Environmental Protection Agency (EPA) plume volume molar ratio method (PVMRM) and the ozone limiting method (OLM) are in the AERMOD model to predict the 1-Hr average NO_2/NO(x) concentration ratio. These ratios are multiplied by the AERMOD predicted NO(x) concentration to predict the 1-hr average NO_2 concentration. This paper first briefly reviewed PVMRM and OLM and points out some scientific parameterizations that could be improved (such as specification of relative dispersion coefficients) and then discussed an evaluation of the PVMRM and OLM methods as implemented in AERMOD using a new data set. While AERMOD has undergone many model evaluation studies in its default mode, PVMRM and OLM are non-default options, and to date only three NO_2 field data sets have been used in their evaluations. In this study, AERMOD/PVMRM and AERMOD/OLM codes are evaluated with a new data set from a northern Alaskan village with a small power plant. Hourly pollutant concentrations (NO, NO_2, Ozone) as well as meteorological variables were measured at a single monitor 500 m from the power plant. Power plant operating parameters and emissions were calculated based on hourly operator logs. Hourly observations covering 1 yr were considered, but the evaluations only used hours when the wind was in a 60 degrees sector including the monitor and when concentrations were above a threshold. PVMRM is found to have little bias in predictions of the $C(NO_2)/C(NO(x))$ ratio, which mostly ranged from 0.2 to 0.4 at this site. OLM over predicted the ratio. AERMOD over predicted the maximum NO(x) concentration but had an under prediction bias for lower concentrations. AERMOD/PVMRM over predicted the maximum $C(NO_2)$ by about 50%, while AERMOD/OLM over predicted by a factor of 2. For 381 hours evaluated, there was a relative mean bias in $C(NO_2)$ predictions of near zero for AERMOD/PVMRM, while the relative mean bias reflected a factor of 2 over prediction for AERMOD/OLM.

Podrez, 2015 studied an update to the ambient ratio method for 1-h NO_2 air quality standards dispersion modeling. This paper describes the Ambient Ratio Method version 2 (ARM2), ARM2 is an empirical approach that uses a variable conversion factor, based on an analysis of ambient air measurements of NO and NO_2, to estimate the portion of the AERMOD predicted air concentration of total NOx species that is in the form of NO_2. The performance of ARM2 has been evaluated and found to compare well to actual ambient measurements and to other more complex EPA conversion methods. EPA has included ARM2 as a “beta-testing” option in AERMOD version 14134, and provided guidance on the use of ARM2 for regulatory modeling analyses in a September 2014 memorandum. This paper also discusses this recent EPA guidance.

CHAPTER III
METHODOLOGY

3.1 Location area planning

3.1.1 Maptaphut industrial area , Rayong

The Maptaphut industrial Port is located 185 kilometers from Bangkok on the Gulf of Thailand's coast between Sattahip district of Chon Buri province and Rayong province, and consists of 117 industrial plants which include 45 petrochemical factories, eight coal-fired power plants, 12 chemical fertilizer factories and two oil refineries. (IEAT, 2012).

In this study, measured data of ambient air concentration, obtained from 10 monitoring stations are used in the analysis. The locations of each station are as presented in figure 3.1 and detail are as shown in Table 3.1.

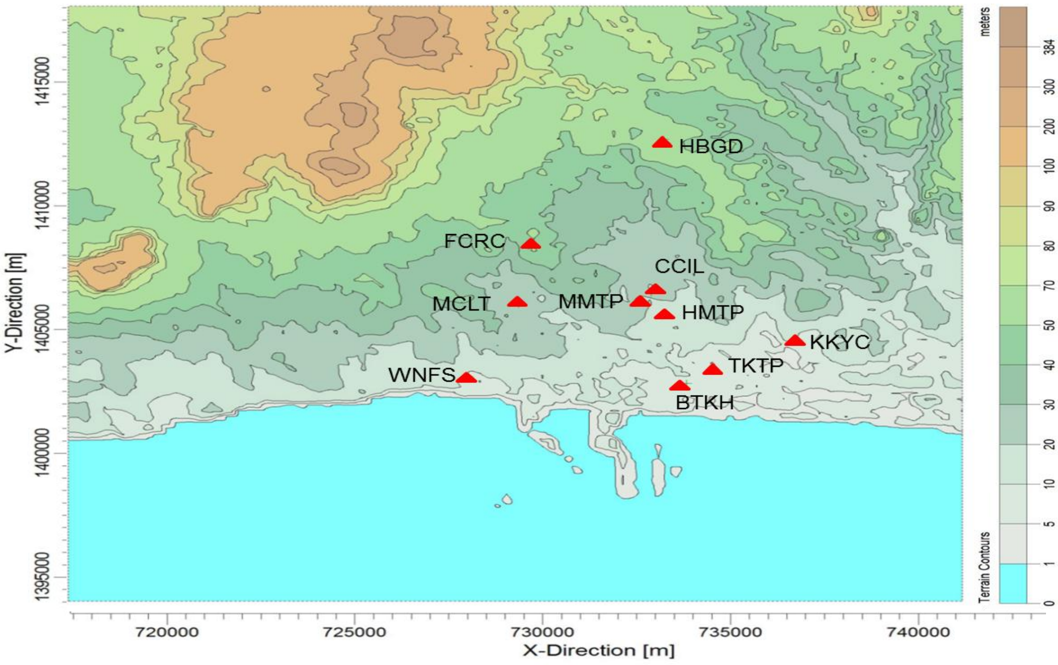


Figure 3.1 Location of air quality monitoring stations in Maptaphut industrial area.

Table 3.1 Detail of 10 monitoring stations are used in the analysis.

Monitoring Station	Geographical location (UTM)		Distance from Reference (km)	Operated by
	X	Y		
1.Health Promotion Hospital Maptaphut (HMTP)	12.70599	101.16798	3.86	PCD
2.Field Crops Research Center (FCRC)	12.73163	101.13541	2.35	PCD
3.Ban Ta Kuan Public Health Center (BTKH)	12.68142	101.17377	5.52	IEAT
4. Wat Nong Fap School (WNFS)	12.68437	101.12011	3.25	IEAT
5. Muang Mai Maptaphut (MMTP)	12.71216	101.16264	3.25	IEAT
6. Krok Yai Cha (KKYC)	12.69691	101.20124	7.59	IEAT
7. Map Chalut Temple (MCLT)*	12.71066	101.13273	0.00	BLCP
8. Ta Kuan Temple (TKTP)	12.68645	101.18002	5.76	BLCP
9. Herbal Garden (HBGD)	12.77022	101.16895	7.74	BLCP
10. Chum Chon Islam (CCIL)	12.71437	101.16537	3.60	BLCP

Note

- PCD : Pollution Control Department
- IEAT : Industrial Estate Authority Of Thailand
- BLCP: BLCP Power Plant, Maptaphut, Rayong
- * : Reference point

3.2 Data Collection

Data Collection is an important aspect of any type of research study for the emission source, dispersion calculation, meteorology and receptors. These data was used for AERMOD model.

3.2.1 Emission Data

The emission data for the year 2012 and 2013 were obtained from Office of Natural Resource and Environment Policy and Planning (ONEP). The Emission of Natural Gas Separation Plant, RIL Industrial Complex and Rayong Electricity Generating were also used in this study. These data were derived from a report on environment impact assessment (EIA report). This data consists of emissions sources coordinates, stack height, exit temperature, exit velocity and NOx emission rate. The detail of these emission data was showed in Table A (Appendix A).

3.2.2 Ambient Air Data

Ambient air data were obtained from Pollution Control Department (PCD), Industrial Estate Authority Of Thailand (IEAT) and BLCP Power Plant, Maptaphut Rayong. Measured data from 10 monitoring stations in the surrounding area of Maptaphut industrial area for the year 2012 and 2013 were collected on basis and were in this study.

3.2.3 Meteorological Data

The surface data were obtained from simulation of MM5 meteorological modeling for the years 2012 and 2013. Meteorological data contained hourly wind speed, temperature, cloud cover, ceiling height, surface pressure and relative humidity. The upper air data, which are vertical profile of wind speed, wind direction, elevation, temperature and pressure, were also analyzed from MM5 modeling.

3.3 Tiering Options

In this study has defined a 3-tier approach to modeling NO_2 concentrations:

Tier 1: total conversion, or all NOx = NO_2 (where the entire NO component of emitted NOx is assumed to immediately react to form NO_2).

Tier 2: use a default NO_2/NOx ratio of 0.60 (Ruangkawsakun and Thepanondh, 2014), the assumption is made that 60% of the NOx emitted from a source is converted to NO_2.

Tier 3: ambient O_3 concentrations are used for calculation in Ozone Limiting Method (OLM) and Plume Volume Molar Ratio Method (PVMRM).

3.4 Treatment of data

Nitrogen oxides concentrations data were obtained from Pollution Control Department (PCD), BLCP Power Plant, Map Ta Phut Rayong and Industrial Estate Authority Of Thailand (IEAT). Monitored data were treated prior be used to compare with those predicted data. Criteria of data treatment were as follows:

1. If the missing data were more than 30% of total data for each month, Data of respective month were rejected.

2. No data (-) and concentration value less than sample value (<samp) were replaced with average concentration of such hourly concentration.

3. Group of missing data for several hour were replaced by those measured data with the same period or were the next following day.

Table 3.2 Example of data treatment

Hourly	**Concentration (ppb)**	
	Data	Data treatment
400	10	10
500	-	11.5
600	13	13
700	16.8	16.8

3.5 Model Configuration

AERMOD (Version 8.7) of Lake Environment were used in this study. Variables/parameters were specified according to the sensitivity analysis simulation conditions.

AERMOD Configuration

The AERMOD modeling system consists of one main program (AERMOD) and three pre-processors, AERSURFACE, AERMAP and AERMET (US. EPA, 2004c). Details of the model configuration in this study were set as follows;

- Grid Center Coordinate

    Latitude 13’16”N

    Longitude 100’93”E

- Grid Parameters

    Number of grid points (nx=40, ny=40)

    Grid resolution (x=500 m, y=500 m)

    Outer grid spacing (x=20,000 m, y=20,000 m)

- Dispersion Options: The regulatory modeling options in this research use the default mode of operation for the urban options of dispersion coefficient. Pollutant types which are NO_x were calculated in 1 hour period on elevated terrain height option.

- Source Options: There were 292 point sources in four areas including; Maptaphut Industrial Complex, Natural Gas Separation Plant, RIL Industrial Complex and Rayong Electricity Generating. Emission rate unit is in grams per sec (g/s) and concentration unit is in microgram per cubic meter ($\mu g/m^3$).

- Receptor Options: Discrete Cartesian receptors for 10 receptors were set as shown in Table 3.1.

- Meteorology Options: The surface met and profile met datum use the default of AERMET format from MM5-preprocessed metrological data. Potential temperature profiles base on elevation above MSL (for primary met tower) which is 36 meters. Data periods read from met data files start from the 1st hour in 1st January 2012 to the 24th hours in 31th December 2013.

- Terrain Options: The terrain area covered by the DEM data on SRTM3/SRTM1.

3.6 Model Simulation Frameworks

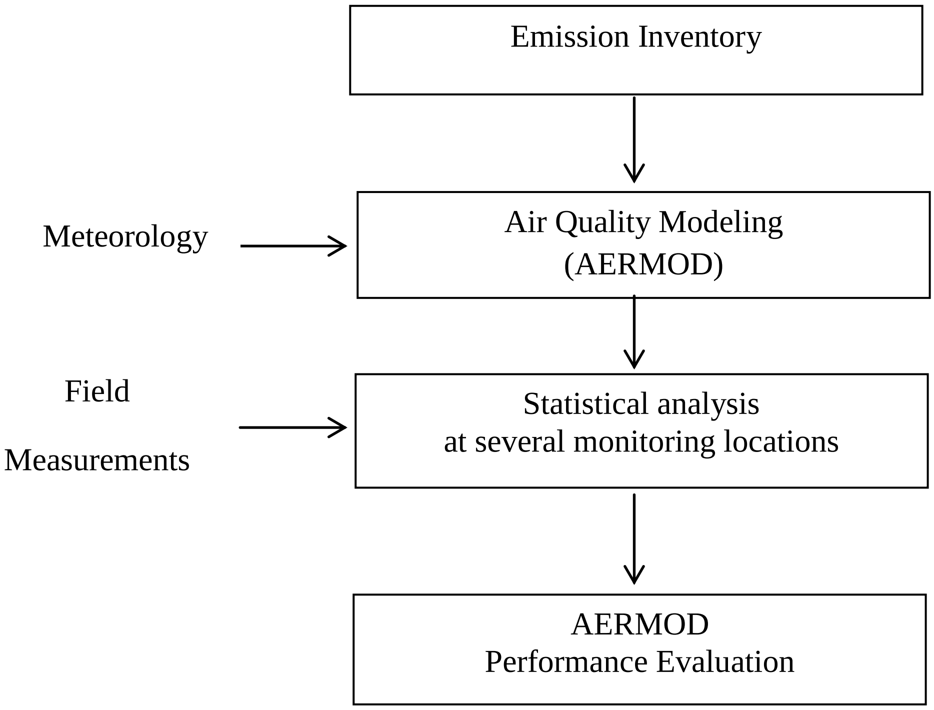


Figure 3.2 Model Simulation Frameworks

3.7 Model Performance Evaluation

The model performance should be evaluated to ensure that the modeling results are appropriate (Venkatram, 1981). The model results have also been validated through computing different statistical errors namely normalized mean square error, fractional bias, fraction variance, and index of agreement (Arya, 1999; Rana, 2005). Numerous steps have been taken by the EPA to ensure that the best model is properly used for each regulatory application and that the model is not arbitrarily imposed. Two types of performance measures are identified: 1) measures of difference and 2) measures of correlation. Measures of difference represent a quantitative estimate of the size of the differences between predicted and observed values. Measures of correlation indicate quantitative measures of the association between predicted and observed values (Kumar *et al.*, 2006).

For evaluation of the applied model in this study area, Observed Mean (O_{mean}), Predicted/modeled Mean (P_{mean}), Observed Standard Deviation/sigma (O_{std}), Predicted/modeled Standard Deviation/sigma (P_{std}), Root Mean Square Error (RMSE), Index Of Agreement (IOA), Fractional Bias (Fb), Fraction Variance (Fs) and the Robust Highest Concentration (RHC) statistical tools were used. For testing model performance, relationship between the the data for NO_X (for each pollutant measured and predicted results separately) of 2012 and 2013 was evaluated. Then, for the overall model evaluation, all yearly data were used and performance results were completed. The purpose of such an analysis is to validate further air quality model predictions (Patel and Kumar, 1998).

The following performance measures were applied in this study

1. Observed Mean (O_{mean})

$$O_{mean} = \frac{1}{N}\sum_{i=1}^{N} O_i$$

2. Predicted/modeled Mean (P_{mean})

$$P_{mean} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

3. Observed Standard Deviation/sigma (O_{std})

$$O_{std} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(O_i - O_{mean})^2}$$

4. Predicted/modeled Standard Deviation/sigma (P_{std})

$$P_{std} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(P_i - P_{mean})^2}$$

5. Pearson Correlation Coefficient (r^2)

$$r^2 = \frac{N(\sum_{i=1}^{N} O_i P_i) - (\sum_{i=1}^{N} O_i)(\sum_{i=1}^{N} P_i)}{\sqrt{[N(\sum_{i=1}^{N} O_i^2) - (\sum_{i=1}^{N} O_i)^2][N(\sum_{i=1}^{N} P_i^2) - (\sum_{i=1}^{N} P_i)^2]}}$$

6. Root Mean Square Error (RMSE)

Correlation analysis involves statistical parameters obtained by linear least-squares regression. The value of correlation close to 1 indicates perfect correlation between the observed and the predicted values that is a sign of good model performance. The coefficient of correlation is given by

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

7. Index Of Agreement (IOA)

The Index of Agreement (IOA) which is designed to better handling differences in predicted and observed means and variances (Willmott *et al.*, 1985).

$$IOA = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - O_{mean}| + |O_i - O_{mean}|)^2}$$

8. Fraction Bias (Fb)

The FB indicates how well the computation produces the average values around the average values of observed variable. The ideal value of this measure is zero, but it can range from −2 to 2 (Arya, 1999). The bias is normalized to make it dimensionless. The FB is given by

$$\mathrm{F_b} = 2\frac{(O_{mean} - P_{mean})}{(O_{mean} + P_{mean})}$$

9. Fraction Variance (Fs)

$$F_s = 2\frac{(O_{std} - P_{std})}{(O_{std} + P_{std})}$$

10. Robust Highest Concentration (RHC)

Cox and Tikvart (1990) proposed a robust test statistic that represents a smoothed estimate of the highest concentrations, based on a tail exponential fit to the upper end of the distribution. With this procedure, the effect of extreme values on model comparison is reduced. This statistic is the robust highest concentration (RHC) and is given by:

$$\text{RHC} = C(R) + (\overline{C} - C(R)\ln(\frac{(3R-1)}{2}$$

Where

Oi = Observed data
Pi = Predicted modeled data
C(R) = the Rth highest concentration
C^- = the mean of the top R-1 concentrations

AERMOD model performance were tested by comparing the predicted pollutant concentrations of NO_2 with those measured actual values (monthly mean concentrations) at ten ambient air quality stations.

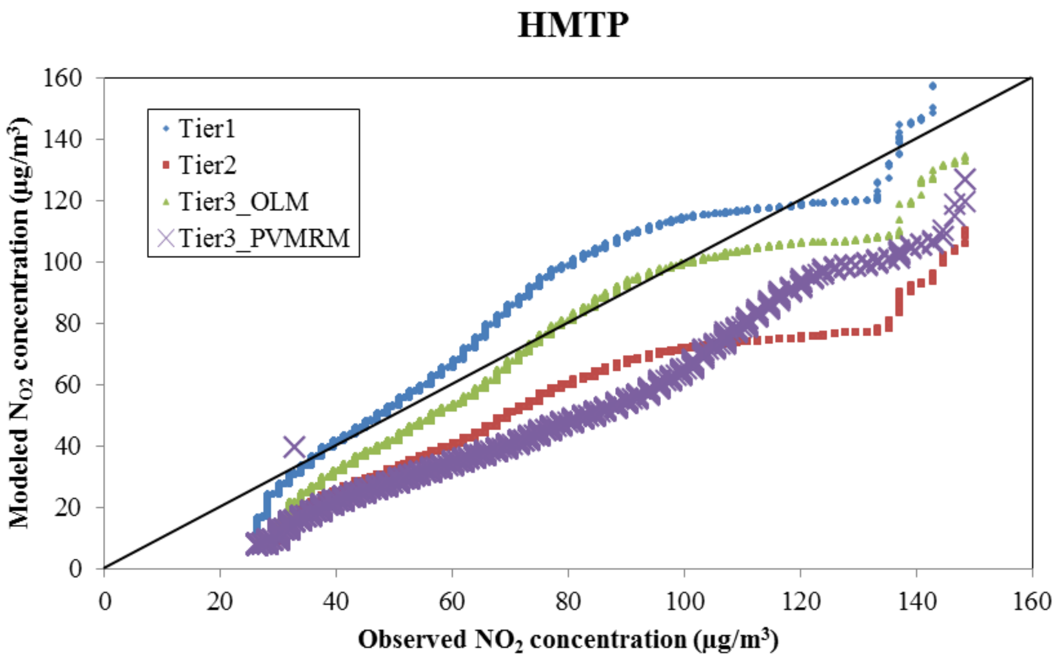
CHAPTER IV

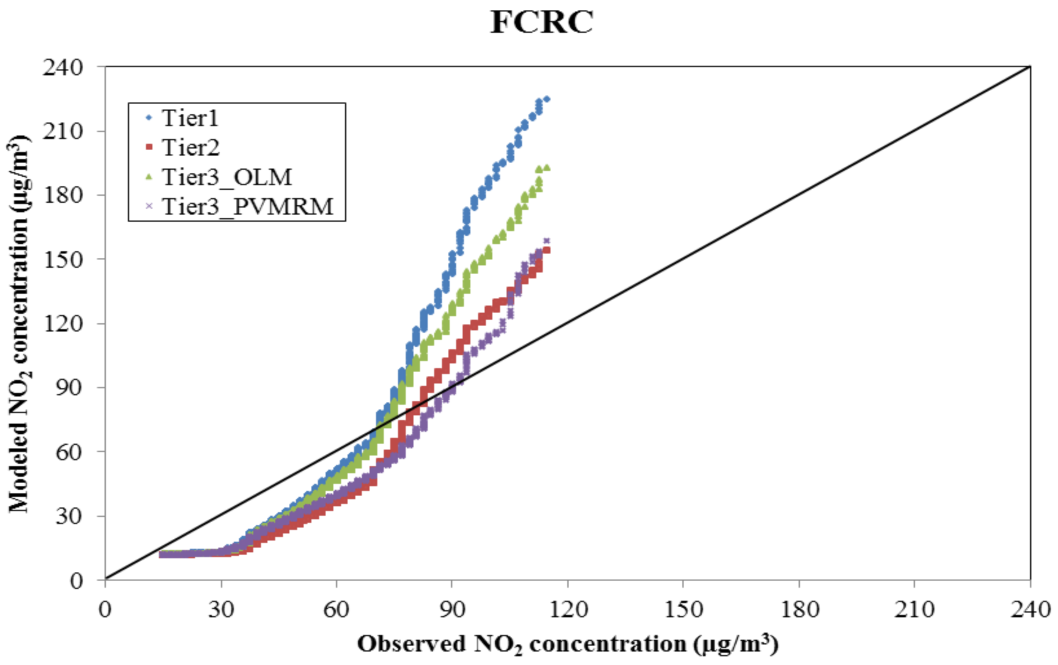
RESULTS AND DISCUSSION

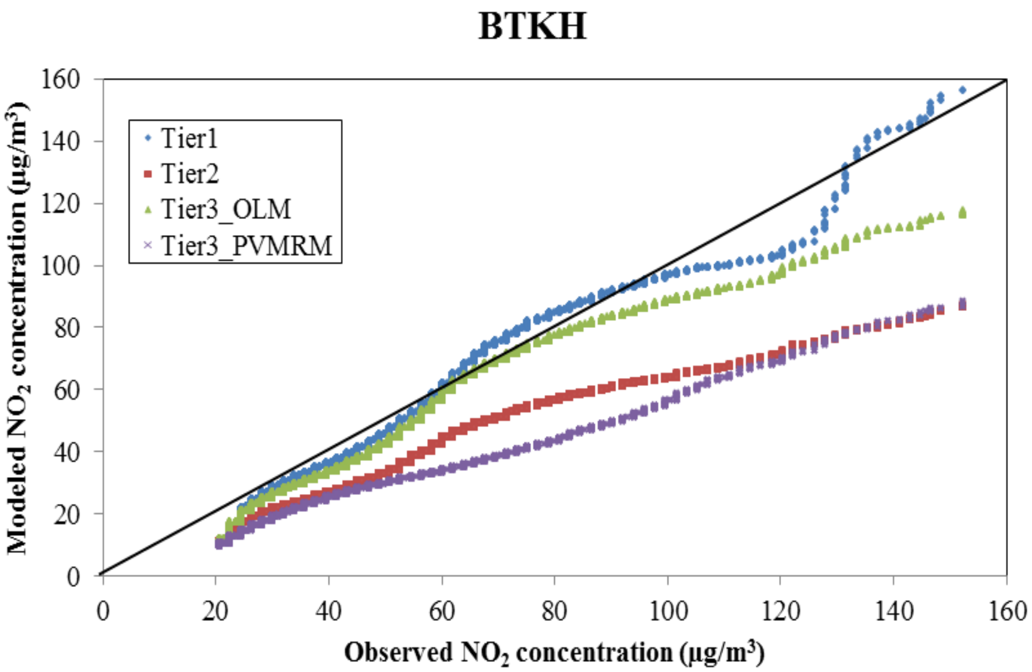
In this chapter, performance of AERMOD dispersion model in predicting 1-hour average nitrogen dioxide (NO_2) concentrations in the vicinity of the largest petrochemical industrial complex in Thailand were evaluated for the year 2012 and 2013. Hourly average ambient ground level concentrations of NO_2 predicted at each of the monitoring site were computed. Results were compared with those measured data at each respective site. Measured data of hourly ambient air concentrations used in this study were provided by Pollution Control Department (PCD), Industrial Estate Authority Of Thailand (IEAT) and BLCP Power Plant, Maptaphut Rayong.

