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Total Flare Emission Inventories of Crude Oil Production Operations from Kuwait Oilfields

by

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Abstract

The State of Kuwait is one of the major oil producing countries with its economy solely and directly dependent on export of crude oil and its refined products. Kuwait Oil Company (KOC) is responsible for the exploration, development and production of marketable quality hydrocarbon, Although KOC has a very strict flaring policy and practices, emission of some gaseous pollutants to the atmosphere; particularly from the flaring of normally undesirable effluent streams and excess gases.

This study provides a comprehensive account and estimates of all emissions of primary pollutants associated with flaring activities from Kuwait Oilfields. This inventory provides the monthly emissions for a decade starting for year 1997 of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons. The emissions are generated from various point sources and aggregated to obtain total pollutants load of ambient air in and around oilfields. The emissions of pollutants from the flaring associated with all types of operations in the oilfields, gathering centres (GC), booster stations (BS), tank areas and other oil production related emission activities.

An inclusive analysis is performed to evaluate the emission status and update the total current emissions by using the Inventory Model, implementing the latest emission factor to provide accurate emissions as a real-time data.

Moreover, the Industrial Source Complex Short Term (ISCST3) model is used to calculate ground concentration of selected primary pollution and predicted values are compared with the real-time measured data from selected Kuwait Environmental Public Authority (EPA) monitoring stations. The meteorological parameters, wind and temperature fields are also generated with diagnostic meteorological model part of ISCST3 model that used surface observations and upper air findings from one year hourly record data for year 2006 obtained from the Kuwait International Airport (KIA) weather station.

Model results have been compared with Kuwait Ambient Air Quality Standards (KAAQS) to identify the most effected area due to pollutants emissions for Kuwait oilfields.

Model validation is based on the comparison of the 50 highest daily measured values and their respective predicted concentrations of primary pollutants associated with flaring activities in the Kuwait Oilfields.   At discrete receptor representing Kuwait EPA monitoring station, it is noticed that the predicted values are in good agreement with the observed data with an error bond of ± 50 %.

The simulation of real hourly air quality in and around oil production facilities in the State of Kuwait for the year 2006, inserting the respective source emission data into the ISCST3 software indicates that the levels of methane and non-methane hydrocarbons from flaring activities in North Kuwait Oilfields exceed the allowable ambient air standard set by Kuwait EPA.   As such, there is a strong need to address this acute problem to minimize the impact of methane and non-methane hydrocarbons released from flaring activities over the urban area of Kuwait.

From the comparison between the simulated results for emission scenarios in the North (NK), South East (SEK) and West Kuwait (WK) Oilfields independently, it is concluded that the NK Oilfields have generated a high ground level concentration of methane and non-methane hydrocarbons than SEK and WK Oilfields. This is because of the unpredictable problems in the NK Oilfields. The highest average ground level concentration of methane and non-methane hydrocarbons in the NK area (hourly, daily and annually) were in the months of January and September due to high emission rates resulted by the malfunctioning of condensate recovery unit. The prevailing meteorological conditions in the month of January have also substantiated the results into the top highest ground concentrations due to low temperatures, low inversion layer and calm wind conditions.

The associated gas in WK area has a significant amount of H_2S resulting in to sour gas, while in NK and SEK the associated gas is sweet. Therefore, ISCST3 is implemented

to evaluate the impact of SO_2 released from flaring activities in WK Oilfields. It is concluded that the ground level concentrations of SO_2 exceeded the allowable hourly, daily and annually ambient air quality standard by Kuwait EPA level. The highest average ground level concentrations of SO_2 (hourly, daily and annually) were in the months of July and August due to high percentage of flaring (87% and 95%) resulted by shutdown in KNPC (Acid Gas Removal Plant, AGRP). There is strong influence of prevailing North West wind in summer in morning hours. Most of the highest predicted values were in summer and early morning hours due to low inversion layer.