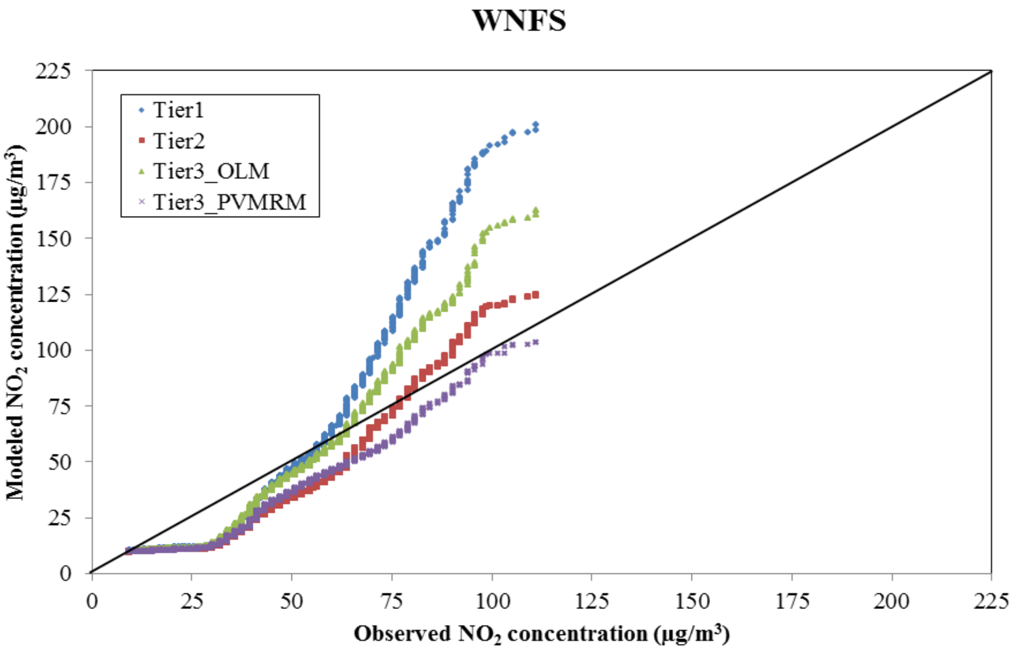
For evaluation of model performance, predicted and measured data were sorted (independent of time) and were plotted using a scatter diagram in order to examine the model bias over the concentration distribution. Comparisons of modeled and observed NO_2 concentrations at each site were shown in Figure 4.1.

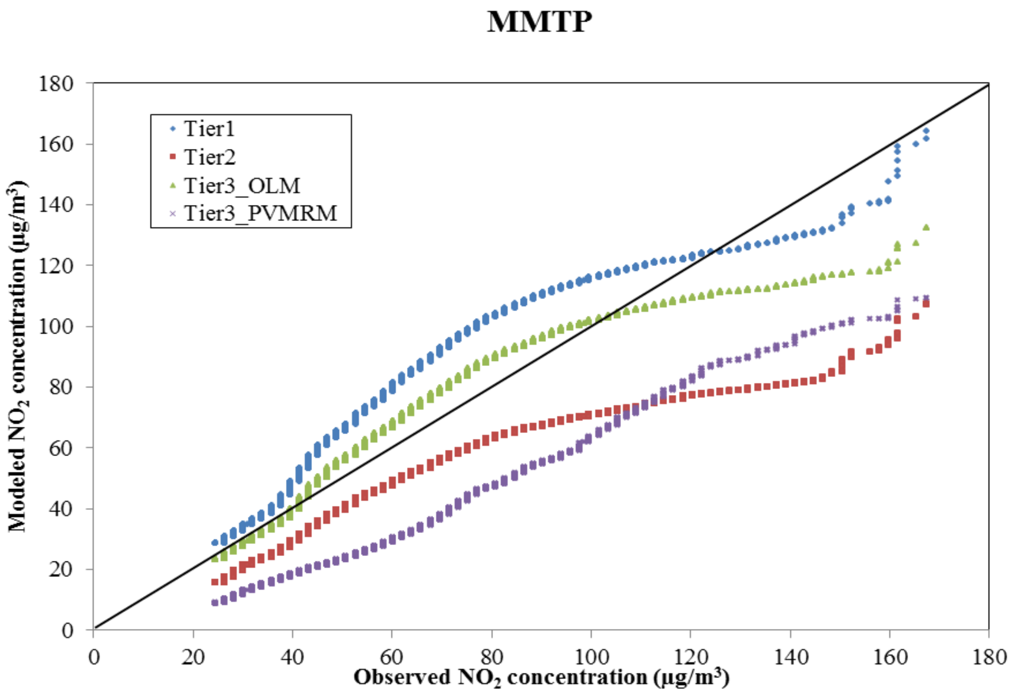
The scatter plots of sorted concentration at all monitoring sites indicated the spread of predicted versus observed NO_2 concentrations. Results (Figure 4.1) indicated that AERMOD performed quiet well and provided high correlations with the observed NO_2 concentrations at every monitoring station for each tier.

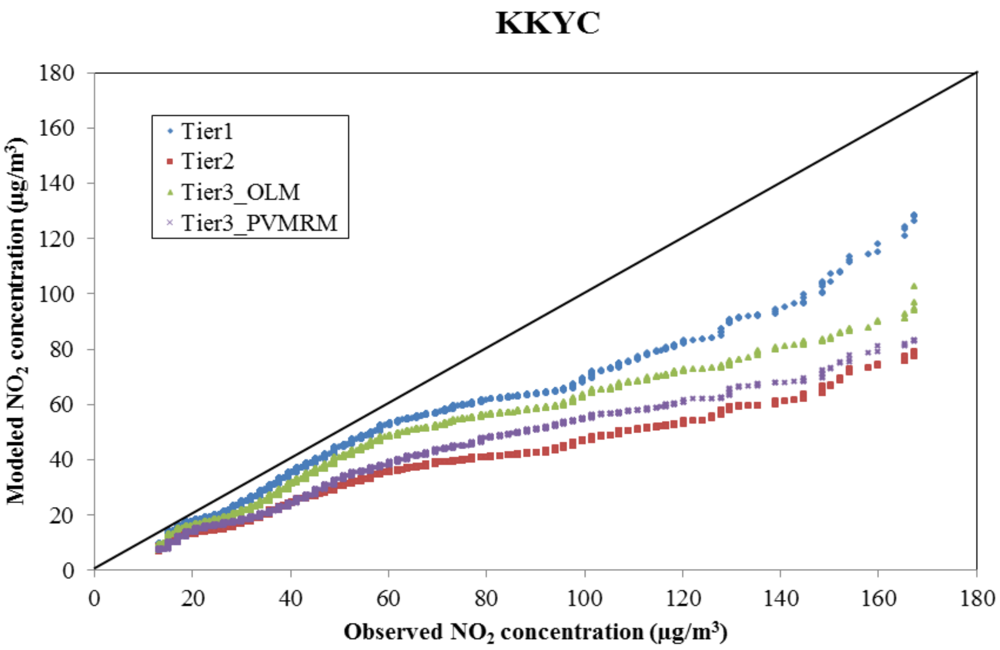

HMTP
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled N_{O2} concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
20
40
60
80
100
120
140
160

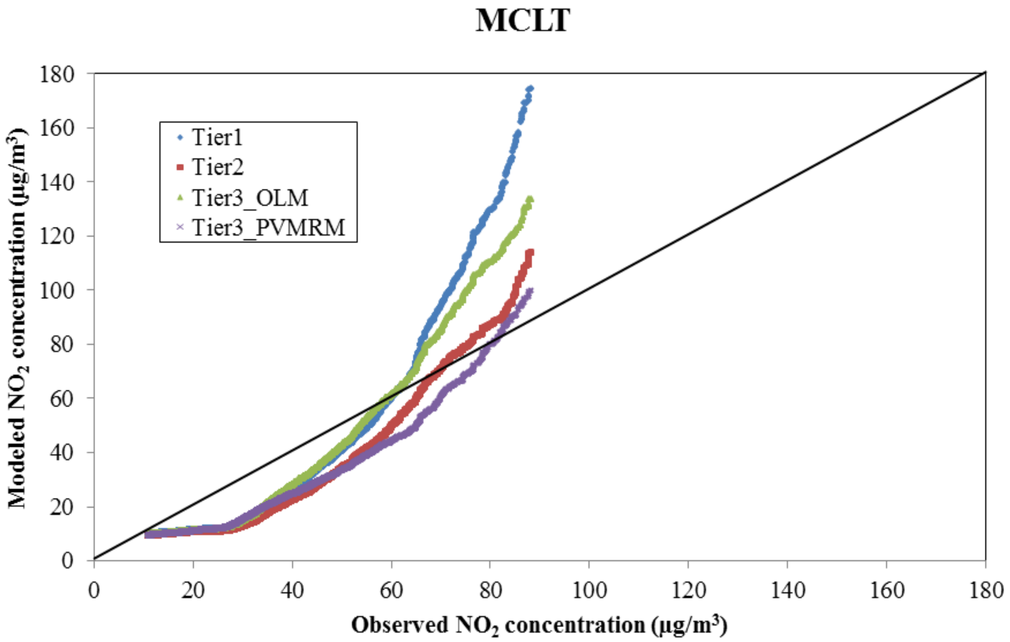

FCRC
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO_2 concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
30
60
90
120
150
180
210
240

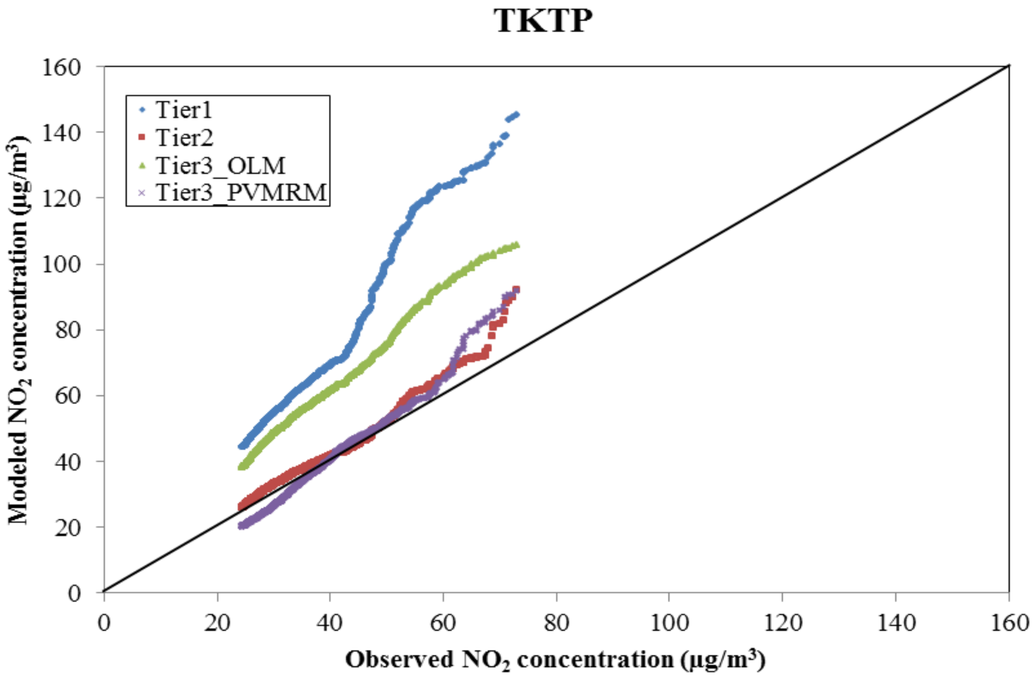

BTKH
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO_2 concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
20
40
60
80
100
120
140
160

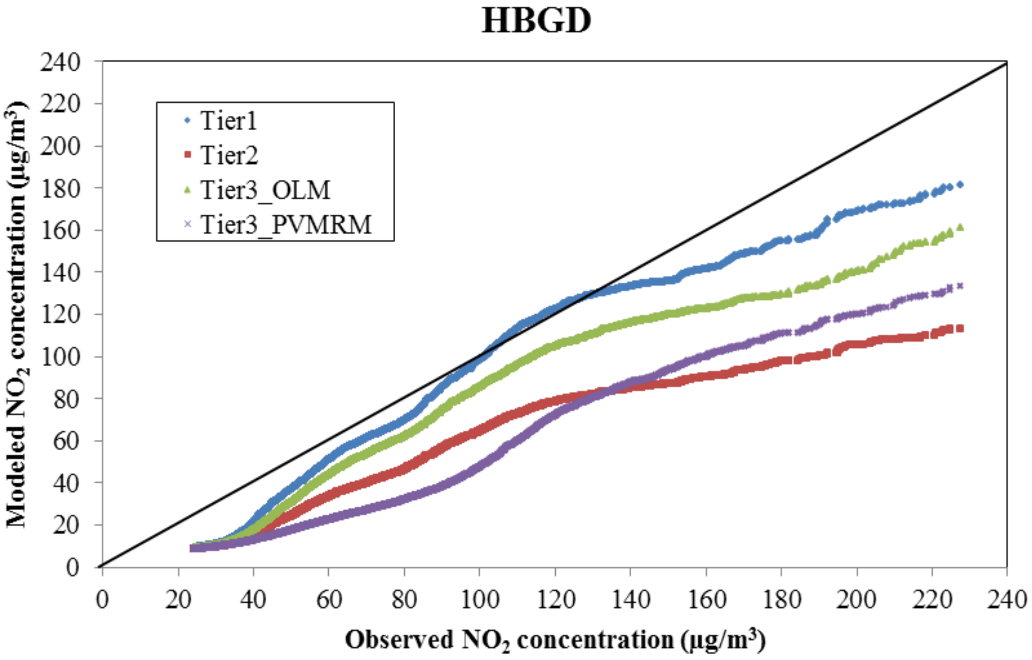

WNFS
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO_2 concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
25
50
75
100
125
150
175
200
225

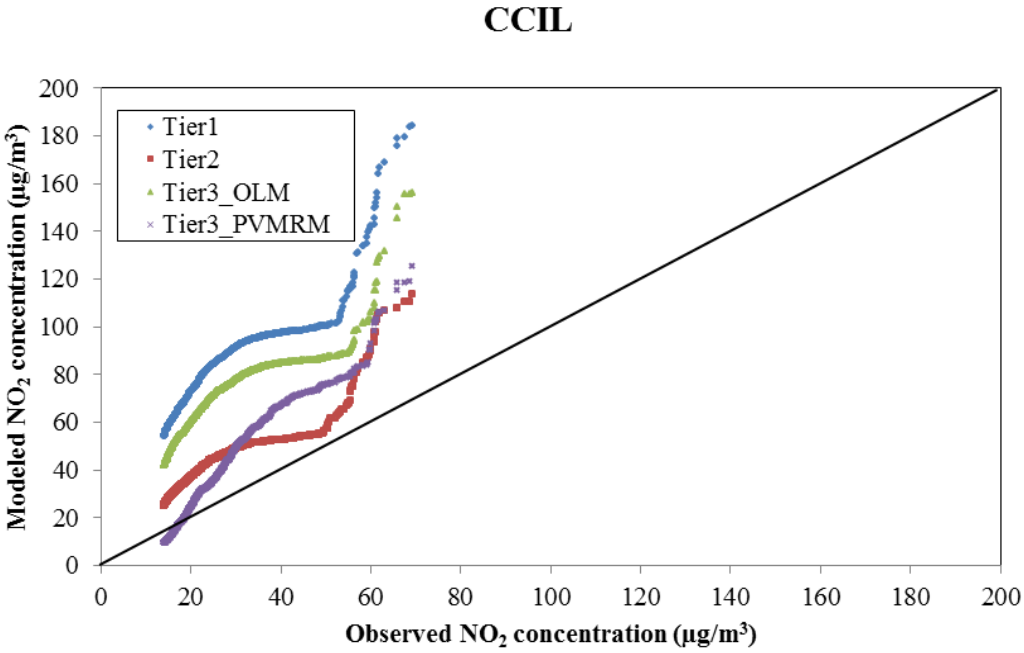

MMTP
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO_2 concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
20
40
60
80
100
120
140
160
180


KKYC
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO_2 concentration (µg/m^3)
Observed NO_2 concentration (µg/m^3)
0
20
40
60
80
100
120
140
160
180


MCLT
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO$_2$ concentration (µg/m^3)
Observed NO$_2$ concentration (µg/m^3)
0
20
40
60
80
100
120
140
160
180


TKTP
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO$_2$ concentration (µg/m^3)
Observed NO$_2$ concentration (µg/m^3)
0
20
40
60
80
100
120
140
160


HBGD
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO2 concentration (µg/m3)
Observed NO2 concentration (µg/m3)
0
20
40
60
80
100
120
140
160
180
200
220
240


CCIL
Tier1
Tier2
Tier3_OLM
Tier3_PVMRM
Modeled NO2 concentration (µg/m3)
Observed NO2 concentration (µg/m3)
0
20
40
60
80
100
120
140
160
180
200

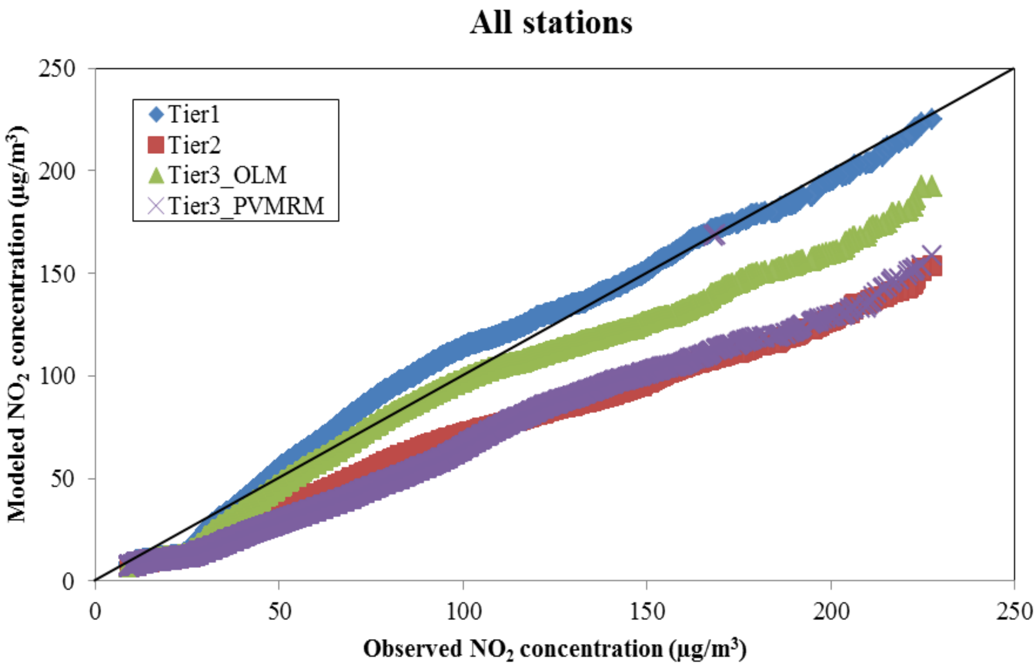


Figure 4.1 Scatter plot between observed and modeled (AERMOD) concentration at each monitoring sites.

Comparison of average concentrations for each tier within the study area at each receptor were as presented in Figure 4.2. that the Tier 1 method provided the highest ground level concentration at every receptors.

Statistical results of model evaluation for NO_2 concentrations were summarized in Table 4.1. Results from statistical evaluation indicated that there were differences between the model and observed values. However, these differences were much lower than their respective standard deviations (sigma) (RMSE < standard deviation), indicating that skill was being shown by the model. Generally, AERMOD performed well for the prediction of average concentration at every monitoring site; at least to within the accuracy of the observations (standard deviation) for every tiering options.

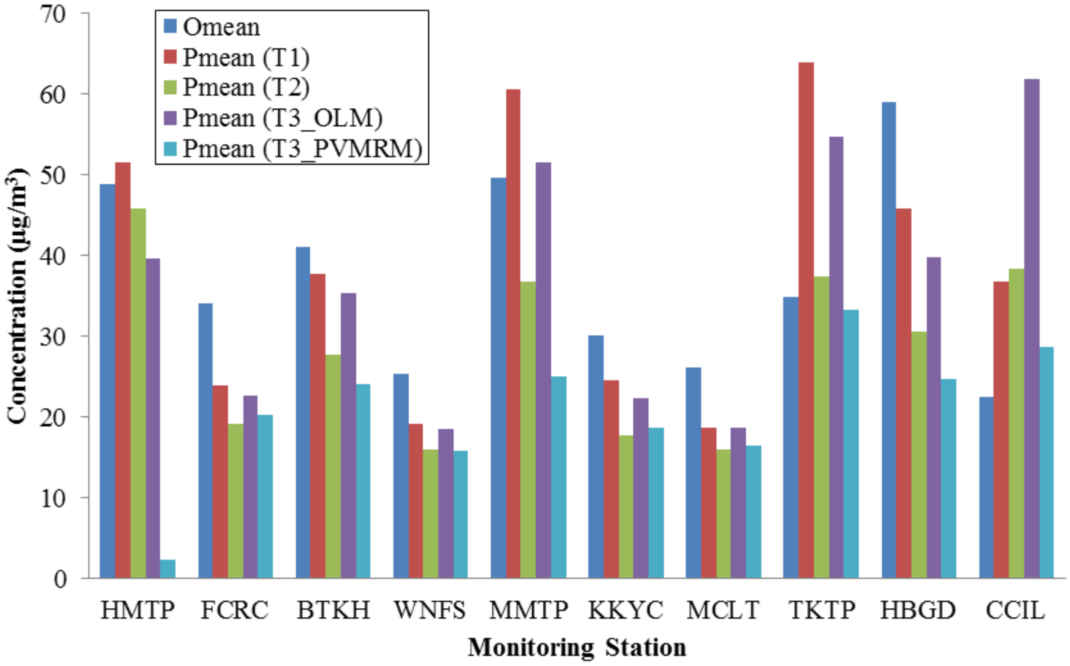


Figure 4.2 Comparison of average concentrations of observed and predicted data (Tier 1-3)

The average of the data at all sites was measured to be 38.74 μg/m^3 (observed), and predicted to be 36.76, 24.84, 32.16, 21.78 μg/m^3 (predicted) for the simulation with Tier 1-3, respectively. There were differences between the model and observed values. However, these differences were much lower than their respective standard deviations (sigma) (RMSE < standard deviation), indicating that skill was being shown by the model. Generally, AERMOD performed well for the prediction of average concentration at every monitoring site; at least to within the accuracy of the observations (standard deviation).

Table 4.1 Statistical evaluation of observed and predicted for NO_2 concentration.

Monitoring Site	**No. of samples**	**Mean**	**Standard deviation**	**r^2**	**RMSE**	**IOA**	**Fb**	**Fs**	**RHC**
1.HMTP									
Observed	12047	48.83	72.04	-	-	-	-	-	65.31
Tier 1	12047	51.54	33.50	0.98	7.79	0.99	-0.05	0.73	80.41
Tier 2	12047	45.93	101.04	0.87	83.61	0.80	0.06	-0.34	75.56
Tier 3_OL	12047	39.62	25.77	0.99	10.69	0.99	0.21	0.95	62.96
Tier 3_PV	12047	2.41	9.47	0.99	8.79	0.99	1.81	1.54	13.23
2.FCRC									
Observed	10089	34.14	85.45	-	-	-	-	-	48.14
Tier 1	10089	23.98	25.83	0.89	16.12	0.99	0.34	1.07	32.76
Tier 2	10089	19.23	20.33	0.88	16.96	0.99	0.56	1.23	24.86
Tier 3_OL	10089	22.67	23.14	0.91	14.94	0.99	0.40	1.15	30.53
Tier 3_PV	10089	20.35	18.92	0.93	15.16	0.99	0.51	1.28	26.77
3.BTKH									
Observed	10265	41.05	79.49	-	-	-	-	-	55.98
Tier 1	10265	37.81	23.16	0.99	4.89	0.99	0.08	1.10	57.65
Tier 2	10265	27.69	14.22	0.98	15.02	0.99	0.39	1.39	40.62
Tier 3_OL	10265	35.45	20.28	0.99	8.46	0.99	0.15	1.19	53.59
Tier 3_PV	10265	24.15	13.25	0.99	19.17	0.99	0.52	1.43	34.69
4.WNFS									
Observed	10768	25.36	93.83	-	-	-	-	-	37.06
Tier 1	10768	19.25	24.12	0.87	12.31	0.99	0.27	1.18	25.93
Tier 2	10768	15.97	19.88	0.89	11.66	0.99	0.46	1.30	20.58
Tier 3_OL	10768	18.53	21.48	0.91	10.02	0.99	0.31	1.25	24.75
Tier 3_PV	10768	15.89	19.23	0.92	11.36	0.99	0.46	1.32	20.26
5.MMTP									
Observed	8187	49.68	72.01	-	-	-	-	-	68.18
Tier 1	8187	60.60	40.47	0.97	13.33	0.99	-0.20	0.56	84.02
Tier 2	8187	36.74	18.04	0.98	14.88	0.99	0.30	1.19	52.18
Tier 3_OL	8187	51.65	31.93	0.97	5.88	0.99	-0.04	0.77	72.44
Tier 3_PV	8187	25.07	17.68	0.99	25.51	0.98	0.66	1.21	36.92
6.KKYC									
Observed	10513	30.08	90.05	-	-	-	-	-	42.48
Tier 1	10513	24.64	16.57	0.99	7.63	0.99	0.20	1.37	37.26
Tier 2	10513	17.73	16.37	0.99	16.15	0.99	0.52	1.39	25.64
Tier 3_OL	10513	22.30	16.10	0.98	10.44	0.99	0.29	1.39	33.39
Tier 3_PV	10513	18.62	16.64	0.99	14.52	0.99	0.47	1.38	27.16
7.MCLT									
Observed	9774	26.17	92.93	-	-	-	-	-	37.35
Tier 1	9774	18.63	23.09	0.88	12.29	0.99	0.34	1.20	24.96
Tier 2	9774	16.07	20.35	0.91	11.78	0.99	0.48	1.28	21.08
Tier 3_OL	9774	18.77	21.54	0.92	10.27	0.99	0.33	1.25	25.31
Tier 3_PV	9774	16.48	18.97	0.94	10.94	0.97	0.45	1.32	21.72
8.TKTP									
Observed	1778	34.88	83.59	-	-	-	-	-	42.39
Tier 1	1778	63.96	38.58	0.98	31.02	0.95	-0.58	0.74	78.28
Tier 2	1778	37.38	11.94	0.99	2.88	0.99	-0.07	1.50	45.69
Tier 3_OL	1778	54.74	27.48	0.99	20.34	0.98	-0.44	1.01	66.65
Tier 3_PV	1778	33.33	12.88	0.99	3.71	0.99	0.05	1.47	42.87

Table 4.1 Statistical evaluation of observed and predicted for NO_2 concentration. (continued)

Monitoring Site	No. of samples	Mean	Standard deviation	r^2	RMSE	IOA	Fb	Fs	RHC
9.HBGD									
Observed	10661	58.97	67.36	-	-	-	-	-	84.41
Tier 1	10661	45.89	39.32	0.99	14.59	0.99	0.25	0.53	72.71
Tier 2	10661	30.67	22.67	0.99	30.30	0.96	0.63	0.99	46.78
Tier 3_OL	10661	39.81	32.59	0.99	18.85	0.98	0.39	0.69	62.37
Tier 3_PV	10661	24.66	22.23	0.98	36.48	0.95	0.82	1.01	36.43
10.CCIL									
Observed	2428	22.52	95.84	-	-	-	-	-	28.69
Tier 1	2428	36.76	30.01	0.99	7.26	0.99	0.05	0.93	89.66
Tier 2	2428	28.44	13.08	0.95	16.29	0.99	-0.52	1.52	48.16
Tier 3_OL	2428	61.95	34.06	0.94	39.96	0.93	-0.93	0.95	76.64
Tier 3_PV	2428	28.68	18.69	0.98	11.62	0.99	-0.24	1.35	42.83
All stations									
Observed	86510	38.74	82.65	-	-	-	-	-	60.24
Tier 1	86510	36.76	30.01	0.99	7.26	0.99	0.05	0.93	58.26
Tier 2	86510	24.84	18.54	0.99	15.42	0.99	0.44	1.27	37.97
Tier 3_OL	86510	32.16	24.91	0.99	7.67	0.99	0.19	1.07	50.48
Tier 3_PV	86510	21.78	17.61	0.99	18.59	0.98	0.56	1.29	32.98

Note: r^2= Correlation Coefficient, RMSE= Root Mean Square Error, IOA= Index of agreement, Fb= Fractional bias, Fs= Factional variance, RHC= Robust highest concentration, Tier 3_OL= Tier 3_OLM, Tier 3_PV= Tier 3_PVMRM.

The fractional bias (Fb) and fractional variance (Fs) varied between -2 (extreme over-prediction) and +2 (extreme under-prediction). The maximum Fb and Fs were found for simulated data at every stations in Tier 3_PVMRM (Fb = 0.56) while the best model performances were found in Tier 1 (Fb = 0.05) as shown in Figure 4.3. These findings are supported by the lowest value of RMSE (root mean square error) at 7.26 µg/m^3 when Tier 1 is used in model simulation as shown in Figure 4.4. Therefore, Overall predicted results, obtained from Tier 1 were less bias with those measured results as compared with other tier and may be considered as appropriate calculation for prediction of annual average concentration. Model verification revealed the fact that emission inventory of oxide of nitrogen used in this study was under estimated. This underestimation also potentially links to large inaccuracy in the emission data sets that do not contain complete data. It is also important that the relative emission rate of NO_2 concentration can affect. NO_2 concentrations are contributed by both industrial and mobile source emissions. However, lack of emission data of mobile sources which generally occurred in many studies given constraint in applying air dispersion model in such areas.

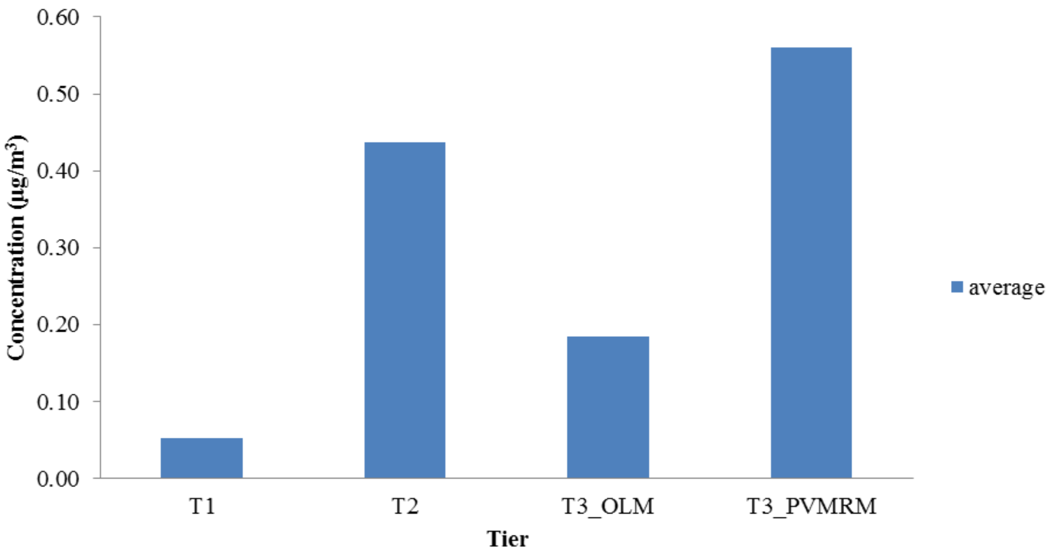


Figure 4.3 Performance evaluation using Fb (Tier 1-3)

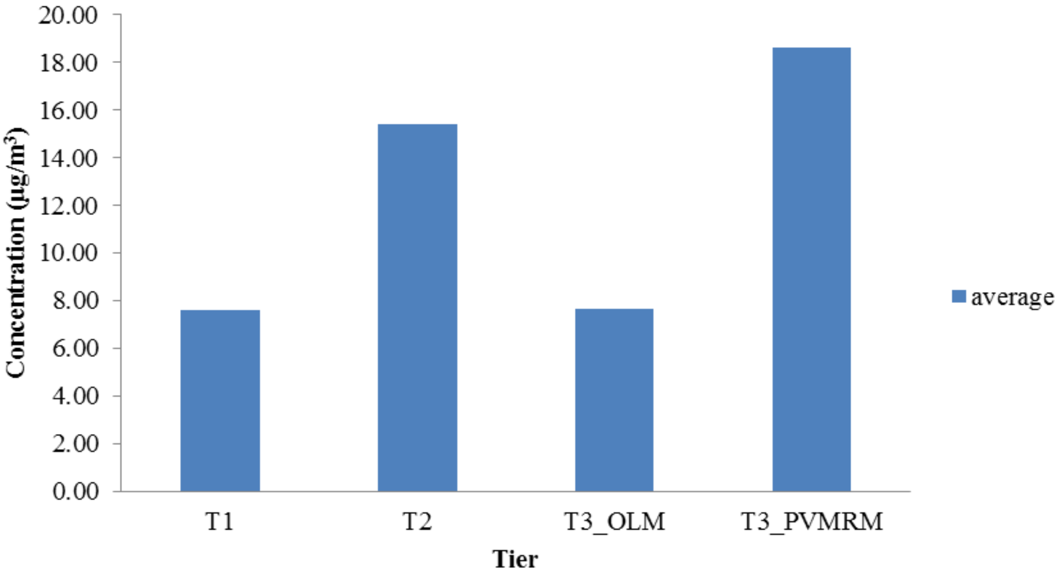


Figure 4.4 Performance evaluation using RMSE (Tier 1-3)

The RHC is preferred to the actual peak value and represents a smoothed estimate of the highest concentrations, based on a tail exponential fit to the upper end of the distribution (Thepanondh, 2004). With this procedure, the effect of extreme values on model comparison is reduced. The equation to calculate RHC is as follows (Cox and Tikvart, 1990):

$$RHC = C(R) + (C^{-} - C(R)\ln(\frac{(3R-1)}{2})$$

Where

Oi = Observed data
Pi = Predicted modeled data
$C(R)$ = the R^{th} highest concentration
C^{-} = the mean of the top R-1 concentrations

The value of R=11 was used here so that C^{-} was the average of the top-ten concentrations, an acceptable basis for evaluation of model performance. Comparison of modeled and observed approaches of the RHC was summarized in Figure 4.5

Results from robust highest concentration indicated that Tier 1 provided the best result in predicting extreme end of NO_2 concentration. Tier 1 performed quite well in predicting the average, 99.5^{th} percentile and also provided optimum results in predicting the upper extreme end statistic as illustrated in Figure. 4.5.

As for ability to predict episode of air pollution, it is found that Tier 1 provided the best result in predicting extreme end of NO_2 concentration. The robust highest concentration of measured data (combining all receptors) was 60.24 $\mu g/m^3$ while predicted results from Tier 1, Tier 2, Tier 3_OLM and Tier 3_PVMRM are 58.26, 37.97, 50.48 and 32.98, respectively.

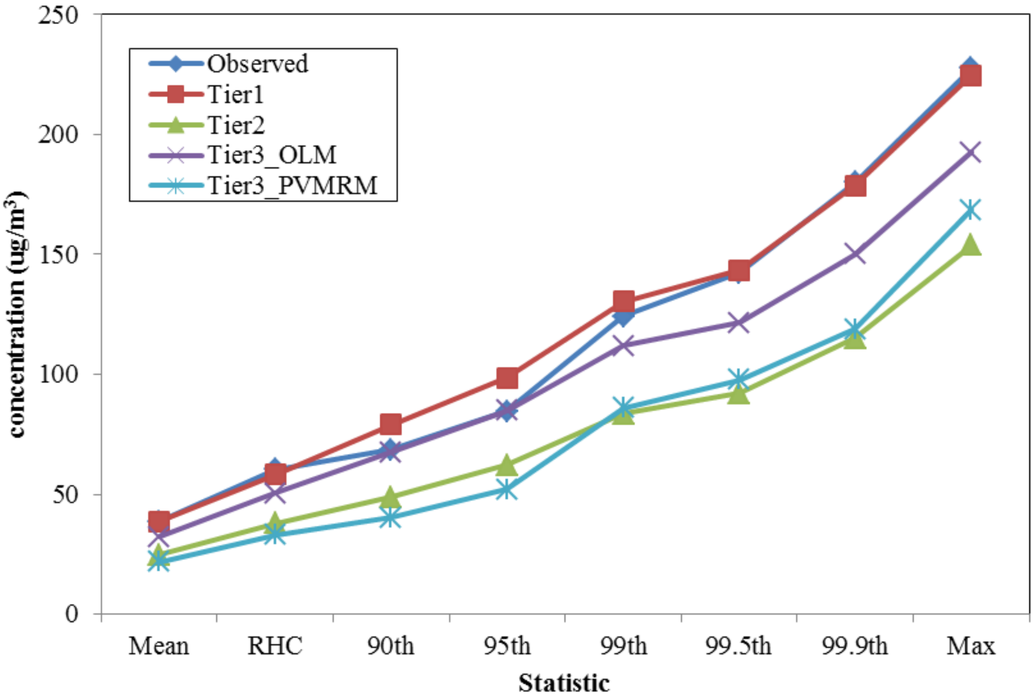


Figure 4.5 Annual mean, maximum, robust highest concentration (RHC) and percentile statistics for modeled and observed NO_2 for all sites.

The maximum ground level concentrations of NO_2 in the modeling domain were also predicted for each tier in the year 2012 to 2013. It should be noted that these values at each receptor (10 monitoring sites) were not exceed the Thai's ambient air quality standards ($NO_2 < 320$ µg/m^3 for 1 hour average). However, the maximum NO_2 concentrations predicted within modeling domain were greater than the Thai ambient standard of NO_2 for every simulated tiers. The maximum ground level concentrations of predicted data (combining all receptors) in Tier 1, Tier 2, Tier 3_OLM and Tier 3_PVMRM for the year 2012 are 4557, 2825, 2521 and 1641 µg/m^3, respectively. While results from Tier 1, Tier 2, Tier 3_OLM and Tier 3_ PVMRM for the year 2013 are 4686, 2905, 2462 and 1538 µg/m^3, respectively. Results found that the maximum ground level concentrations of predicted data for the year 2012 and 2013 were not much different. Therefore, this study period can be used as representative of meteorological characteristics in this area. Spatial distributions of NO_2 simulated map were as presented in Figure 4.6-4.13.

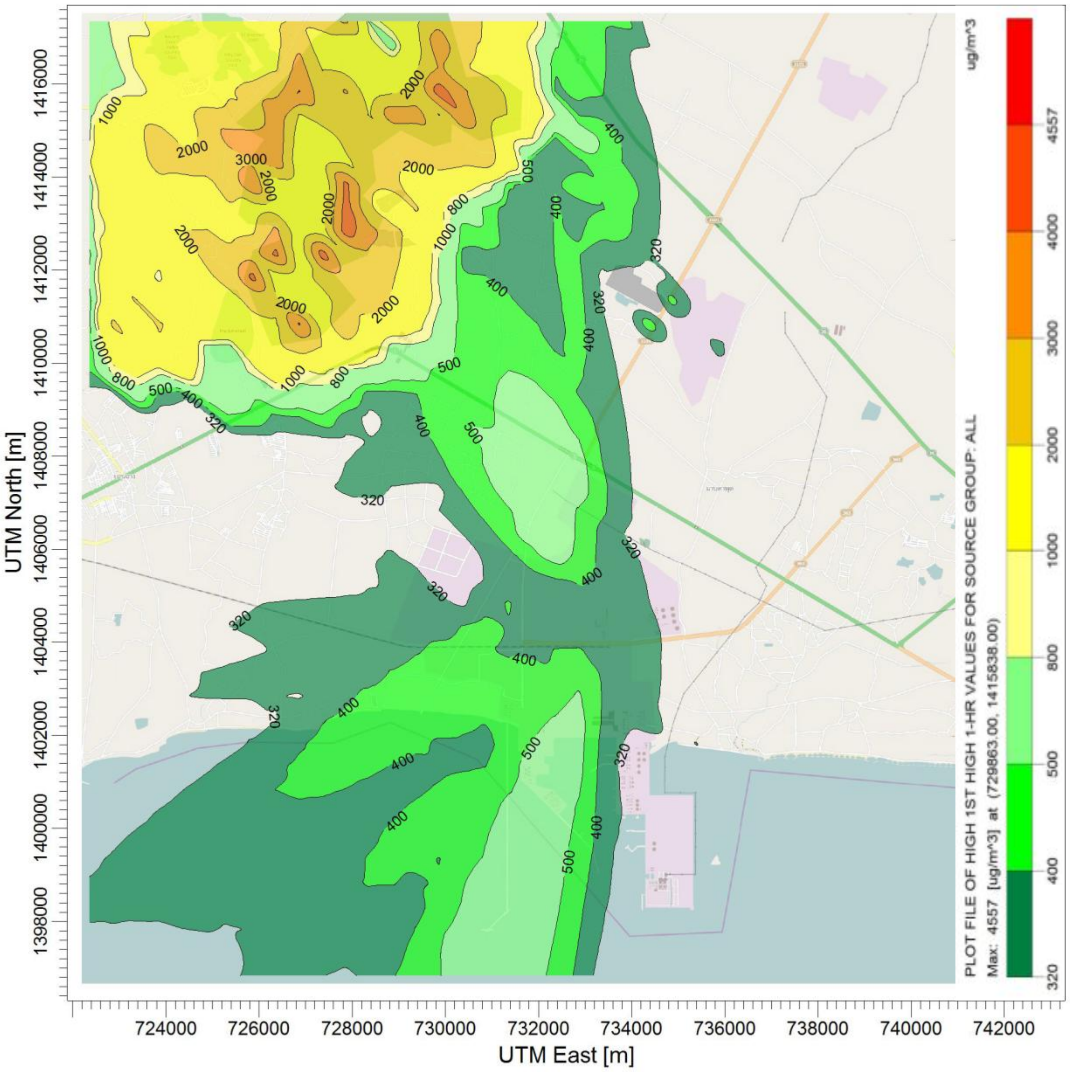


Figure 4.6 Plot file of the 1st highest 1-hour values of Tier 1 in the year 2012.