Overall it seems that the levels of pollutants in winter period are higher than summer. This is because the winters in Kuwait portray a low temperature, low inversion layers, lesser wind movements, which relegate the dispersion of pollutants as compared to summers, which have high temperature, high inversion layers, and high wind movements strongly influencing the dispersion of pollutants.

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Chapter 1
General Introduction

1.1 Introduction

Air pollution is defined as the contamination of air by the discharge of harmful substances, leading to health problems and deterioration of environmental quality. The primary contaminants include Hydrocarbons, Ozone, Carbon Monoxide, Oxides of Nitrogen, Sulphur Dioxide, Hydrogen Sulphide and Particulate matter. Hazardous air pollutants are released by various sources such as factories, refineries, automobiles, power plants, sewage plants, etc.

Air Pollution continues to be a major cause of concern all over the world and requires urgent attention. The contamination of the atmosphere affects the quality of life and has serious consequences for human health and climatic change. As the energy demands of the world's population continue to increase at accelerating rate, air pollution increases and the problem is becoming more difficult to solve.

This situation, which may become out of control, has resulted in a widespread awareness of the public to the degree of air pollution. This has led to demands to find ways of curtailing it further.

The world energy demand is mainly fulfilled by fossil fuel and many countries depend on oil. They will go to great lengths to acquire an oil production capability or to be assured access to the free flow of oil and they have even become involved in conflicts over areas which may only possibly have oil resources.

This trend is likely to continue in the future until a more economical resource is discovered or until the world's oil wells run dry. One problem associated with this dependence on oil is the extremely damaging effects that production, distribution, and use have on the environment.

Although much of the world countries depend on the production or the trade of oil to fuel their economies, these activities can cause severe damage to the environment. In, Kuwait the most significant impacts on air quality have been from the oil industries. Oil industrial activities emit toxic organic chemicals into the atmosphere.

Air pollution and its effects on the ecosystem has been a source of concern for many environmental pollution organizations in the world. In particular climatologists who are not directly involved in petroleum industry sometimes express concerns about the environmental impacts of gaseous emissions from flaring at various despised points. For environmental and resource conservation reasons, flaring should always be minimized as much as practicable and be consistent with safety considerations. However, any level of flaring has a local environmental impact, as well as producing emissions which have the potential to contribute to the global warming.

Flaring is the typical method for the safe disposal of excess hydrocarbons. By burning these hydrocarbons, thereby converting them largely to carbon dioxide and water, their environmental impact is greatly reduced. For example, the global warming potential of methane is about 21 times higher than that of CO_2.

To safe guard the environment, one should have a thorough knowledge of gaseous emissions resulting from the flaring of associated gaseous mixture of known composition on daily basis through combustion activities under several operating conditions. This helps in the control of gaseous emission from flares and thus in the protection of immediate and distant localities against environmental degradation due to air pollution.

The flaring of excess gas is the largest single source of atmospheric emissions arising from Kuwait Oil Company (KOC) operations. KOC is a state owned subsidiary of Kuwait Petroleum Corporation (KPC) that explores, produces and exports crude oil from the State of Kuwait. With a production of over 317,975 m^3/day (two million barrels of oil a day), it is one of the largest oil producing companies in the world. KOC manages the production and export of oil and gas with the associated facilities from more than twelve developed oil fields in the state of Kuwait. The oilfields spread over the State and split off into four main parts of North Field, West Field, South and East Field that are locally

administered at the site headquarters. The oilfields involve various types of industrial operations and activities, such as drilling, production of crude oil, fuel combustion, and flaring of gases which all result in gas emission into atmosphere. In practice, all other sources of emissions are small compared with emissions from flaring. Consequently, a wide range of air pollutant emissions is generated on various sites on oil fields. Such emissions include carbon dioxide, nitrogen and sulfur oxide gases, methane and non-methane hydrocarbons and suspended particulates matter (SPM). Although most gas that is produced from KOC operations is put to use, mainly for power generation, this is not always possible. Rather than release any excess gas direct to the atmosphere, it is burnt in flares. However, flaring produces carbon dioxide, oxides of sulphur and nitrogen (NOx) and products that arise from incomplete combustion, such as carbon monoxide, methane and other hydrocarbons known as Volatile Organic Compounds (VOCs). It can also produce unsightly smoke and is, of course, a waste of a resource.