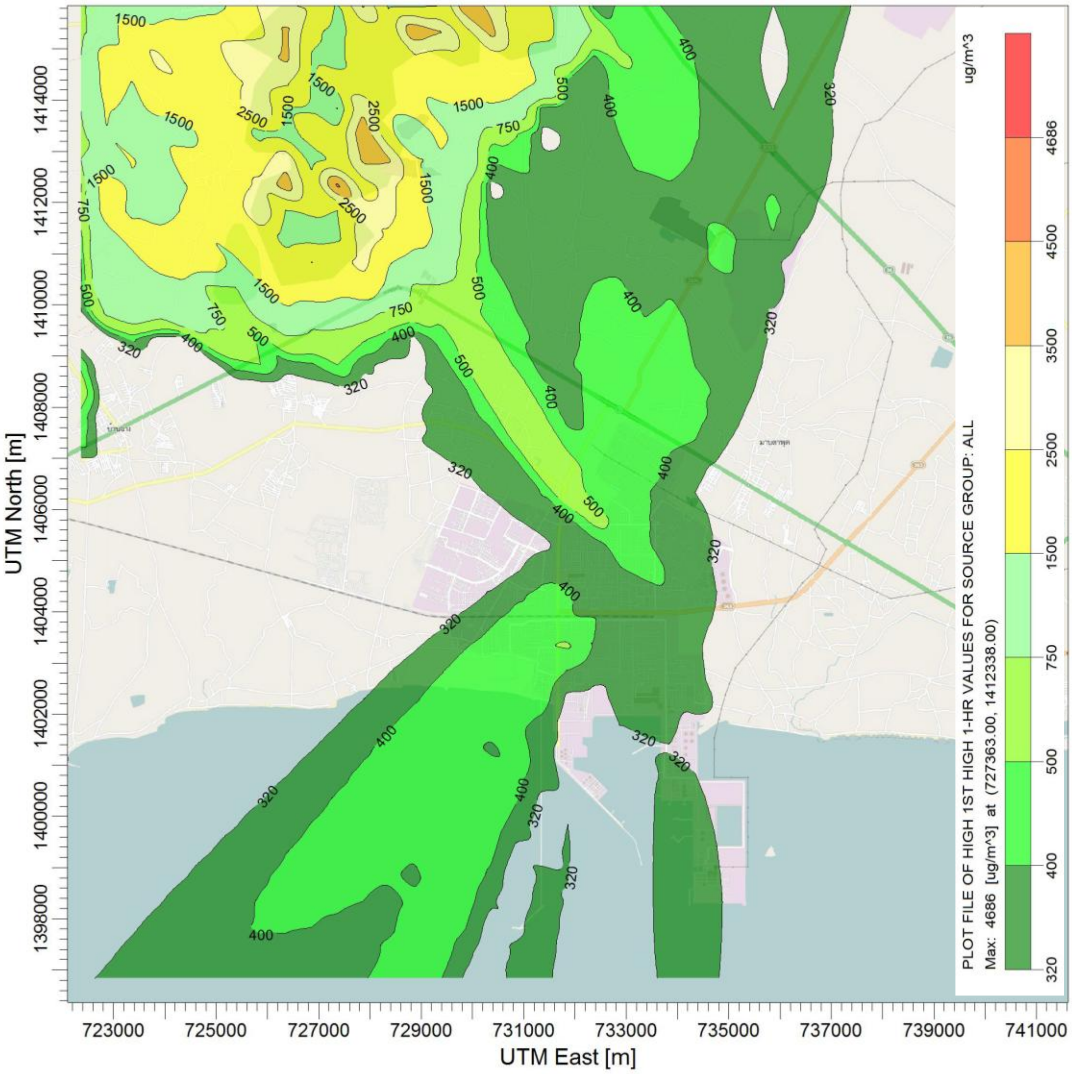


Figure 4.7 Plot file of the 1st highest 1-hour values of Tier 1 in the year 2013.

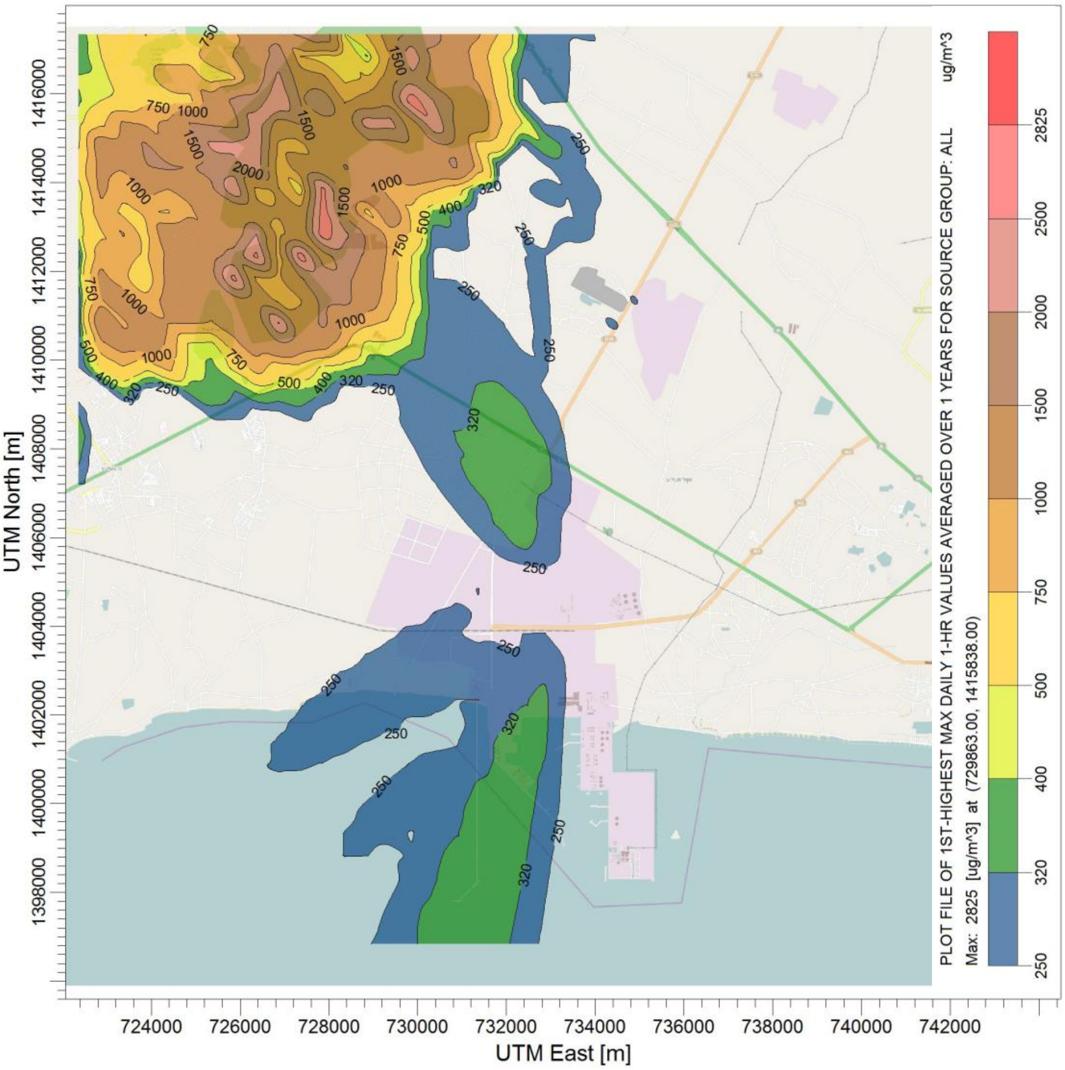


Figure 4.8 Plot file of the 1st highest 1-hour values of Tier 2 in the year 2012.

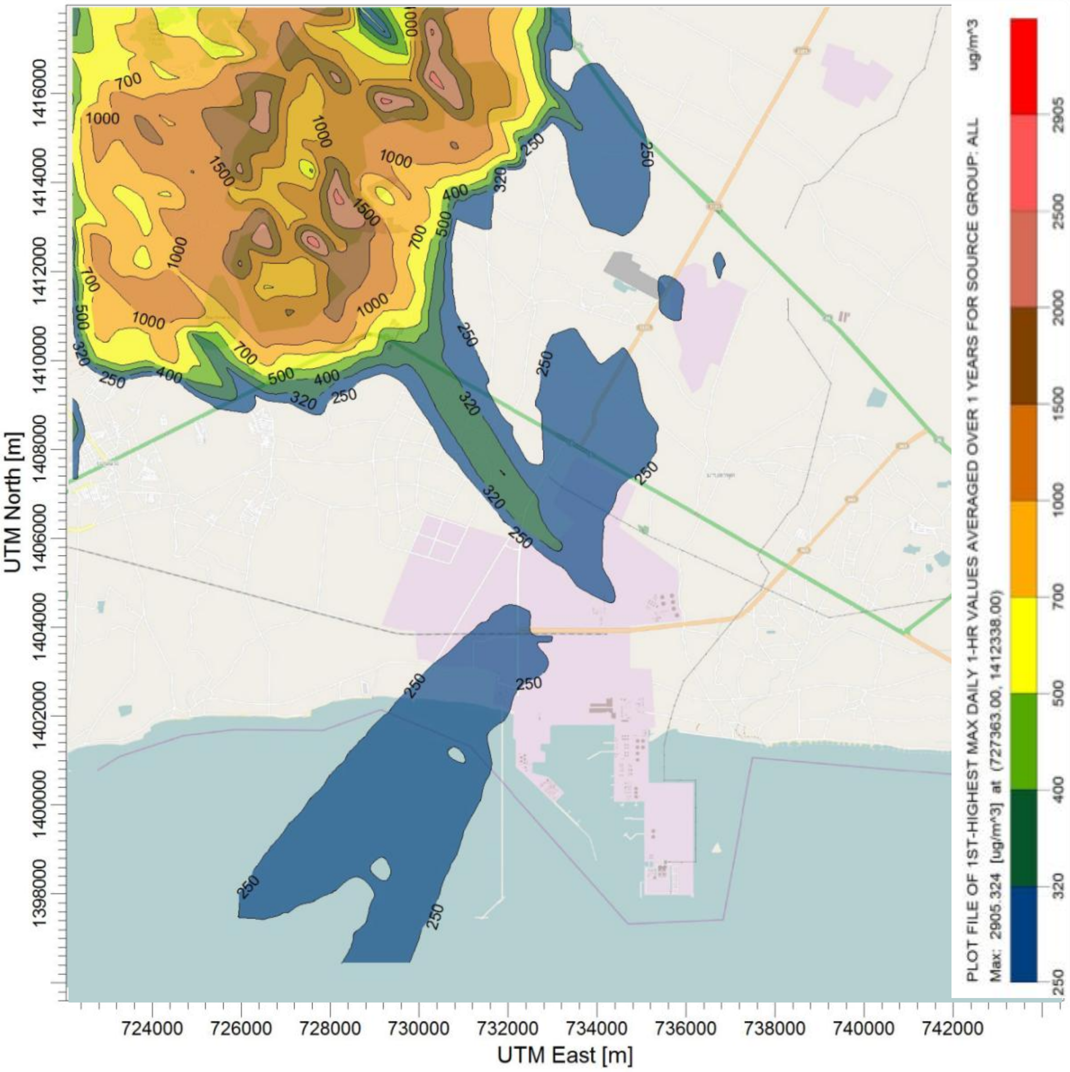


Figure 4.9 Plot file of the 1st highest 1-hour values of Tier 2 in the year 2013.

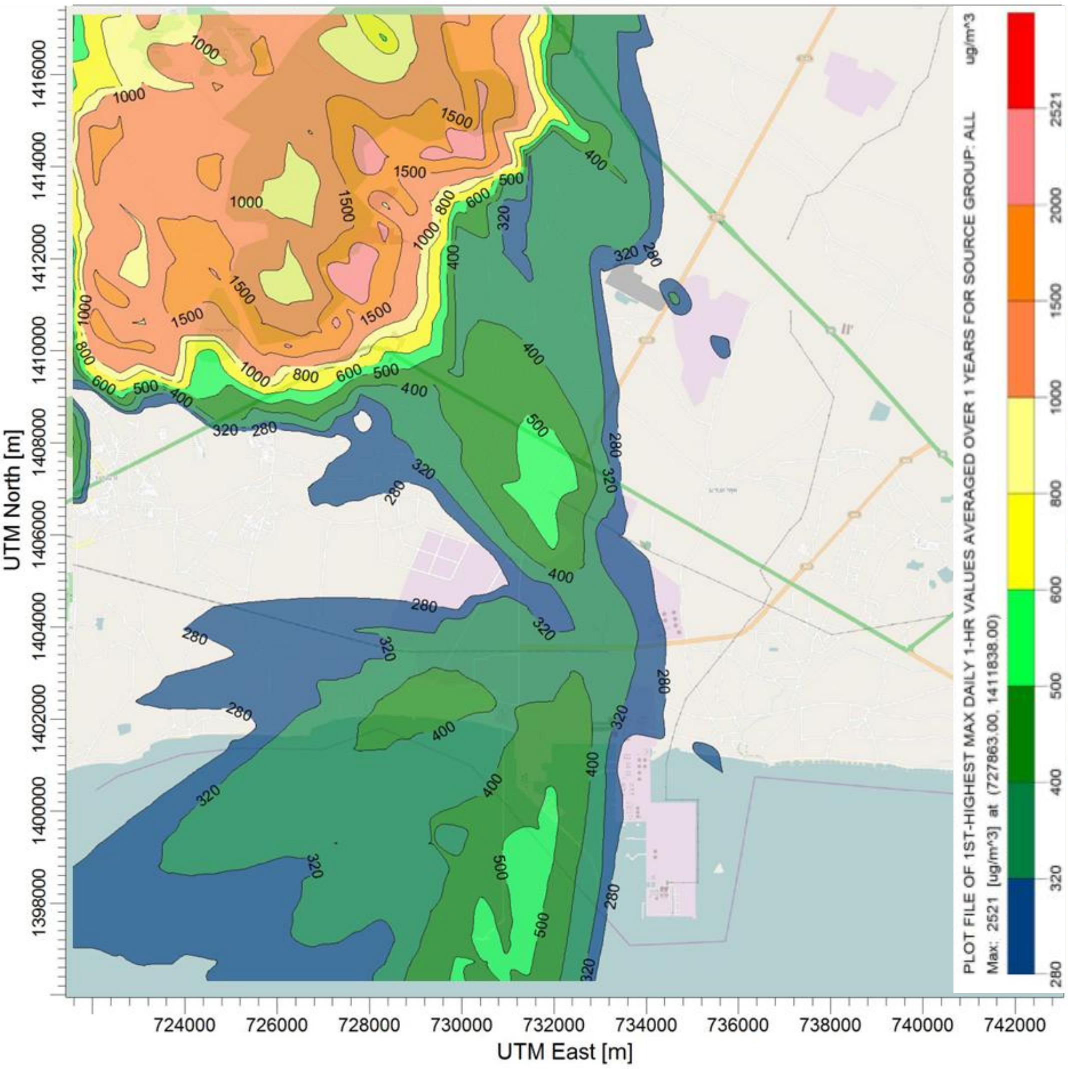


Figure 4.10 Plot file of the 1st highest 1-hour values of Tier 3_OLM in the year 2012.

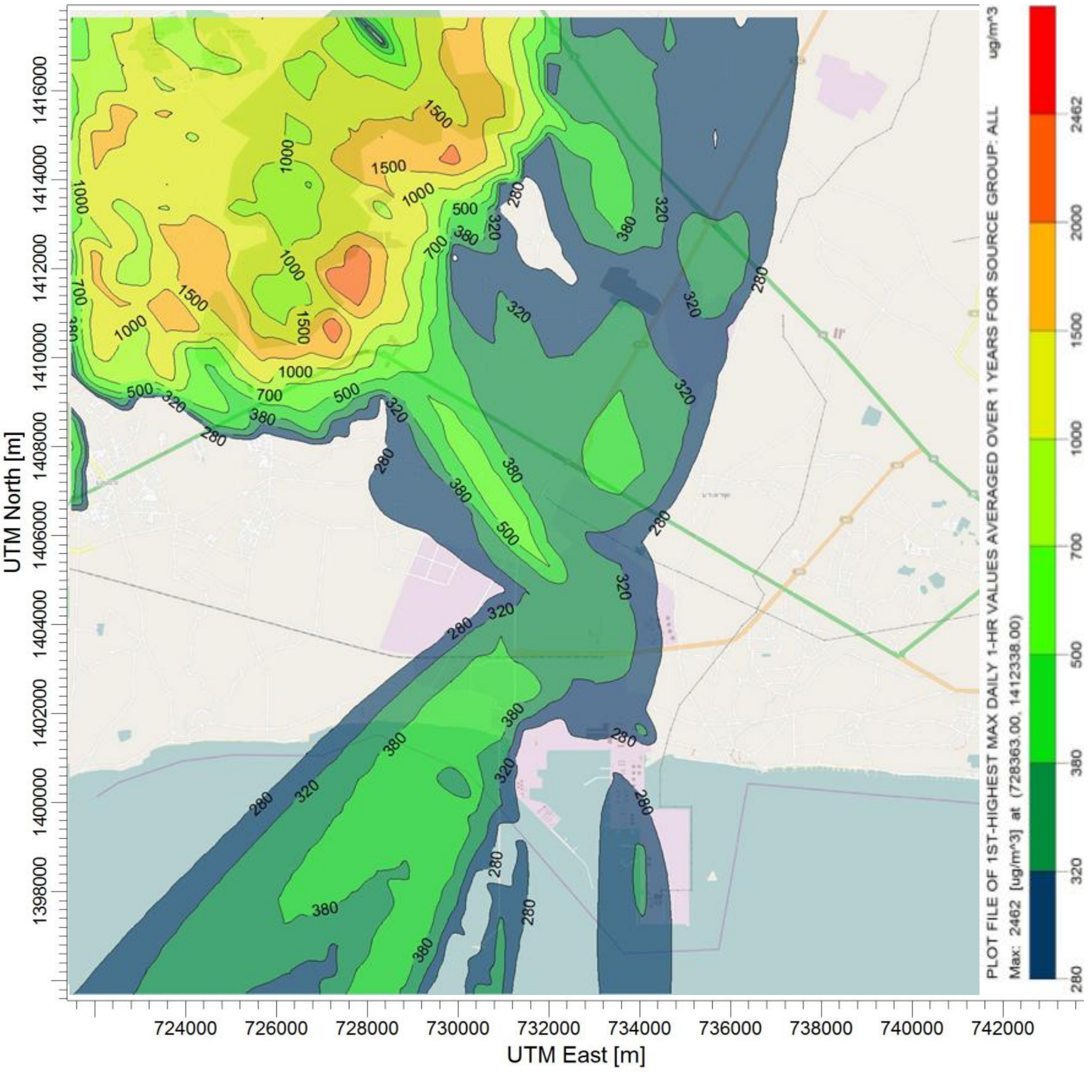


Figure 4.11 Plot file of the 1st highest 1-hour values of Tier 3_OLM in the year 2013.

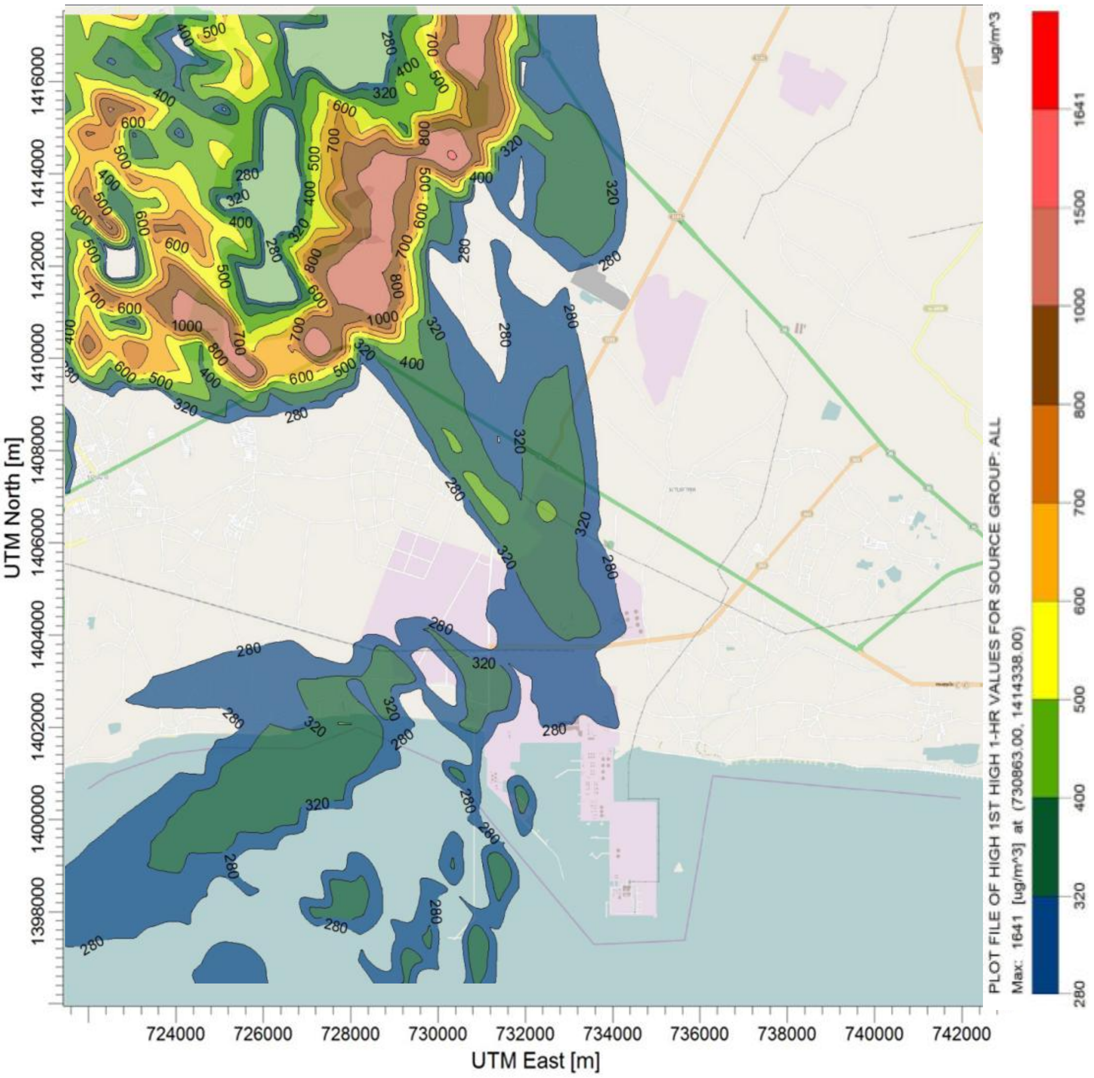


Figure 4.12 Plot file of the 1st highest 1-hour values of Tier 3_PVMRM in the year 2012.

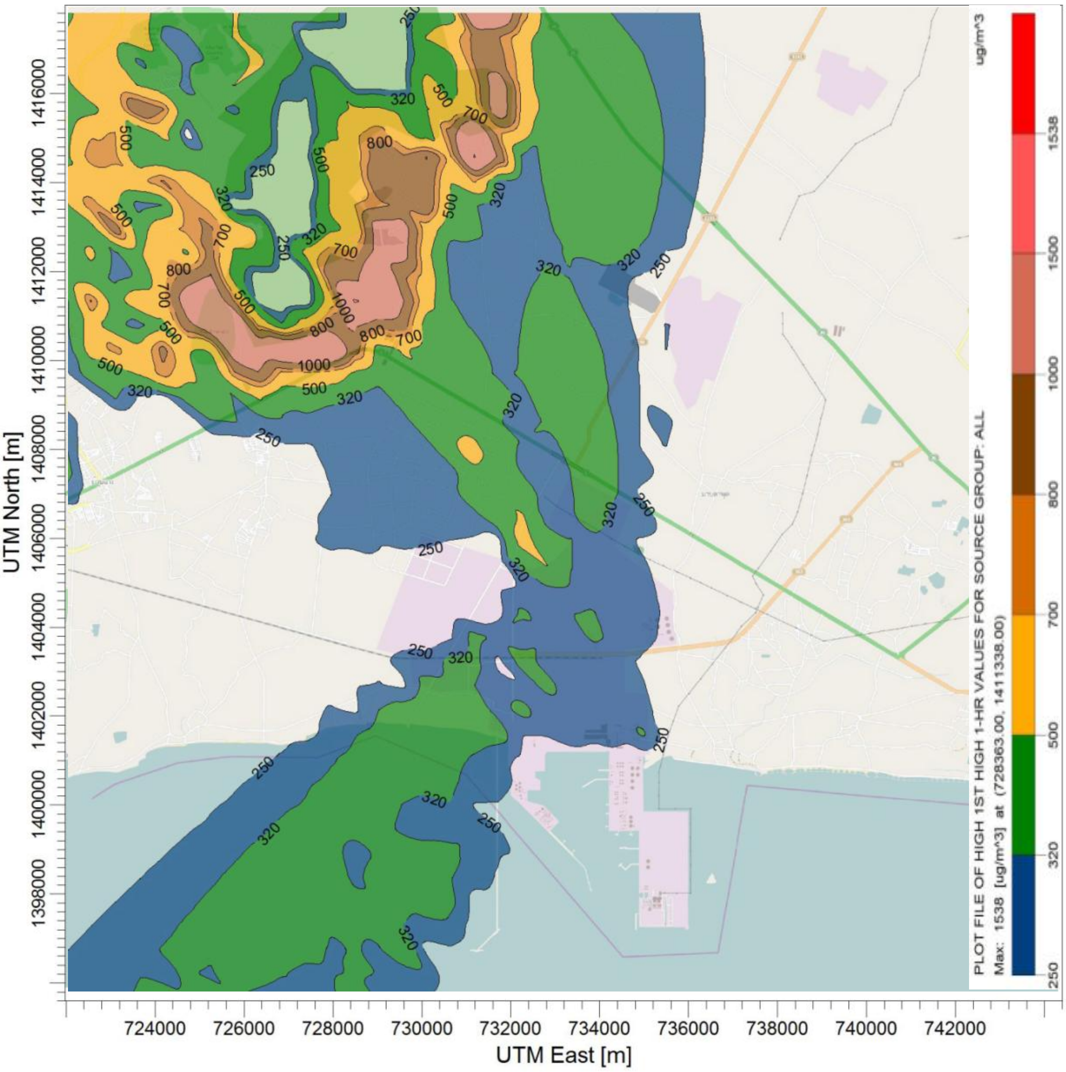


Figure 4.13 Plot file of the 1st highest 1-hour values of Tier 3_PVMRM in the year 2013.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

Maptaphut industrial area (MA), Rayong province in the eastern region is the largest industrial complex in Thailand. There has been concern about many air pollutants over this area including sulfur dioxide (SO_2), particulate matter, volatile organic compounds (VOC) especially nitrogen dioxide (NO_2) are mainly pollutants over this area. In this study, a dispersion study of NO_2 was conducted using the AERMOD model.

The AERMOD modeling system was here applied to predict the dispersion of NO_2 in Maptaphut industrial area (MA), Thailand. The performance evaluation of AERMOD model to predict 1-hour average NO_2 concentrations emitted from total stack in MA are conducted for the year 2012 to 2013 (from 1 January 2012 to 31 December 2013). In this study, measured data of ambient air concentration, obtained from 10 monitoring stations were used in the analysis. For evaluation of model performance, predicted and measured data were sorted (independent of time) and were plotted using a scatter diagram in order to examine the model bias over the concentration distribution. Comparisons of modeled and observed NO_2 concentrations at each site

NO_2 ambient concentration data were predicted using AERMOD model. Three difference tiers approaches of NOx to NO_2 conversion were tested for their performance in predicting NO_2 ambient concentration of this study were summarized as follows. In this study has defined a 3-tier approach to modeling NO_2 concentrations:

Tier 1: Total conversion, or all NOx = NO_2

Tier 2: use NO_2/NOx ratio of 0.60 (Ruangkawsakun and Thepanondh, 2014)

Tier 3: case by case detailed screening method, such as Ozone Limiting Method (OLM) and Plum Volume Molar Ratio Method (PVMRM)

5.1 Application of AERMOD for simulation of NO_2 concentrations in the study area

AERMOD is a steady-state plume model which calculates atmospheric dispersion based on the planetary boundary layer turbulence structure and on some scaling concepts, and can account for both surface and elevated sources. Moreover, it can be used in either simple (flat) or complex terrain scenarios (AERMOD, 2012). In the stable boundary layer, the dispersion is assumed to be Gaussian in both the vertical and the horizontal directions. In the convective boundary layer, the horizontal distribution is assumed to be Gaussian whereas the vertical distribution is described by a bi-Gaussian probability density function. AERMOD uses surface and profile meteorological data obtained from a single meteorological station (Tartakovsky *et al.*, 2013)

The predicted NO_2 concentrations agree well with the measured data, although the model over-estimates the concentration at all monitoring stations. From the simulation, it was found that AERMOD provided more precise results (less bias) when Tier 1 (in which it is assumed that all modeled emissions of total NOx have been fully converted to NO_2) approach was used in model simulation.

In summary, the result indicated that AERMOD performed very satisfactorily in predicting the average concentration, and in modeling the maximum values and the extreme end statistics, particularly when Tier 1 was applied.

The Tier 1 approach (100% conversion of NO_x to NO_2) resulted to the highest predictions of NO_2 concentrations. Overall predicted results, obtained from Tier 1 were less bias with those measured results as compared with other tier and may be considered as appropriate calculation for prediction of annual average concentration. Therefore, tier 1 could be considered as the best choice to determine the maximum ground level concentration of NO_2 in this study. Model verification revealed the fact that emission inventory of oxide of nitrogen used in this study was under estimated. NO_2 concentrations are contributed by both industrial and mobile source emissions. However, lack of emission data of mobile sources which generally occurred in many studies given constraint in applying air dispersion model in such areas. Effort in using the background concentration of NO_2 to compensate mobile source contribution still cannot overcome this problem. In the present of O_3 data, behavior of NO_2 should be more refined. Therefore, Tier 3 which involve chemistry of O_3 and NOx has been developed to explain characteristic of atmospheric chemistry of these pollutants once emitted from emission sources. However, this latest tier cannot perform well when emissions of NOx are under estimated. Therefore, availability of input data is the most crucial factor when considering types and options of model simulated in each area.

5.2 Recommendations for further study

AERMOD is the U.S. EPA's recommended model for evaluating near-field impacts, defined as occurring within 50 km of the sources, caused by pollutant emission sources. The results of this study suggested that Tier 1 is the best choice to determine the maximum ground level concentration of NO_2 in this study for the prediction in Maptaphut industrial area of Thailand. Therefore, the performance evaluation of AERMOD model to predict 1-hour average NO_2 concentrations emitted from total stack in this area should be focused on Tier 1 only. In addition, AERMOD users should also be cautious when using ozone data sets that do not contain complete hourly data. It is also important that the relative emission rate of the sources modeled can affect whether or not the use of Tier 3 methodologies will result in considerably lower AERMOD-predicted NO_2 concentrations compared with the Tier 1 full conversion assumption. In addition, availability of input data is the most crucial factor when considering types and options of model simulated in each area. Other recommendation for further study include studying on grid spacing of the model which will provide appropriate result in term of both accuracy and simulated run time of the model in this area.

REFERENCES

Arya, S., (1999). *Air pollution meteorology and dispersion*, Oxford University Press, New York.

Allen, J. (2002). *Highways of a Global Traveler: Tracking Tropospheric Ozone.* NASA Earth Observatory. Retrieved Marc 5, 2014, from: http:// www. earthobservatory. nasa.gov/Study/GlobalTraveler/.

Alen, E., & Schuler, P.E. (2004). *Sensitivity analysis of PVMRM and OLM in AERMOD.* Final Report. Alaska Department of Environmental Conservation. Alaska DEC Contract No. 18-8018-04.

Bange, P., Jannsen, L.H.J.M., Nieuwstadt, F.T.M., Visser, H. and Erbrink, J.J. (1991). Improvement of the modeling of daytime nitrogen oxidation in plumes by using instantaneous plume dispersion parameters. *Atmos. Environ.* 25(10): 2321-2328.

Beltagui, SA., Kenbar, A.M.A., & McCallum, N.R.L. (2010). *NOx Generation and Control in Confined Swirling* Flames – *Review and Parametric Study*. HTFS Paper No RS 827.

Cox,W., and Tikvart, J. (1990). A statistical procedure for determining the best performing air quality simulation model. *Atmos. Environ.* 24:2387–2395

Clean Air Strategic Alliance (CASA). (2004). *NITROGEN OXIDES (NOx).* Retrieved March 11, 2014, from: http://www.dwb.unl.edu/teacher/nsf/c09/c09links/ www.casahome.org/nitrogen.htm.

Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D. and Brode, R.W. (2005). AERMOD: a dispersion model for industrial source applications. Part I: General model

Chusai, C., Manomaiphiboon, K., Saiyasitpanich P., & Thepanondh, S. (2012). NO_2 and SO_2 dispersion modeling and relative roles of emission sources over Map Ta Phut industrial area, Thailand. *Air Waste Manage. Assoc.* 62(8):932–945.

Dolwick, P., Akhtar, F., Baker, K.R., Possiel, N., Simon, H. and Tonnesen, G. (2015). Comparison of background ozone estimates over the western United States based on two separate model methodologies. *Atmos. Environ.* 109: 282-296.

Faulkner, W.B., Shaw, B.W., and Grosch, G.T. (2008). Sensitivity of Two Dispersion Models (AERMOD and ISCST3) to Input Parameters for a Rural Ground-Level Area Source. *Air Waste Manage. Assoc*. 58(10):1288-1296.

Glandt, E.D., Klein, M.T., and Edgar, T.F. (1995). *Air Pollution Control Engineering* (2nd ed.). Singapore: McGrawHill.

Holmes, N.S. and Morawska, L. (2006). A review of dispersion modeling and its application to the dispersion of particles: an overview of different dispersion models available. *Atmos. Environ*. 40: 5902–5928.

Hesselmann, G. and Rivas, M. (2010). *What are the main NOx formation processes in combustion plant?.* Retrieved May 18, 2014, from: http://www.handbook.ifrf.net/handbook/cf.html?id=66.

Huertas, J.I., Huertas, M.E., Izquierdo, S., and González, E.D. (2012). Air quality impact assessment of multiple open pit coal mines in northern Columbia. *Environ. Manage*. 93:121–129.

Hendrick, E.M., Tino, V.R., Egan, B.A., & Hanna, S.R. (2013). Evaluation of NO_2 predictions by the plume volume molar ratio method (PVMRM) and ozone limiting method (OLM) in AERMOD using new field observations. *Air Waste Manage. Assoc.* 63(7), 844.

Industrial Estate Authority Of Thailand (IEAT). (2012). *The Map Ta Phut Industrial Port.* Retrieved June 11, 2014, from: http://www.ieat.go.th/ieat/index.php/en/investment/map-ta-phut-industrial-port/about-map-ta-phut-industrial-port#the-map-ta-phut-industrial-port.

Kuma, A., Dixit, S., Varadarajan, C., Vijayan, A. and Masuraha, A. (2006). Evaluation of the AERMOD Dispersion Model as a Function of Atmospheric Stability for an Urban Area, E. Progress, Editor 25(2).

Karamchandani, P., Koo, A., and Christian, S. (1998). Reduced gas-phase kinetic mechanism for atmospheric plume chemistry. *Environ. Sci. Technol.* 32(11): 1709-1720.

Long, G.E. (2004). An analysis of AERMOD sensitivity to input parameters in the San Francisco Bay Area. *13th Conference On the Applications of Air Pollution Meteorology with the Air and Waste Management Assoc,* USA

Lyatt, J. (2008). *Atmospheric Chemistry.* Retrieved June 9, 2014, from: http://www.faculty.washington.edu/jaegle/558/.

Lakes Environmental Software. (2013). *AERMOD Tech Guide.* Retrieved June 9, 2014, from: http://www.weblakes.com/guides/aermod/section2/index html.

Miller, J. A. and Bowman, C. T. (1989). Mechanism and Modeling of Nitrogen Chemistry in Combustion Progress in Energy and Combustion Science. 15. pp. 287-338.

Ministry for the Environment Manatū Mō Te Taiao. (2009). *Nitrogen dioxide (NO_2).* Retrieved June 15, 2014, from: http://www.mfe.govt.nz/issues/air/breathe/ nitrogen-dioxide. html.

Ma, J., Yi, H., Tang, X., Zhang, Y., Xiang Y. and Pul, Li. (2010). Application of AERMOD on near future air quality simulation under the latest national emission control policy of China: A case study on an industrial city. *Environ. Sci.* 25(8): 1608–1617

MTPIE. (2013). *Main industries in the Maptaphut Industrial area*. Retrieved April 2, 2015, from: http://www.iceh.or.th/iceh/img_news%20activity/_56%20 June18/MTP-02.pdf.

Podrez, M. (2015). An update to the ambient ratio method for 1-h NO_2 air quality standards dispersion modeling. *Atmos. Environ.* 103:163-170.

Paine, R. J. (1987). User's guide to the CTDM meteorological preprocessor (METPRO) Program. *Atmos. Sci.* USA.

Patel, V.C., and Kumar, A. (1998). Evaluation of three air dispersion models: ISCST2, ISCLT2, and SCREEN 2 for mercury emissions in an urban area. *Environment Monitoring Assess. 53*:259–277.

Paine, R.J. (2003). AERMOD: Latest Features and Evaluation Results: EPA-454/R-03-003. United States Environmental Protection Agency. USA.

Perry, S.G. Cimorelli, A.J., Paine R.J., Brode, R.W., Weil, J.C., Venkatram, A., Wilson, R.B., Lee, R.F., and Peters, W.D. (2005). AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *Appl. Meteorol.* 44:694–708.

Rethinking the Ozone Problem in Urban and Regional Air Pollution. (1991). National Academy of Sciences, ISBN 0-309-56037-3.

Rana, S.V.S. (2005). *Essentials of Ecology and Environmental Science, second ed*, Prentice Hall of India Private Limited, New Delhi.

Ruangkawsakun, J., and Thepanondh, S. (2014). Air Assimilative Capacity for Sulfur Dioxide and Nitrogen Dioxide: Case Study the Eastern Region of Thailand. *Environ. Sci. and Develop.* 5(2):187-190.

Silverman, K.C. and Tell, J.G. (2007). Comparison of the industrial source complex and AERMOD dispersion models: Case study for human health risk assessment. *Air Waste Manage. Assoc.* 57:1439–1446.

Seangkiatiyuth, K., Surapipith, V., Tantrakarnapa, K. and Lothongkum, A.W. (2011). Application of the AERMOD modeling system for environmental impact assessment of NO_2 emissions from a cement complex. *Environ. Sci.* 23(6): 931–940.

Schroeder, A.J. (2012). AERMOD Tiering Approach Case Study for 1-Hour NO_2. TRINITY CONSULTANTS. Paper No. 481.

Tartakovsky, D., Broday, D. and Stern, E. (2013). Evaluation of AERMOD and CALPUFF for predicting ambient concentrations of total suspended particulate matter (TSP) emissions from a quarry in complex terrain. *Environmental Pollution 179*, 138-145.

U.S. Environmental Protection Agency (US. EPA). (2004). *DESCRIPTION OF MODEL FORMULATION.* (EPA-454/R-03-004), 13, Office of Air Quality Planning and Standards. Emissions Monitoring and Analysis Division Research Triangle Park, NC.

U.S. Environmental Protection Agency (US. EPA). (2004). User’s Guide for the AMS/EPA Regulatory Model-AERMOD. EPA-454/B–03–001. Retrieved June 17, 2014, from: http://www.epa.gov/scram001/7thconf/aermod/aermodugb.pdf.

U.S. Environmental Protection Agency (US. EPA). (2004). User's Guide for the AERMOD Terrain Preprocessor (AERMAP). Office of Air Quality Planning and Standards, Research Triangle Park, USA.

U.S. Environmental Protection Agency (US. EPA). (2004a). User's Guide for the AERMOD Meteorological Preprocessor (AERMET), USA.

U.S. Environmental Protection Agency (US. EPA). (2004b). User's Guide for the AERMOD Meteorological Preprocessor (AERMET). Office of Air Quality Planning and Standards, Research Triangle Park, NC, USA.

U.S. Environmental Protection Agency (US. EPA). (2004c). User's guide for the AMS/EPA Regulatory Model –AERMOD, USA.

U.S. Environmental Protection Agency (US. EPA). (2005). National Emissions Inventory 2005, USA.

U.S. Environmental Protection Agency (US. EPA). (2012). *Health and Environmental Effects on* NO_2. Retrieved June 29, 2014, from: http://www.epa.gov/airtrends/aqtrnd95/no2.html.

U.S. Environmental Protection Agency (US EPA). (2012). *Ground-level Ozone*. Retrieved June 8, 2014, from: http://www.epa.gov/air/ozonepollution/basic.html.

U.S. Environmental Protection Agency (US EPA). (2013). *Ground level ozone*. Retrieved March 20, 2014, from http://www.epa.gov/air/ozone pollution/basic.html.

U.S. Environmental Protection Agency (US EPA). (2014). *Definition of air pollution.* Retrieved May 5, 2014, from: http://www.epa.vic.gov.au/air/aq4kids/pollution.asp.

Venkatram, A. (1981). Model predictability with reference to concentrations associated with point sources. *Atmos. Environ.* 15(9): p. 1517-1522.

Venkatram, A., Brode, R.W., Cimorelli, A.J., Lee, R.F., Paine, R.J., Perry, S.G., Peters, W.D., Weil, J.C., and Wilson, R.B. (2001). A complex terrain dispersion model for regulatory applications. *Atmos. Environ*. 35:4211–4221.

Willmott, C. and Wicks, D,E. (1985). An empirical method for the spatial interpolation of monthly precipitation within California. *Physical Geography 1*, 59–73.

Wroclawska, P. (n.d.). *Nitrogen oxides in combustion processes*. Instytut Techniki Cieplnej i Mechaniki Płynów. Retrieved June 24, 2014, from: http://www.fluid.wme.pwr.wroc.pl/~spalanie/dydaktyka/combustion_en/NOx/NOx_formation.pdf.