Kuwait was invaded and annexed by Iraq on August 2, 1990. After six weeks of fierce fighting in early 1991, the coalition forces compelled Iraq to withdraw its troops from Kuwait on February 26, 1991. During their retreat, the Iraqi armed forces earth policy by setting fire to Kuwaiti oil wells and released oil from those wells into the gulf. The fires took more than nine months to extinguish fully and the cost of repairs to the oil infrastructure exceeded 5.12 billion US dollars.

As a result environmental issues, and especially the air pollution problems, have become a priority for the government of Kuwait. In response, the Kuwait EPA was established in 1995. The Kuwait EPA established a number of fixed monitoring stations to collect the air quality data in the urban areas, through network. These stations continuously measure the levels of pollutants such as SO_2, NO_2, CO, NO, CO_2, H_2S, O_3, and TSP in the air. The hourly air pollutants concentrations are measured continuously by fixed ambient air stations located over the State of Kuwait. These monitoring stations are equipped with the latest instruments and analyzer for above mentioned pollutants with meteorological sensors.

Air pollution has high dependency on geographical and meteorological factors. The meteorological conditions play a major role in the dispersion of the pollutions over the State of Kuwait. The main aim here is to report on real metrological data being measured and recorded so that a clear picture can be withdrawn about the climate in the State of Kuwait and hence affect the ground level concentration of the selected primary pollutants in the residential areas. Kuwait enjoys a variable continental climate. Summer months are between April and October and the rainy season runs from November to March, when humidity can also be high. In summer temperatures can get over 38°C (100°F), but they drop below 21°C (70°F) in winter. The prevailing wind in Kuwait is from the north westerly direction most of the year.

In this research work, an air quality screening study was performed to assess the impacts of emissions from flaring in and around Kuwait Oilfields. A preliminary air quality model simulation was performed to observe the transport and dispersion patterns of selected primary pollutants emitted from flaring in and around Kuwait Oilfields. The meteorological wind and temperature fields were generated with the ISCST3 model, a diagnostic meteorological model that used surface observations and upper air finding from one year hourly record data for year 2006 obtained from the Kuwait International Airport (KIA) weather station.

The application of a mathematical modelling approach to calculate ground level concentration of selected primary pollution and compare it with the monitoring data from selected site used as receptor in the model. Monitored data have been compared with Kuwait EPA Standards to categorize the most area affected by air emissions for Kuwait Oilfields. Hence, through comparisons with filed survey data, the performance of the most widely used air quality dispersion model (ISCST3) (U.S. EPA, 1995), has been evaluated.

1.2 The Objectives of the Current Research

The objective of the present research is to develop a comprehensive emission inventories from Kuwait Oilfields, which provides a comprehensive account and estimates of all

emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields. This inventory records the monthly emissions of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons and an air quality screening study was performed to assess the impacts of emissions from flaring in and around Kuwait Oilfields Therefore, accurate emission inventory strategy for KOC as means of monitoring and minimizing the impact of NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons emissions is of prime importance.

The objectives of this research study are to;

- Provide a comprehensive account and estimates for all emissions of primary pollutants associated with flaring activities in the Kuwait Oilfields to determine total emissions and plan future strategies to control emissions

- Establish the role of weather conditions as the important factors in the dispersion of pollutants within residential areas and draw attention to the air pollution problem in Kuwait and. (Chapter 7).

- Investigate and predict the dispersion of SO_2, methane and non-methane hydrocarbons emitted by flaring in and around Kuwait oilfields using ISCST3 dispersion model modified by US-EPA in 1999 (Chapters 6 and 9).

- Validate the ISCST3 model by comparing the model prediction with the experimental data under the meteorological conditions of the state of Kuwait.

- Assess the impact of SO_2, methane and non-methane hydrocarbons emitted by flaring in and around Kuwait Oilfields on the residential areas in the state of Kuwait.

1.3 Importance of This Research to Kuwait Oilfields

The inventory which is being established is fully aligned with Kuwait Oilfields Health, Safety and Environment Policy which aims to provide environmental protection by minimising the impact of the company's activities. The inventory provides the basic

input emissions data for environmental health and ecological impact assessments. The inventory also serves as the baseline for progressive improvement of environmental performance.

The key benefits to Kuwait Oilfields of the inventory are summarised as:

- **Provide a complete record of all emission sources**

  The process of developing and refining the inventory ensure that all of Kuwait Oilfields emission sources are identified and understood.

- **Basis for understanding the environmental impact of Kuwait Oilfields operations**

  The data within the inventory can be used as input for environmental impact assessment tools such as atmospheric dispersion modelling. Thus the source emissions can be related to meteorological conditions and other environmental parameters in order to estimate the likely impact from pollution for any receptors, such as population centres or sites of special ecological interest.

- **Priorities and initiatives to reduce losses and emissions at each facility**

  The inventory can be used to understand the value of future initiatives to reduce hydrocarbon losses, emissions and discharges. Pollution abatement projects can then be compared and assessed in terms of their environmental impact and cost benefit. The facilities which offer the greatest prizes in terms of emission reduction can be identified in terms of both total emissions and the impact on receptors.

- **Set achievable overall reduction targets for Kuwait Oilfields**

  The cost and benefits derived from an understanding of abatement options can be prioritised and planned within a time-scale for implementation. The resulting cost benefit analysis assists Kuwait Oilfields management to set realistic targets for reduction of emissions for each pollutant, across the whole company and for each facility.

- **Provide a baseline over next years against which future achievements can be measured**

  The data collectively provide a baseline against which Kuwait Oilfields progress on emission reduction projects and overall environmental performance can be judged and reported. Open reporting of environmental performance by the oil industry is increasing. Once the baseline is regarded as sufficiently refined and robust, it can be used to demonstrate the effectiveness of Kuwait Oilfields environmental policies and strategy.

- **Improved internal reporting of Kuwait Oilfields environmental performance**

  Inside Kuwait Oilfields, the knowledge of emissions from individual facilities provides greater ownership of the environmental impact which results from exploration, production and export operations. Measures to reduce pollution by individual facilities can be undertaken and the resulting achievements recognised.

- **Enable benchmarking against other companies or countries**

  Kuwait Oilfields management is able to review their overall position relative to others, allowing an international perspective on the environmental performance of the company. Kuwait Oilfields emissions can be put into context when considering major global issues such as climate change.

1.4 Research Methodology

This research is divided into several tasks conducted in the following sequence. The first and major activity of this investigation is to locate and apply suitable emission factors to compute and then categorize as aggregated the air pollutant emissions to include many individual emissions centred on the development of emission factor for oil production operations in the Kuwait Oilfields. The second task is selection of case study for air quality modelling along with a regional meteorological simulation of the selected case study using a prognostic model for which surface and upper air data are available becomes the third task. This step is of utmost importance for delimiting the size of the dispersion modelling domain if the loss of pollutant mass at the boundary of the

computational grid boundary is to be avoided when applying the modelling system. The chosen event is decided upon air quality data becoming available that, conjointly with historic meteorological data, can allow us to study dispersion patterns of plumes from flaring operations in the Kuwait oilfields. The last task focuses on performing an analysis of the source–receptor relationship for flares at the oil production operations in the Kuwait Oilfields complex.