Zhang, R., Lei, W., Tie, X., & Hess, P. (2004). *Industrial emissions cause extreme urban ozone diurnal variability*. PNAS 101(17),6346 – 6350.Doi:10.1073/ panas. 0401484101

APPENDICES

APPENDIX A
DETAIL OF EMISSION SOURCES

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013

PLANT NAME	**NO.**	**COORDINATES**		**STACK**		**EXIT TEMP. (K)**	**EXIT VELOSITY (m/s)**	**EMISSION RATE (g/s) NOx**
		E (m.)	**N (m.)**	**Height (m)**	**Dia. (m)**			
1. PTT	1	732800	1405000	42	1.5	430.15	7.95	2.0519
Global	2	732800	1405003	42	1.5	430.15	7.95	2.0519
Chemical	3	732800	1405021	42	1.5	430.15	7.95	2.0519
(Branch 2)	4	732800	1405024	42	1.5	430.15	7.95	2.0519
	5	732800	1405042	42	1.5	430.15	7.95	2.0519
	6	732800	1405045	42	1.5	430.15	7.95	2.0519
	7	732800	1405063	42	1.5	430.15	7.95	2.0519
	8	732800	1405096	42	1.5	430.15	7.95	2.0519
	9	732800	1405000	42	1.5	430.15	7.95	2.0519
	10	732783	1405332	60.5	1.25	430.15	5.71	0.7792
	11	732783	1404983	52.4	1.05	469.15	5.58	0.5026
	12	732780	1404807	30	4.2	442.15	19.12	14.47
	13	732836	1404859	30	2.8	446.15	9.3	2.02
		732861	1404775	30	4.2	442.05	19.14	14.46
		732500	1404829	30	3.6	379.1	13.69	8.66
		732500	1404849	30	3.6	379.1	13.69	8.66
		732459	1405270	35	3.26	399	17.1	2.44
		732615	1405270	35	3.26	399	17.1	2.44
		732703	145270	35	3.26	399	17	2.44
		732562	1405231	35	1.8	471	10.5	1.5
		732562	1405298	35	1.8	471	10.5	1.5
	14	732861	1404775	30	4.2	442.05	19.14	14.46
	15	732500	1404829	30	3.6	379.1	13.69	8.66
	16	732500	1404849	30	3.6	379.1	13.69	8.66
	17	732459	1405270	35	3.26	399	17.1	2.44
	18	732615	1405270	35	3.26	399	17.1	2.44
	19	732703	145270	35	3.26	399	17	2.44
	20	732562	1405231	35	1.8	471	10.5	1.5
	21	732562	1405298	35	1.8	471	10.5	1.5

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	NO.	COORDINATES		STACK		EXIT TEMP. (K)	EXIT VELOSITY (m/s)	EMISSION RATE (g/s) NOx
		E (m.)	N (m.)	Height (m)	Dia. (m)			
2. Star	1	734749	1404787	63.2	3	443	7.7	2
Petroleum	2	734712	1404821	54	2	443	7.7	0.9
Refining	3	734608	1404864	65	3.1	461	7.3	2.83
Public	4	734486	1404955	36.2	1.6	654	13.7	0.73
Company	5	734521	1404926	36.2	1.6	681	6	0.92
Limited	6	734345	1404999	73.8	3.2	551	19.2	22.07
	7	734278	1405078	70.1	2.2	840	9.3	0.32
	8	734773	1404658	32.4	1.5	449	9.6	1.5
	9	734764	1404636	32.4	1.5	449	9.6	1.5
	10	734867	1404644	21.7	3	477	15.9	5.75
	11	734867	1404621	21.7	3	477	15.9	5.75
	12	734450	1405285	32.5	0.58	654	15	0.125
	13	734445	1404568	32.4	1.52	450	13.8	2.2
3. PTT	1	733408	1403127	52.61	1.44	488.15	8.28	0.57
Global	2	733410	1403159	52.61	1.44	595.15	5.87	0.53
Chemical	3	733397	1403082	35.7	1.44	467.15	9.54	0.8
(Branch 4)	4	733397	1403048	84	3.42	507.75	4.17	3.77
	5	733399	1402968	45	1.44	607.15	10.02	1.13
	6	733399	1402913	37.5	1.88	585.15	8.05	0.99
	7	733399	1402873	40.84	2.03	566.15	9.12	1.74
	8	733399	1402863	32.06	1.28	643.15	7.9	0.42
	9	733401	1402844	46.05	2.66	527.15	8.14	3.22
	10	733399	1402940	36.28	1.74	625.15	8.91	1.08
	11	733333	1403330	30	1.35	461.15	9.74	1.06
	12	733409	1403101	34.8	0.89	476.15	6.42	0.15
	13	733409	1403203	30	0.94	556.15	8.75	0.21
4.Peroxythai	1	732192	1405866	20	0.6	523	10	0.607
5.Siam	1	733824	1404505	15	1	453	6.82	0.7
synthetic								
Latex								
6. Siam	1	733766	1404568	11.76	0.61	757	4.68	0.37
Polystylene	2	733766	1404578	15.58	0.7	1273	27.49	3.98
7. Aditya	1	732114	1403435	30	0.75	533	3.78	0.2
Birla								
Chemicals								
8. HMT	1	731869	1403329	20	0.45	582	4.18	0.022
Polystylene	2	731869	1403323	22	0.6	489	3.25	0.035

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	**NO.**	**COORDINATES**		**STACK**		**EXIT TEMP. (K)**	**EXIT VELOSITY (m/s)**	**EMISSION RATE (g/s) NOx**
		E (m.)	**N (m.)**	**Height (m)**	**Dia. (m)**			
9. ThaiMFC	1	731802	1403380	20	0.485	608	6.48	0
	2	731802	1403390	30	0.508	323	0.02	0
	3	731802	1403400	30	1.2	343	14	0
10.Tantalum	1	733068	1405787	25	0.42	523	14	0.045
	2	733069	1405788	25	0.42	523	14	0.045
	3	733063	1405857	15	0.23	523	14	0.008
	4	732580	1405857	15	0.23	523	14	0.008
	5	732995	1405835	30	0.2	623	12	0.061
	6	732994	1405840	30	0.2	623	12	0.061
11.NOVA	1	732459	1403198	35	1.8	573	2.95	1.3335
steel								
(Nikko)								
12. Siam	1	733827	1402100	63	1.8	473	3.26	2.66
Construction	2	733845	1402234	20	4	383	17.9	0.72
Steel	3	733864	1402220	20	3.7	340	20.76	0
13. Siam	1	733880	1401810	20	4	382	6.85	0.72
Yamato	2	733857	1401930	63	1.8	-	5.18	2.66
Steel								
14. Laperth	1	733100	1405700	16	0.3	353	15	0
	2	733110	1405690	20	0.35	398	4	1.05
	3	733120	1405680	30	0.25	313	19	0
15. PTT	1	733413	1404398	33.5	1.5	403-447	10-20	0.86-1.72
Global	2	733411	1404393	33.5	1.5	403-447	10-20	0.86-1.72
Chemical	3	733413	1404376	33.5	1.5	403-447	10-20	0.86-1.72
(Branch 3)								
Plant 1	4	733411	1404371	33.5	1.5	403-447	10-20	0.86-1.72
	5	733413	1404354	33.5	1.5	403-447	10-20	0.86-1.72
	6	733411	1404349	33.5	1.5	403-447	10-20	0.86-1.72
	7	733413	1404331	33.5	1.5	447	26.45	3.59
	8	733411	1404326	33.5	1.5	447	26.45	3.59
	9	733413	1404309	33.5	1.5	447	26.45	3.59
	10	733411	1404243	33.5	1.5	403-447*	10-20*	0.86-1.72
	11	733411	1404238	33.5	1.5	403-447*	10-20*	0.86-1.72
	12	733411	1404300	15	0.63	447	6.5	0.12
Plant 2	1	733416	1404298	46.5	1.5	437.9	28.5	1.72

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	**NO.**	**COORDINATES**		**STACK**		**EXIT TEMP. (K)**	**EXIT VELOSITY (m/s)**	**EMISSION RATE (g/s) NOx**
		E (m.)	**N (m.)**	**Height (m)**	**Dia. (m)**			
	2	733416	1404290	46.5	1.5	437.9	28.5	1.72
	3	733416	1404282	46.5	1.5	437.9	28.5	1.72
	4	733416	1404273	46.5	1.5	437.9	28.5	1.72
	5	733416	1404265	46.5	1.5	437.9	28.5	1.72
	6	733416	1404257	46.5	2.0x 1.26	403	13.4	1.25
	7	733300	1404800	40	1	480	45	1.97
Plant 3	1	733600	1404164	46.5	1.5	403-447	10-20*	0.86-1.72
	2	733600	1404159	46.5	1.5	403-447	10-20*	0.86-1.72
	3	733600	1404142	46.5	1.5	403-447	10-20*	0.86-1.72
	4	733600	1404137	46.5	1.5	403-447	10-20*	0.86-1.72
	5	733600	1404120	46.5	1.5	403-447	10-20	0.86-1.72
Butadiene	1	733120	1404210	30	0.9	636	21	0.65
and Butene-1	2	733130	1404210	30	0.9	636	21	0.65
16. Thai	1	734277	1403244	30	0.98	473	4.1	0.84
Shinkong	2	734277	1403249	30	0.98	473	4.1	0.84
17. TPT	1	733335	1402885	80	3	423	12.42	4.4458
petrochemi-								
cal								
18.Indodama	1	734023	1403253	35	3	465	1.62	0.619
polyester	2	733963	1403203	35	1.45	493	2.61	0.466
	3	734003	1403203	35	1.2	481	12.65	1.334
	4	733893	1403078	35	1.45	476	11.12	1.035
	5	733873	1403038	35	1.45	493	5.97	1.064
	6	734103	1401968	25	2.364	413.15	12.33	2.223
19. PTT	1	734420	1401968	140	4.5	493	12.5	30
Global	2	734461	1402131	60	2.5	453	18.9	6
Chemical	3	734461	1402153	60	2.5	453	18.9	6
(Branch 6)	4	734461	1402175	60	2.5	453	18.9	6
	5	734415	1401793	61	1.7	483	7.7	1.07
	6	734468	1401928	60	2.4	448	13.7	4.45
	7	734576	1401408	12	0.95	396	12.4	0.22
	8	734384	1402181	100	1.66	453	11	2.4
	9	734491	1401719	80	1.2	453	9.8	0.933
20.Vinythai	1	733100	1404950	40	1.65	423.15	5.8	1.44
(PVC Plant)	2	733100	1404960	40	1.65	423.15	5.8	1.44
	3	733100	1404900	40	0.55	317.15	7.7	0.11

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	NO.	COORDINATES		STACK		EXIT TEMP. (K)	EXIT VELOSITY (m/s)	EMISSION RATE (g/s) NOx
		E (m.)	N (m.)	Height (m)	Dia. (m)			
	4	733100	1404925	40	0.55	317.15	7.7	0.13
	5	733500	1405040	20	0.4	306	16.7	0
	6	733500	1405045	20	0.4	338.15	16.7	0
	7	733500	1405030	20	0.6	300.15	18.1	0
	8	733500	1405020	25	1.43	338.15	21.6	0.84
	9	733500	1405025	25	2.592	338.15	21.6	1.36
	10	733500	1405010	25	0.6	338.15	23.4	0
	11	733500	1405015	25	0.6	338.15	21.9	0
	12	733500	1405000	35	1.8	338.15	6.2	0
	13	733750	1405005	35	1.8	338.15	6.2	0
	14	733320	1405302	40	0.8	363	7.7	0.48
21.NFC	1	733070	1402618	36	2.5	329	7.8	0.19
fertilizer	2	733056	1402907	38	4.5	327	3	0.2382
	3	733056	1402904	37	2.65	332	17	0.1979
	4	733056	1402943	35	0.6	353	1.11	0
	5	733056	1402873	51.5	0.65	378	7.7	0.0052
	6	733095	1403067	23	2.25	433	13.1	1.424
	7	733015	1402585	30	0.5	363	23.4	0
Sulphuric	8	732954	1402914	75	2.4	355	7.6	0
acid plant	9	732954	1402899	75	2.4	355	7.6	0
22. PPG	1	733262	1405884	20	0.975	952	6.45	0.0007
Siam Silica	2	733261	1405882	20	0.975	943	6.15	0.001
	3	733261	1405881	12	0.075	436	3.61	0
	4	733261	1405906	8	0.6	470	8.91	0.0023
	5	733221	1405887	22	0.88	361	16.16	0.171
	6	733201	1405896	3	0.2	311	25.87	0
	7	733202	1405898	8	0.2	321	22.36	0
23. Oriental	1	732827	1405508	35	1	346	1.13	0
Silica	2	732518	1405833	35	0.6	313	1.1	0
	3	732518	1405838	35	0.6	313	1.1	0
24. TPC-	1	732757	1403836	33.5	1.83	326	15.94	1.8
Oxy								
25. Glow	1	732946	1404138	37	3.25	392.8	19.11	11.5
Energy	2	732971	1404143	37	3.25	388.1	18.33	11.54
Public	3	732971	1404148	37	3.25	382.3	19.74	11.57
Company	4	732971	1404153	37	3.25	386	17.58	11.66
Limited	5	732971	1404158	37	3.25	386	19.01	11.62

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	**NO.**	**COORDINATES**		**STACK**		**EXIT TEMP. (K)**	**EXIT VELOSITY (m/s)**	**EMISSION RATE (g/s) NOx**
		E (m.)	**N (m.)**	**Height (m)**	**Dia. (m)**			
	6	732971	1404163	37	3.25	417.5	18.91	10.76
	7	733278	1404132	40	1.55	433	8.02	1.96
	8	733278	1404132	40	1.55	433	12.83	3.2
26. Glow	1	732469	1402060	35	3.06	466.8	25.19	10.33
SPP 3	2	732469	1402014	35	3.06	487	26.42	10.31
	3	732296	1402000	60	2.78	402	28.57	10.03
	4	732311	1402000	60	2.78	398	29.19	10.32
	5	732185	1402000	60	2.78	398	27.14	10.27
	6	732200	1402000	60	2.78	405	29.99	10.26
	7	732344	1401931	100	2.82	448	31.3	28.77
	8	732233	1401931	100	2.82	448	31	28.77
	9	732074	1402000	35	3.06	428.6	24.06	10.02
	10	732089	1402000	35	3.06	429.8	24.57	10.25
	11	732122	1401931	100	2.82	448	31	28.77
27. GLOW	1	732071	1401838	150	6.8	353	17.8	74.07
SPP3 Area								
28. GLOW	1	732473	1401993	60	6.4	364	26	27.92
SPP3 Area								
29.Thai	1	733073	1404210	15.9	1.4	318	14.03	0
Plastic and	2	733050	1404106	30	1.4	334	13.4	0
Chemical								
	3	733059	1403956	30	1.4	334	13.4	0
	4	733070	1403882	27	1.24	333	14.56	0
	5	733068	1403818	20	1.54	323	11.03	0
	6	733017	1404333	28	0.31	304	19.2	0
	7	733067	1404333	28	0.31	304	19.2	0
	8	733114	1403932	28	0.31	304	19.2	0
	9	733124	1403871	28	0.16	333	27.48	0
	10	733123	1403798	28	0.4	313	13.7	0
TPC	11	732913	1404200	28.5	1.5	480	7.26	0.34
(VCM 1)	12	732727	1404206	18.2	0.8	338	5.27	0.158
	13	732699	1404196	35	0.52	338	13.03	0.092
TPC	14	732787	1404072	40.5	1.5	480	7.06	0.331
(VCM 2)	15	732787	1404067	40.5	1.5	480	7.06	0.331
	16	732796	1404049	40	0.52	313	13.42	0.107
	17	732796	1404041	40	0.52	313	11.48	0.092

Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	NO.	COORDINATES		STACK		EXIT TEMP. (K)	EXIT VELOCITY (m/s)	EMISSION RATE (g/s) NOx
		E (m.)	N (m.)	Height (m)	Dia. (m)			
30.Bangkok	1	733927	1405327	46	3.84	355	18.32	11.15
Cogeneration								
31.BLCP	1	735006	1398382	200	6.8	350	28.08	681
Power Plant								
32. Rayong	1	733484	1406167	30	2.31	440	11.4	6.73
Refinery	2	733503	1406156	30	2.31	440	11.6	6.85
	3	733526	1406178	30	2.31	440	12.7	6.99
	4	733537	1406227	37.5	1.347	400	25.9	3.14
	5	733548	1406247	37.5	1.347	400	24.8	3.05
	6	733549	1406250	37.5	1.347	400	26.1	4.04
	7	733560	1406269	37.5	1.347	400	24.9	3.12
	8	733561	1406271	37.5	1.347	400	25.4	3.3
	9	733572	1406291	37.5	1.347	400	27.8	3.44
	10	733574	1406293	37.5	1.347	400	27.5	3.59
	11	733584	1406312	37.5	1.347	400	27.2	3.39
	12	733586	1406314	37.5	1.347	400	25.8	3.51
	13	733533	1406226	37.5	1.19	400	23	2.83
	14	733617	1406414	20	0.8	795	1.9	0.15
	15	733598	1406339	37.5	1.897	400	25.6	2.05
	16	733600	1406337	37.5	1.897	400	23.6	3.03
	17	733555	1406200	37.5	1.897	400	24.9	3.22
33.Rayong	1	731911	1405248	34	1.52	540	5.93	5.05
Purifiers	2	731905	1405317	30	0.95	376	20.5	0.0034
(RPC)	3	730102	1404195	34	1.52	523	5	0.7638
	4	730077	1404085	30	0.65	555	5.93	0.0034
34. Siam	1	733672	1404350	51	1.5	433	5.6	0.99
stylene	2	733672	1404365	47	1.6	423	5.53	1.14
monomer	3	733721	1404303	40	2.75	413	3.56	8.23
35.Bayer								
Thai								
PC Plant	1	734405	1402514	14.5	0.74	673	21.87	0.458
(*max values:								1.958*
start-up)	2	734381	1402531	35	0.4	480	25	0.14
								0.682*
	3	734401	1402548	17.3	0.15	313	18	0
	4	734434	1402572	19.7	0.2	313	27.86	0
	5	734419	1402634	30	0.23	313	3.51	0

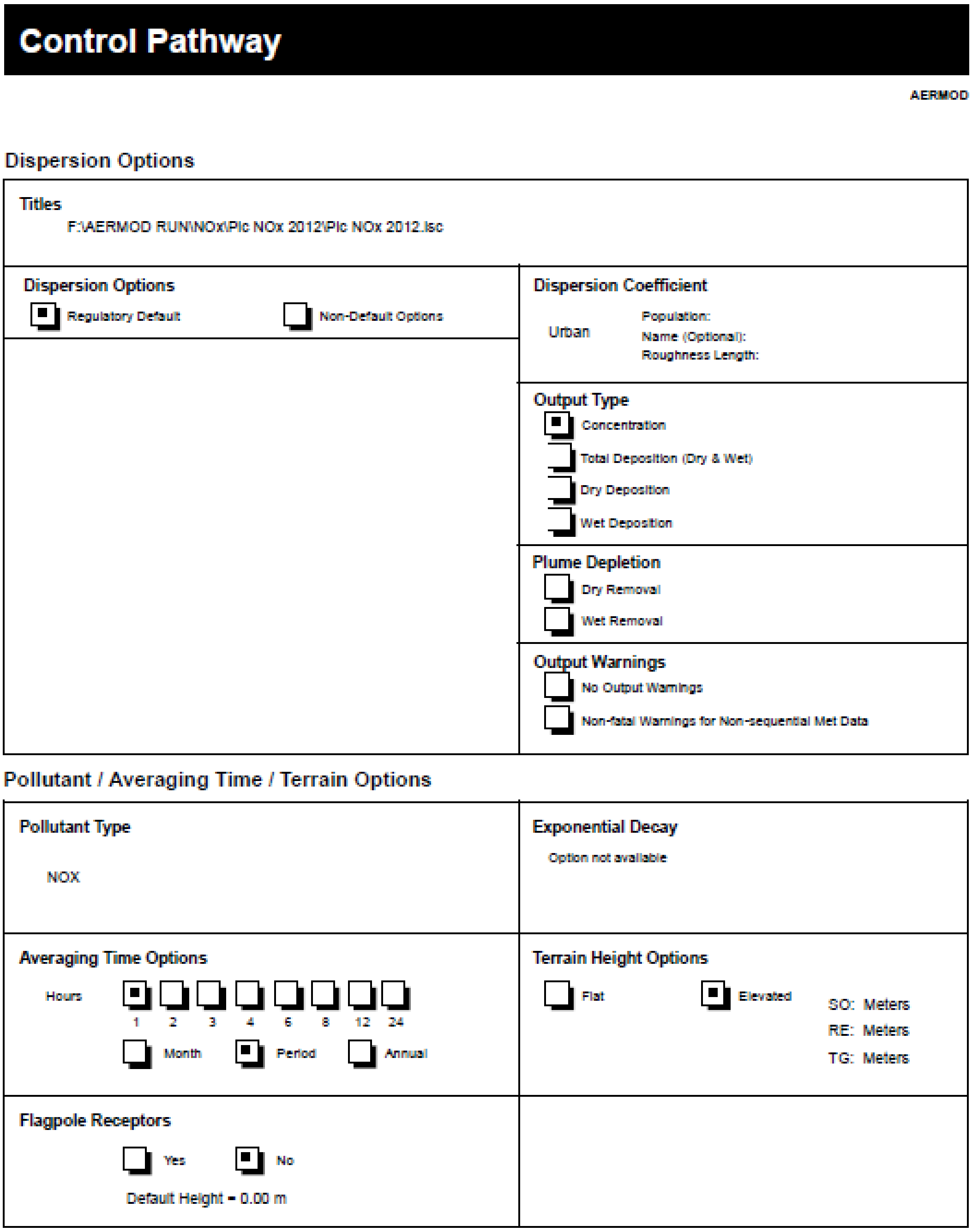
Table A Emission sources of NOx in Maptaphut industrial area in the year 2012-2013 (cont.)