Among the most important emission sources from the oil industry are flares. Nonetheless, the impacts of atmospheric emissions of current petroleum operations in the region has been assessed through this screening study using, for instance, records of flaring operations taken by the personnel at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources.

1.4.1 Literature Review

A search of detailed literature on the subject under investigation has been under taken during the first phase of study. Developments in the subject have also been regularly reviewed during the course of the study period to identify the current gaps of research for different area. The review includes:

- Literature on the subject for most relevant publications related to average annual emissions of air pollutants in the oilfields production operations facilities in the world

- Literature on associated emissions

- Literature on environmental impact

- Literature on emission from flaring

- Literature on the air pollution monitoring and data analysis related to climatic parameters with respect to the pollutants measured within the residential areas.

- Literature on the subject of air modelling as a research tool to study and assess the impact of industrial activities on urban areas.

- Literature on emission mitigation Strategy

Other sources of information on the air pollution problem in the state of Kuwait as well as impact assessment studies of pollutants released by oilfield production operation were also obtained.

1.4.2 Data Collection and Analysis

Many different kinds of data related to the state of Kuwait were collected and analysed for the purpose of the emission inventories and the modelling and dispersion of methane, non-methane hydrocarbons and SO_2 emitting from flaring within Kuwait Oilfields to provide a comprehensive account and estimates of all emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields and plan future strategies to control emissions. These data consists of:

- **Sources Identification**

The location of Kuwait oilfields in the North, East, South and West has a strong impact on the ambient air quality in the State of Kuwait. Nonetheless, the impacts of atmospheric emissions of current petroleum operations in the region can be assessed through a screening study using, for instance, records of flaring operations taken by the personnel at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources. A comprehensive account and estimates of all emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields. This inventory records the monthly emissions of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons. The emissions are generated from various point and aggregated sources to obtain total pollutants load of ambient air in and around oil fields. The emissions of pollutants from the flaring associated with all types of operations in the oilfields. In this work the data on methane, non-methane hydrocarbons and SO_2 emissions are used as the necessary input for the ISCST3 model.

- **Information on Kuwait Oilfields**

Kuwait Oilfields information such as pollutant emission rate (g/s), Sources coordinates Universal Transverse Mercator (UTM), source height (m), exit inner diameter (m), exit gas speed (m/s), and exit gas temperature (°C). The required information on all the location coordinates, the respective emission rates and stacks characteristic (height, diameters), flue gas velocity and temperature at the discharge have been obtained from all flares from Kuwait Oilfields.

- **Geographical Data**

Geographical information such as terrain elevation of Kuwait, location coordinates in UTM for all Kuwait Oilfields as well as for the Kuwait EPA monitoring stations and the residential areas were obtained.

- **Kuwait EPA Air Quality Monitoring Network Data**

In order to assess the air quality in Kuwait, measurement of the concentrations of pollutants for year 2006 are collected from the existing Kuwait EPA air quality monitoring network.

- **Meteorological Conditions of State of Kuwait**

Meteorological conditions play a major role in the dispersion of the pollutions over the State of Kuwait. One year hourly records of the surface and upper air meteorological data for year 2006 obtained from the KIA weather station. The meteorological data required are anemometer height (m) wind speed (m/s), wind direction (degree) clockwise from the north, air temperature, total and opaque cloud cover (%), stability class at the hour of measurement (dimensionless) and mixing height (m).

1.4.3 Modelling and Simulation

The Industrial Source Complex for short term (ISCST3) dispersion modelling which is modified and approved by the US EPA in 1999 was used. The ISCST3 is an air quality model based on the Gaussian plume simplification of the diffusion equation that assumes steady state (time independence) in the input meteorology and source concentration. This

model is used in calculation and prediction of methane, non-methane hydrocarbons and SO_2 pollutant concentrations resulting from flaring activities of Kuwait oil field. Different scenarios based on the meteorological conditions in the state of Kuwait were used to investigate the impact of methane, non-methane hydrocarbons and SO_2 on the residential areas. The model result data are discussed in Chapter 9.