PLANT NAME	NO.	COORDINATES		STACK		EXIT TEMP. (K)	EXIT VELOCITY (m/s)	EMISSION RATE (g/s) NOx
		E (m.)	N (m.)	Height (m)	Dia. (m)			
	6	734435	1402589	22	0.55	313	28.25	0
ABS Plant	1	734395	1402272	30.5	1.82	379.15	14.52	11.88
	2	734392	1402254	30.5	1.45	473.15	9.15	3.33
	3	734472	1402277	30.5	0.61	354.15	17.45	1.72
	4	733938	1402715	30.5	1.45	413	3.53	0.02
	5	733938	1402725	30.5	1.45	473	9.2	3.33
	6	734429	1402322	30.5	1.82	379	14.5	7.43
36. Air	1	734231	1402851	20	0.5	533	30.36	0.63
Chaisidhi	2	733411	1405786	20	0.8	453	4.4	0.088
	3	733404	1405710	15	0.8	453	4.4	0.073
	4	733411	1405710	15	0.8	453	4.4	0.073
39. HMC	1	732559	1405250	15	0.85	460	2.4	1.58
Polymer								
40. Siam	1	734455	1404206	49	1.4	450	7.3	0.39
Polyethylene	2	734455	1404227	47	1.53	450	6.8	0.429
41. Thai	1	734206	1406179	25.05	1.75	395.1	22.9	2.743
MMA	2	734173	1406100	25.05	1.56	393	30	1.35
42. Siam	1	731806	1403295	18	0.6	464	7.4	0.188
Tinplate								
(STP)								
43. JER	1	732385	1403558	45	1.8	353	13.58	0.24
BST	2	732386	1403558	45	1.8	353	13.58	0.24
Elastomer	3	732982	1403225	15	0.305	1093	5.09	0.06
	4	732982	1409225	15	0.305	1093	5.09	0.06

Source: IEAT and BLCP Power (2012-2013)

APPENDIX B

MODEL CONFIGURATIONS



Control Pathway

AERMOD

Dispersion Options

Titles
F:\AERMOD RUN\NOx\Plc NOx 2012\Plc NOx 2012.isc

Dispersion Options
☒ Regulatory Default ☐ Non-Default Options

Dispersion Coefficient
Urban
Population:
Name (Optional):
Roughness Length:

Output Type
☒ Concentration
☐ Total Deposition (Dry & Wet)
☐ Dry Deposition
☐ Wet Deposition

Plume Depletion
☐ Dry Removal
☐ Wet Removal

Output Warnings
☐ No Output Warnings
☐ Non-fatal Warnings for Non-sequential Met Data

Pollutant / Averaging Time / Terrain Options

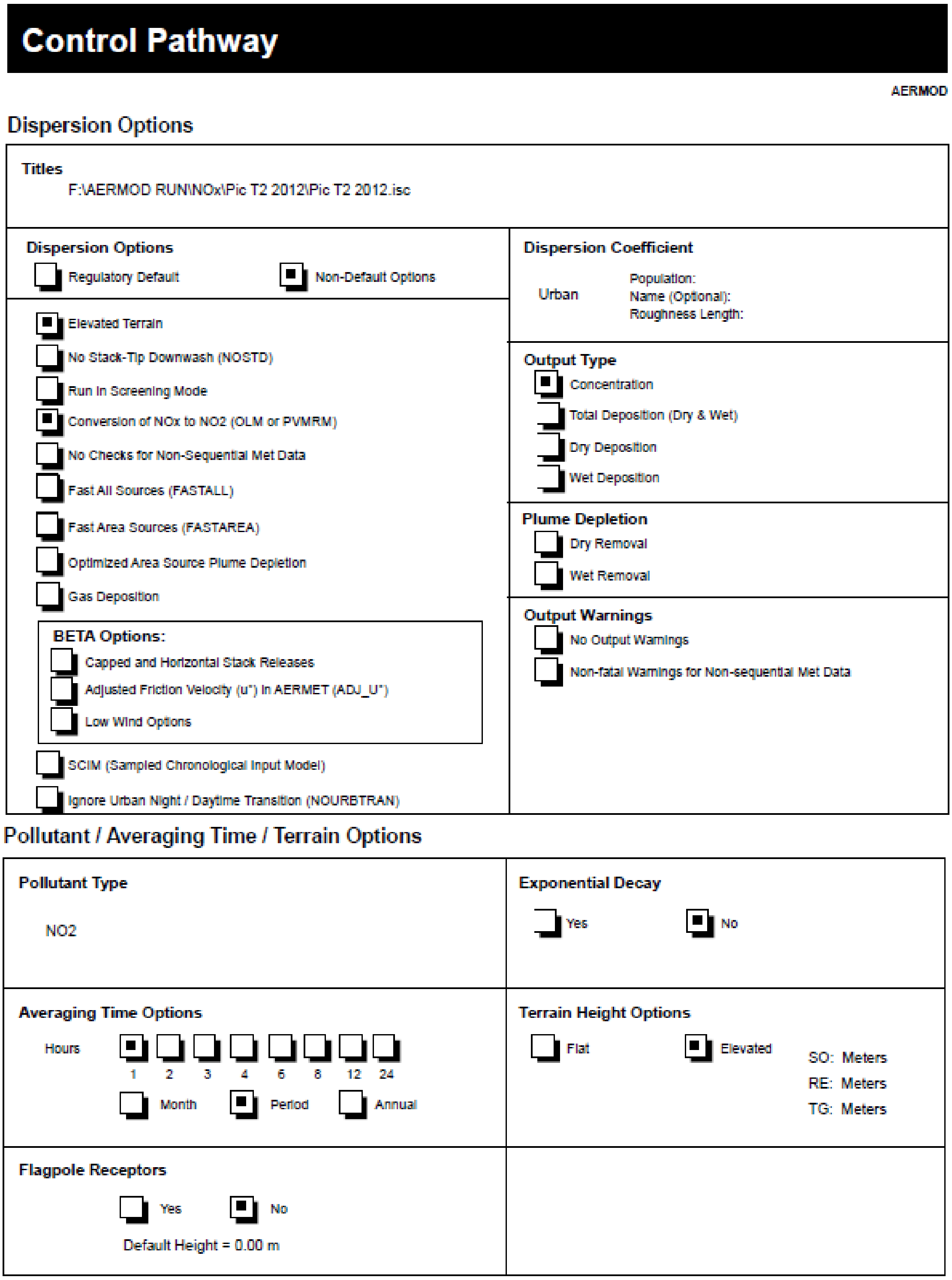
Pollutant Type
NOX

Exponential Decay
Option not available

Averaging Time Options
Hours ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 6 ☐ 8 ☐ 12 ☐ 24
☐ Month ☒ Period ☐ Annual

Terrain Height Options
☐ Flat ☒ Elevated
SO: Meters
RE: Meters
TG: Meters

Flagpole Receptors
☐ Yes ☒ No
Default Height = 0.00 m



Control Pathway

AERMOD

Dispersion Options

Titles
F:\AERMOD RUN\NOx\Pic T2 2012\Pic T2 2012.isc

Dispersion Options

☐ Regulatory Default ☒ Non-Default Options

☒ Elevated Terrain
☐ No Stack-Tip Downwash (NOSTD)
☐ Run in Screening Mode
☒ Conversion of NOx to NO2 (OLM or PVMRM)
☐ No Checks for Non-Sequential Met Data
☐ Fast All Sources (FASTALL)
☐ Fast Area Sources (FASTAREA)
☐ Optimized Area Source Plume Depletion
☐ Gas Deposition

BETA Options:
☐ Capped and Horizontal Stack Releases
☐ Adjusted Friction Velocity (u*) in AERMET (ADJ_U*)
☐ Low Wind Options

☐ SCIM (Sampled Chronological Input Model)
☐ Ignore Urban Night / Daytime Transition (NOURBTRAN)

Dispersion Coefficient

Urban
Population:
Name (Optional):
Roughness Length:

Output Type
☒ Concentration
☐ Total Deposition (Dry & Wet)
☐ Dry Deposition
☐ Wet Deposition

Plume Depletion
☐ Dry Removal
☐ Wet Removal

Output Warnings
☐ No Output Warnings
☐ Non-fatal Warnings for Non-sequential Met Data

Pollutant / Averaging Time / Terrain Options

Pollutant Type

NO2

Exponential Decay

☐ Yes ☒ No

Averaging Time Options

Hours ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 6 ☐ 8 ☐ 12 ☐ 24
☐ Month ☒ Period ☐ Annual

Terrain Height Options

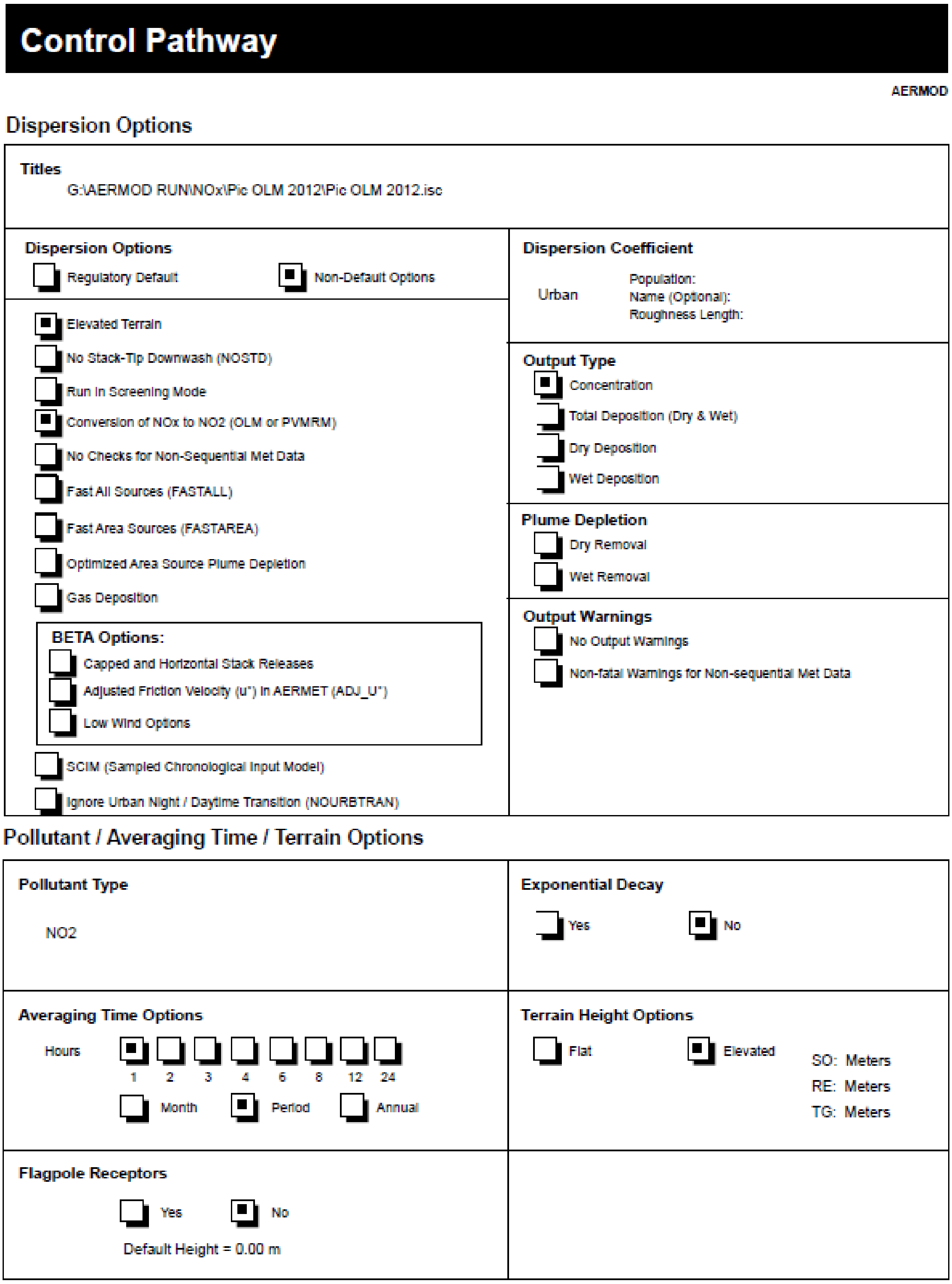
☐ Flat ☒ Elevated

SO: Meters
RE: Meters
TG: Meters

Flagpole Receptors

☐ Yes ☒ No

Default Height = 0.00 m



Control Pathway

AERMOD

Dispersion Options

Titles
G:\AERMOD RUN\NOx\Pic OLM 2012\Pic OLM 2012.isc

Dispersion Options
☐ Regulatory Default ☑ Non-Default Options

- ☑ Elevated Terrain
- ☐ No Stack-Tip Downwash (NOSTD)
- ☐ Run in Screening Mode
- ☑ Conversion of NOx to NO2 (OLM or PVMRM)
- ☐ No Checks for Non-Sequential Met Data
- ☐ Fast All Sources (FASTALL)
- ☐ Fast Area Sources (FASTAREA)
- ☐ Optimized Area Source Plume Depletion
- ☐ Gas Deposition

BETA Options:
- ☐ Capped and Horizontal Stack Releases
- ☐ Adjusted Friction Velocity (u*) in AERMET (ADJ_U*)
- ☐ Low Wind Options

- ☐ SCIM (Sampled Chronological Input Model)
- ☐ Ignore Urban Night / Daytime Transition (NOURBTRAN)

Dispersion Coefficient
Urban
Population:
Name (Optional):
Roughness Length:

Output Type
- ☑ Concentration
- ☐ Total Deposition (Dry & Wet)
- ☐ Dry Deposition
- ☐ Wet Deposition

Plume Depletion
- ☐ Dry Removal
- ☐ Wet Removal

Output Warnings
- ☐ No Output Warnings
- ☐ Non-fatal Warnings for Non-sequential Met Data

Pollutant / Averaging Time / Terrain Options

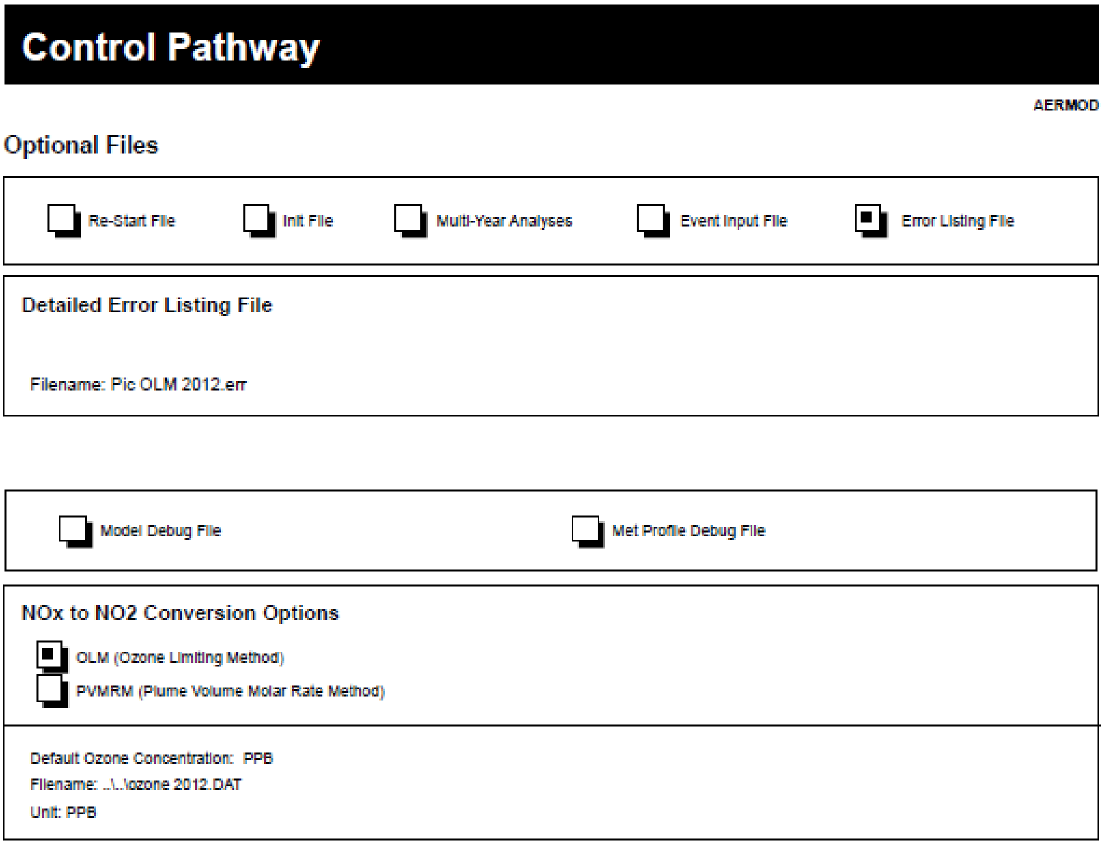
Pollutant Type
NO2

Exponential Decay
☐ Yes ☑ No

Averaging Time Options
Hours ☑ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 6 ☐ 8 ☐ 12 ☐ 24
☐ Month ☑ Period ☐ Annual

Terrain Height Options
☐ Flat ☑ Elevated
SO: Meters
RE: Meters
TG: Meters

Flagpole Receptors
☐ Yes ☑ No
Default Height = 0.00 m



Control Pathway

AERMOD

Optional Files

☐ Re-Start File ☐ Init File ☐ Multi-Year Analyses ☐ Event Input File ☒ Error Listing File

Detailed Error Listing File

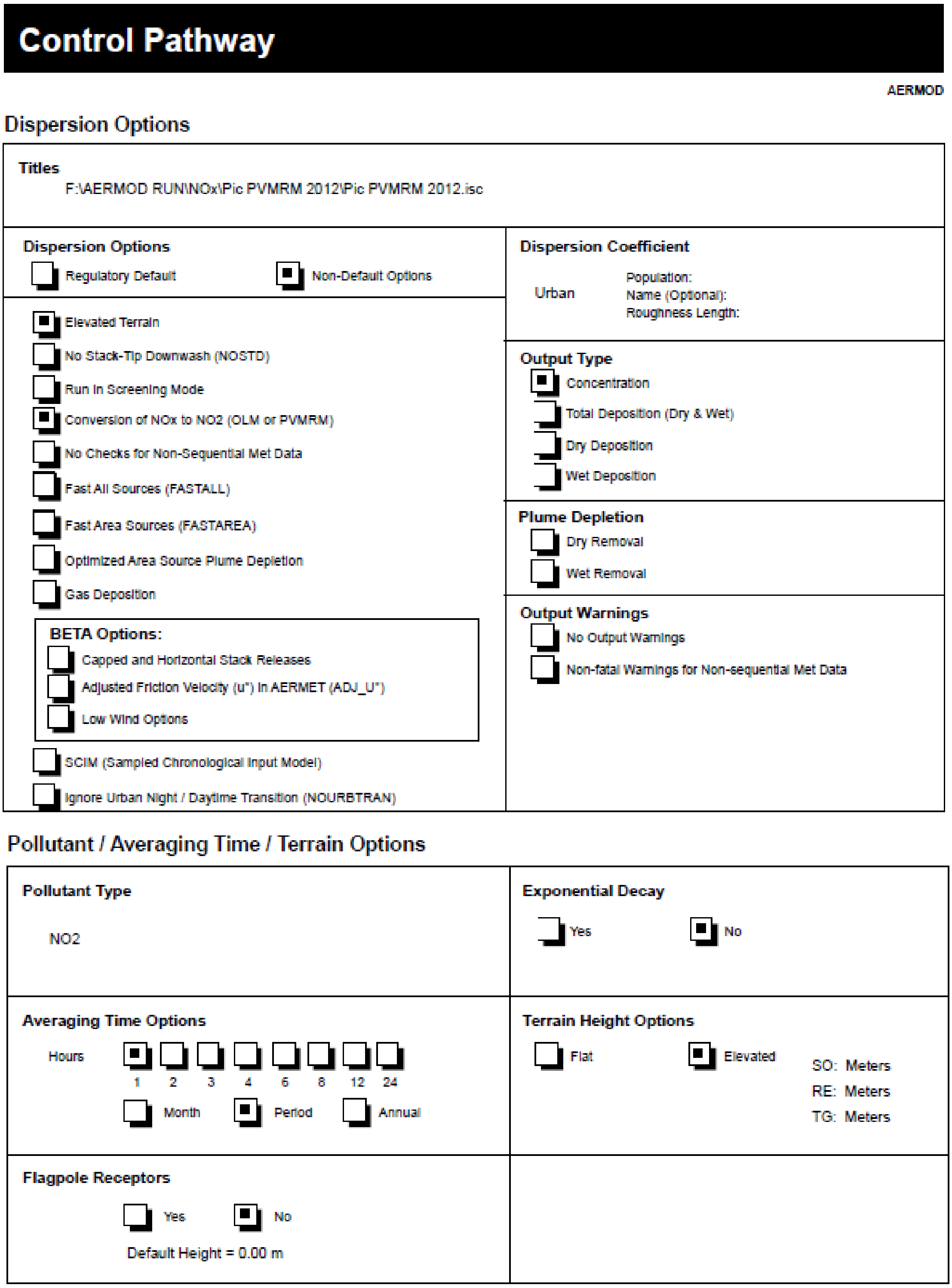
Filename: Pic OLM 2012.err

☐ Model Debug File ☐ Met Profile Debug File

NOx to NO2 Conversion Options

☒ OLM (Ozone Limiting Method)
☐ PVMRM (Plume Volume Molar Rate Method)

Default Ozone Concentration: PPB
Filename: ..\..\ozone 2012.DAT
Unit: PPB



Control Pathway

AERMOD

Dispersion Options

Titles

F:\AERMOD RUN\NOx\Pic PVMRM 2012\Pic PVMRM 2012.isc

Dispersion Options

☐ Regulatory Default ☒ Non-Default Options

- ☒ Elevated Terrain
- ☐ No Stack-Tip Downwash (NOSTD)
- ☐ Run in Screening Mode
- ☒ Conversion of NOx to NO2 (OLM or PVMRM)
- ☐ No Checks for Non-Sequential Met Data
- ☐ Fast All Sources (FASTALL)
- ☐ Fast Area Sources (FASTAREA)
- ☐ Optimized Area Source Plume Depletion
- ☐ Gas Deposition

BETA Options:

- ☐ Capped and Horizontal Stack Releases
- ☐ Adjusted Friction Velocity (u*) in AERMET (ADJ_U*)
- ☐ Low Wind Options

- ☐ SCIM (Sampled Chronological Input Model)
- ☐ Ignore Urban Night / Daytime Transition (NOURBTRAN)

Dispersion Coefficient

Urban

Population:
Name (Optional):
Roughness Length:

Output Type

- ☒ Concentration
- ☐ Total Deposition (Dry & Wet)
- ☐ Dry Deposition
- ☐ Wet Deposition

Plume Depletion

- ☐ Dry Removal
- ☐ Wet Removal

Output Warnings

- ☐ No Output Warnings
- ☐ Non-fatal Warnings for Non-sequential Met Data

Pollutant / Averaging Time / Terrain Options

Pollutant Type

NO2

Exponential Decay

☐ Yes ☒ No

Averaging Time Options

Hours	☒	☐	☐	☐	☐	☐	☐	☐
	1	2	3	4	6	8	12	24

☐ Month ☒ Period ☐ Annual

Terrain Height Options

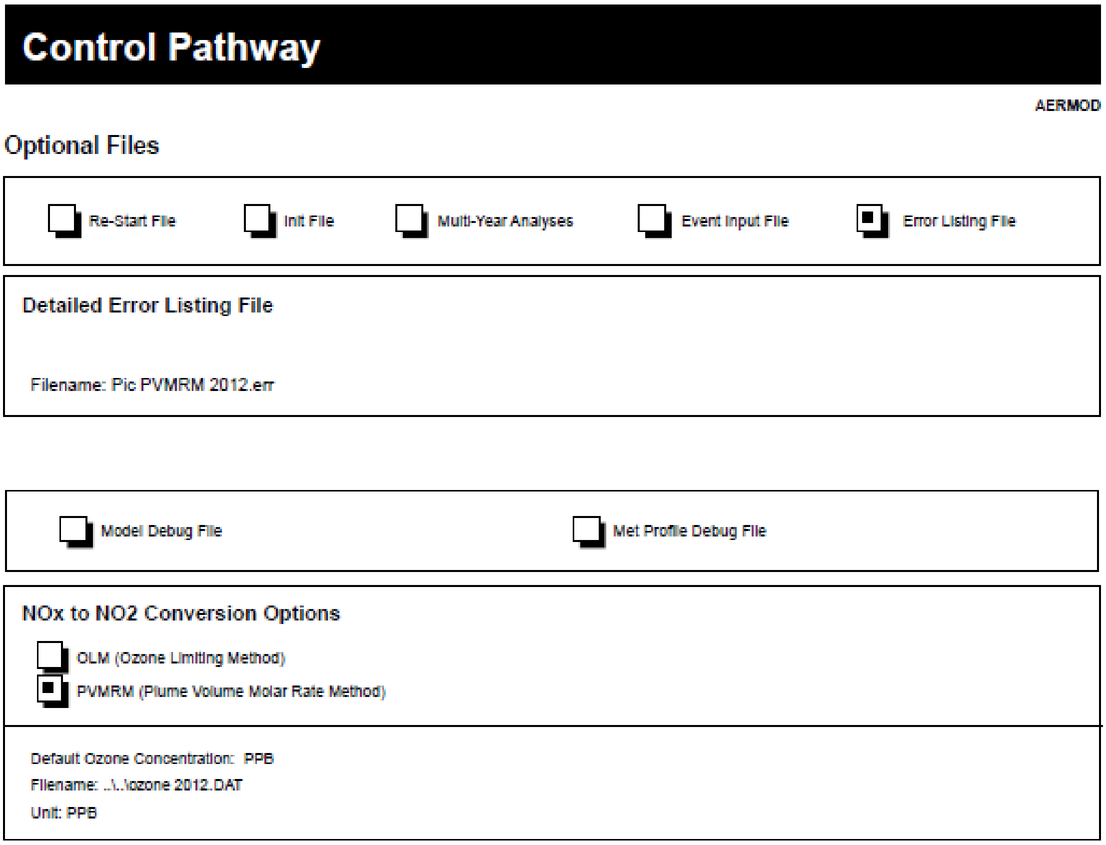
☐ Flat ☒ Elevated

SO: Meters
RE: Meters
TG: Meters

Flagpole Receptors

☐ Yes ☒ No

Default Height = 0.00 m



Control Pathway

AERMOD

Optional Files

☐ Re-Start File ☐ Init File ☐ Multi-Year Analyses ☐ Event Input File ☑ Error Listing File

Detailed Error Listing File

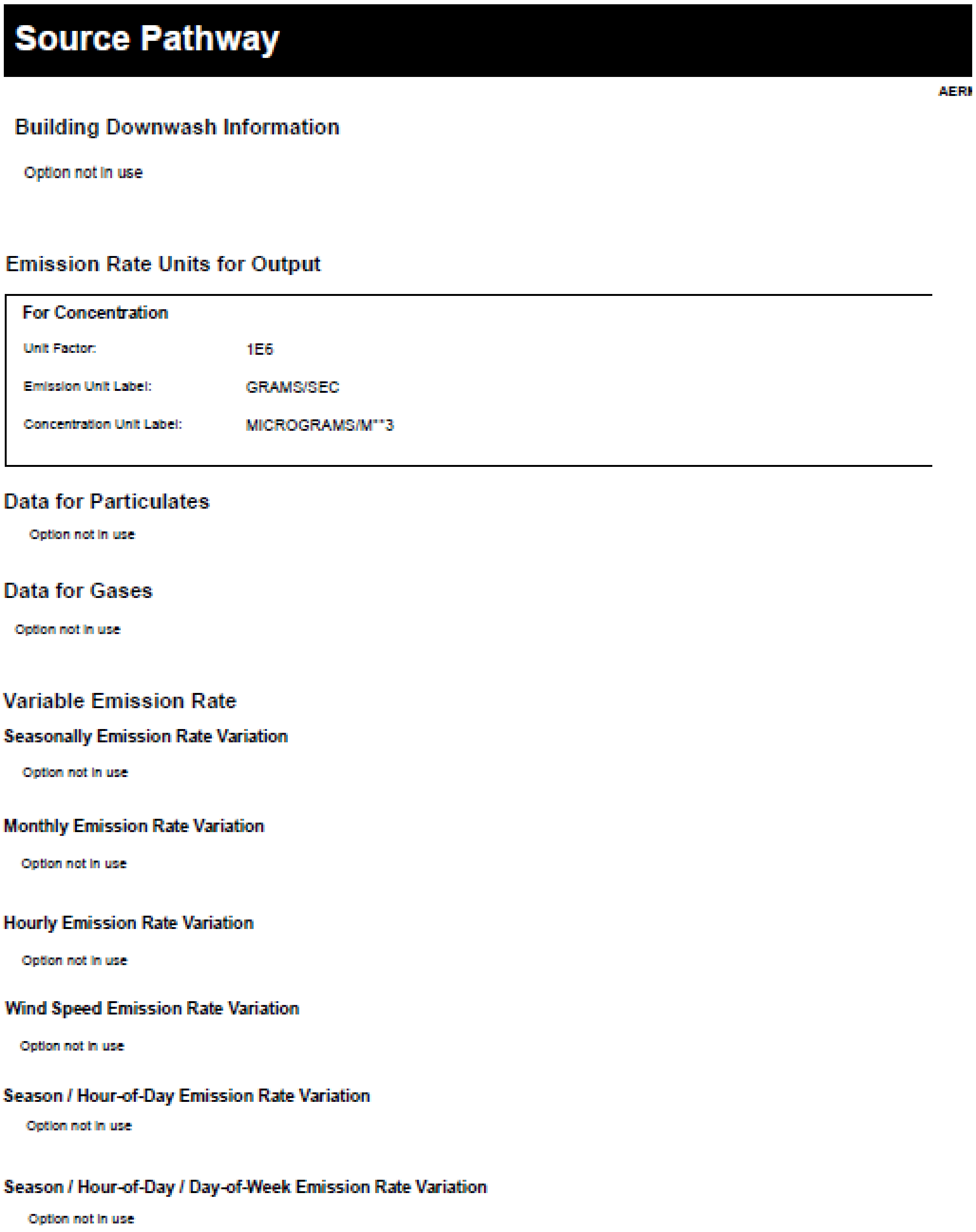
Filename: Pic PVMRM 2012.err

☐ Model Debug File ☐ Met Profile Debug File

NOx to NO2 Conversion Options

☐ OLM (Ozone Limiting Method)
☑ PVMRM (Plume Volume Molar Rate Method)

Default Ozone Concentration: PPB
Filename: ..\..\ozone 2012.DAT
Unit: PPB



Source Pathway

AERI

Building Downwash Information

Option not in use

Emission Rate Units for Output

For Concentration

Unit Factor: 1E6

Emission Unit Label: GRAMS/SEC

Concentration Unit Label: MICROGRAMS/M**3

Data for Particulates

Option not in use

Data for Gases

Option not in use

Variable Emission Rate

Seasonally Emission Rate Variation

Option not in use

Monthly Emission Rate Variation

Option not in use

Hourly Emission Rate Variation

Option not in use

Wind Speed Emission Rate Variation

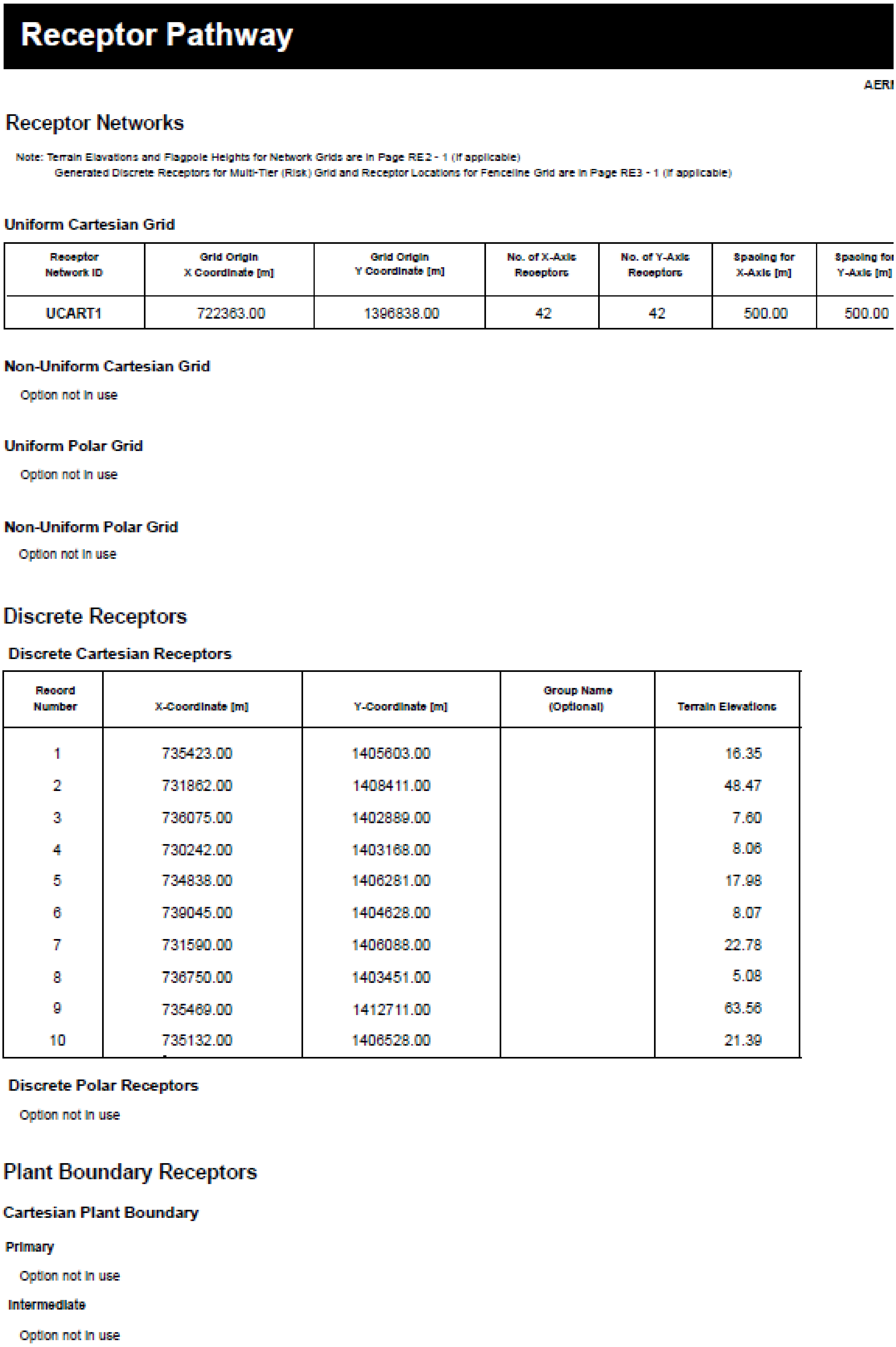
Option not in use

Season / Hour-of-Day Emission Rate Variation

Option not in use

Season / Hour-of-Day / Day-of-Week Emission Rate Variation

Option not in use



Receptor Pathway

AERI

Receptor Networks

Note: Terrain Elevations and Flagpole Heights for Network Grids are in Page RE2 - 1 (if applicable)
Generated Discrete Receptors for Multi-Tier (Risk) Grid and Receptor Locations for Fenceline Grid are in Page RE3 - 1 (if applicable)

Uniform Cartesian Grid

Receptor Network ID	Grid Origin X Coordinate [m]	Grid Origin Y Coordinate [m]	No. of X-Axis Receptors	No. of Y-Axis Receptors	Spacing for X-Axis [m]	Spacing fo Y-Axis [m]
UCART1	722363.00	1396838.00	42	42	500.00	500.00

Non-Uniform Cartesian Grid

Option not in use

Uniform Polar Grid

Option not in use

Non-Uniform Polar Grid

Option not in use

Discrete Receptors

Discrete Cartesian Receptors

Record Number	X-Coordinate [m]	Y-Coordinate [m]	Group Name (Optional)	Terrain Elevations
1	735423.00	1405603.00		16.35
2	731862.00	1408411.00		48.47
3	736075.00	1402889.00		7.60
4	730242.00	1403168.00		8.06
5	734838.00	1406281.00		17.98
6	739045.00	1404628.00		8.07
7	731590.00	1406088.00		22.78
8	736750.00	1403451.00		5.08
9	735469.00	1412711.00		63.56
10	735132.00	1406528.00		21.39

Discrete Polar Receptors

Option not in use

Plant Boundary Receptors

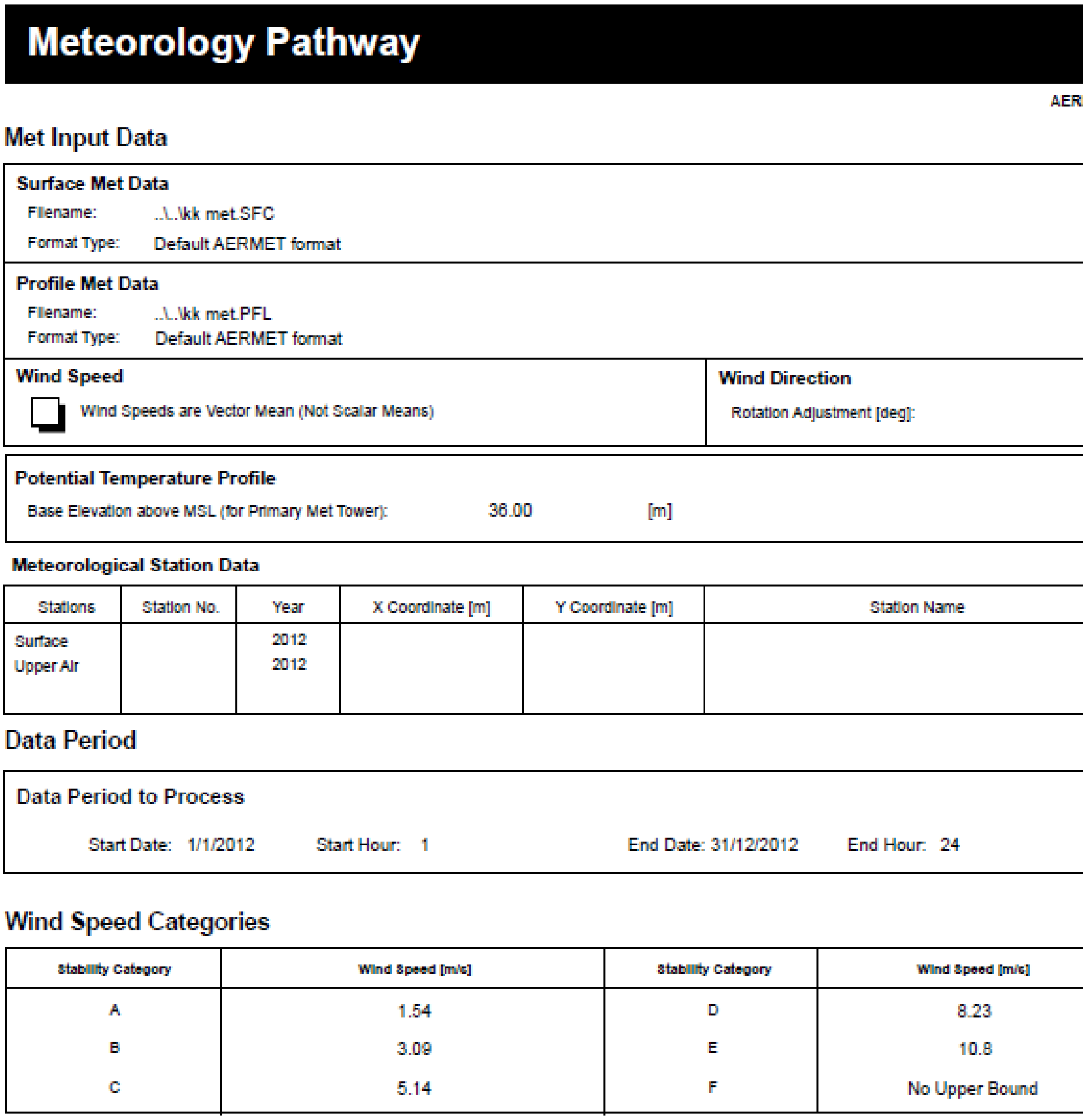
Cartesian Plant Boundary

Primary

Option not in use

Intermediate

Option not in use



Meteorology Pathway

AER

Met Input Data

Surface Met Data

Filename: ..\..\kk met.SFC
Format Type: Default AERMET format

Profile Met Data

Filename: ..\..\kk met.PFL
Format Type: Default AERMET format

Wind Speed

☐ Wind Speeds are Vector Mean (Not Scalar Means)

Wind Direction

Rotation Adjustment [deg]:

Potential Temperature Profile

Base Elevation above MSL (for Primary Met Tower): 36.00 [m]

Meteorological Station Data

Stations	Station No.	Year	X Coordinate [m]	Y Coordinate [m]	Station Name
Surface		2012			
Upper Air		2012			

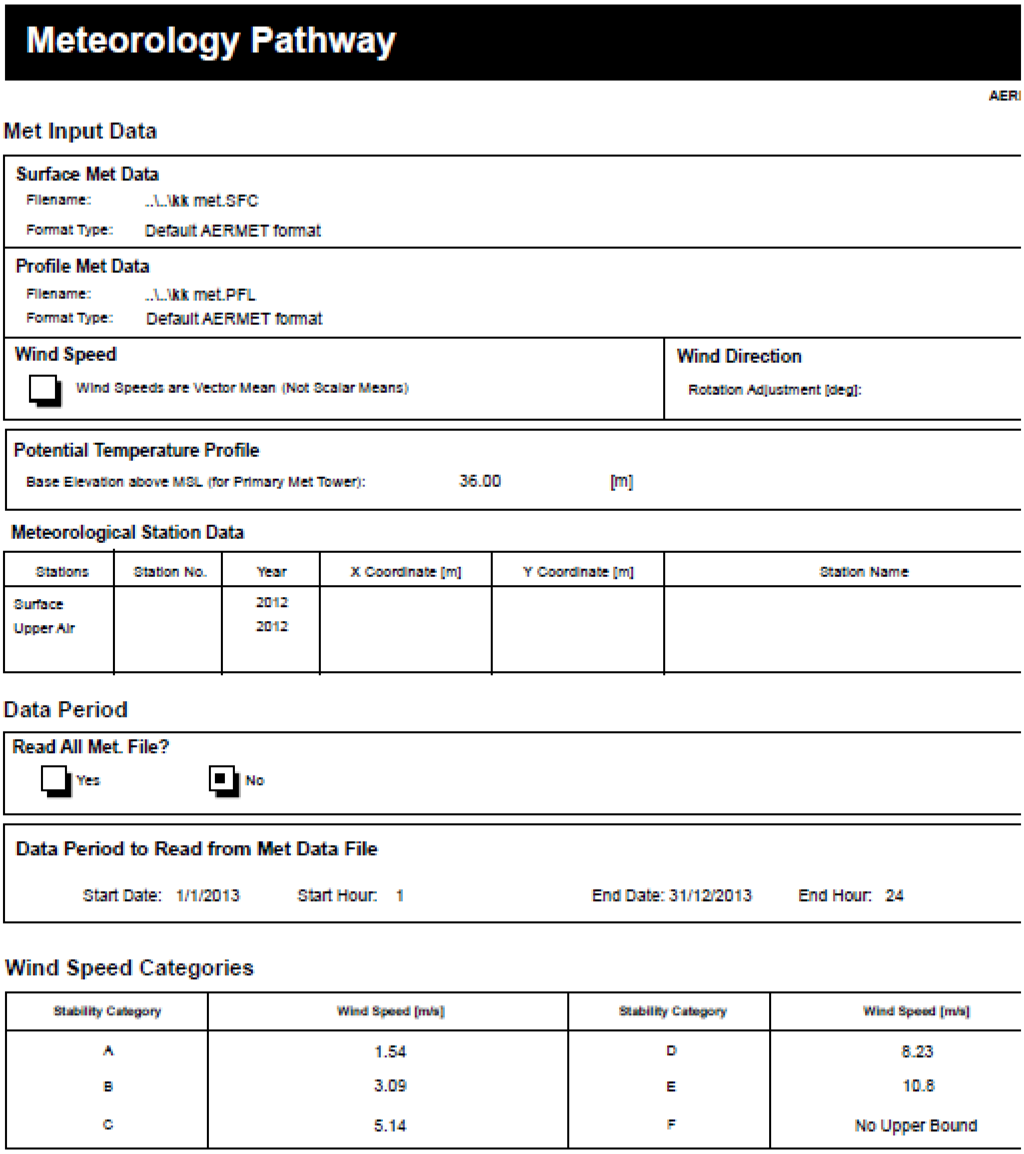
Data Period

Data Period to Process

Start Date: 1/1/2012 Start Hour: 1 End Date: 31/12/2012 End Hour: 24

Wind Speed Categories

Stability Category	Wind Speed [m/s]	Stability Category	Wind Speed [m/s]
A	1.54	D	8.23
B	3.09	E	10.8
C	5.14	F	No Upper Bound



Meteorology Pathway

AERI

Met Input Data

Surface Met Data

Filename: ..\..\kk met.SFC

Format Type: Default AERMET format

Profile Met Data

Filename: ..\..\kk met.PFL

Format Type: Default AERMET format

Wind Speed

☐ Wind Speeds are Vector Mean (Not Scalar Means)

Wind Direction

Rotation Adjustment [deg]:

Potential Temperature Profile

Base Elevation above MSL (for Primary Met Tower): 36.00 [m]

Meteorological Station Data

Stations	Station No.	Year	X Coordinate [m]	Y Coordinate [m]	Station Name
Surface		2012			
Upper Air		2012			

Data Period

Read All Met. File?

☐ Yes ☒ No

Data Period to Read from Met Data File

Start Date: 1/1/2013 Start Hour: 1 End Date: 31/12/2013 End Hour: 24

Wind Speed Categories

Stability Category	Wind Speed [m/s]	Stability Category	Wind Speed [m/s]
A	1.54	D	8.23
B	3.09	E	10.8
C	5.14	F	No Upper Bound

BIOGRAPHY

NAME	Miss Supitchaya Tunlathorntham
DATE OF BIRTH	June 22, 1991
PLACE OF BIRTH	Bangkok, Thailand
INSTITUTIONS ATTENDED	Silapakorn University, 2010-2013 Bachelor of Science (Environmental Science) Mahidol University, 2013-2015 Master of Science (Environmental Technology)
HOME ADDRESS	29/10 Moo 9 Bang Hua Suea, Puchao Saming Phrai Rd., Phra Pradaeng Samut Prakan, Thailand 10130. E-mail: tunlathorn_som@hotmail.com
PUBLICATION / PRESENTATION	5th International Conference on Environmental Science and Information Application Technology (ESIAT 2014) November 7-8, 2014, Hong Kong