1.5 Overview of the Structure

This thesis is documented in ten chapters as follows:

Chapter 1: General Introduction

An introduction is to cover the air pollution problem in Kuwait and to provide a comprehensive account and estimates of all emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields and to plan future strategies to control emissions. The importance of the research, the aims and objectives, and the research methodology are presented in detail.

Chapter 2: History of Kuwait Oilfields

This chapter provides the background information about Kuwait oilfields and their history. Moreover, this chapter present, the state of Kuwait environmental concern, air pollution and health effects.

Chapter 3: Emission Inventory

The development of a complete emission inventory is an important step in an air quality management process. Emission inventories are used to help determine significant sources of air pollutants establish emission trends over time, target regulatory actions, and estimate air quality through computer dispersion modelling. A step by step guide is presented in preparation of emission inventories. It contains information on the purpose, process, methodology and application of emission inventory investigations.

Chapter 4: Total Emissions from Flaring

Total flare emissions inventory of air pollutant in all Kuwait Oilfields area's has been prepared. The data produced flare air pollution inventory, extent of air pollutant emissions and assessment of the ambient air quality in the sites studied, comparison with local and international standards, identification of major sources for pollution, preliminary proposal for reduction, control and treatment methods.

Chapter 5: Emission Inventory Results

The total emissions of primary pollutants associated from flaring activities from Kuwait Oilfield have been estimated. A comprehensive inventory records the monthly emissions of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane: resulting from oil production operations in the Kuwait Oilfields. The emissions are prepared from various point sources and aggregated to have total pollutants load of ambient air. Emissions of flaring pollutants are associated with all operations in Oilfields, GC's, BS's, Tank areas and other oil production related activities. Detailed emission inventory data is a necessary input parameter for atmospheric dispersion modelling.

Chapter 6: Air Pollution Dispersion Model

The air pollution modelling techniques for analyses of the dispersion of the pollutants are introduced. Overview of the present state of air quality modelling and the application of the model that has been used during this research to predict ground level concentrations of gases emitted from Kuwait Oilfields has been provided.

Chapter 7: Meteorological condition and Data Analysis for State of Kuwait

As discussed in proceeding chapters, ISCST3 model needs to process the meteorological data representative of the general area being modelled. The collected meteorological data is not always in the format supported by this model; therefore, the meteorological data

needs to be pre-processed using the U.S. EPA PCRAMMET program. So, meteorological conditions are discussed in details.

Chapter 8: Air Quality Monitoring Stations in the State of Kuwait

This chapter present the description and background information of the Kuwait air quality monitoring network and the design methodology of the air pollution monitoring sites.

Chapter 9: Dispersion Model Results

This chapter presents the application of ISCST3 dispersion model to obtain the spatial and temporal variation of the selected primary pollution (methane, non-methane hydrocarbons and SO_2) from Kuwait Oilfields flaring over the State of Kuwait. Also, evaluating the ISCST3 model, by comparing the model prediction with the observed concentration of methane, non-methane hydrocarbons and SO_2 obtained from the monitoring sites are presented.

Moreover in this chapter, the impacts of methane and non-methane hydrocarbons emissions emitted from flaring activities at oil production facilities at Kuwait Oilfields have been assessed through a screening study using, for instance, records of flaring operations taken at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources. Also, the impact of SO_2 emissions from flaring activities of crude oil production operation at WK Oilfields has been discussed.

Chapter 10: Conclusions and Future Work

Finally, in this chapter an overview of the contributions and conclusions with recommendation and future research ideas are presented.

Chapter 2
History of Kuwait Oilfields

2.1 Introduction

Air pollution is a major environmental health problem affecting the developing and the developed countries alike. The effects of air pollution on health are very complex as there are many different sources and their individual effects vary from one to the other. It is not only the ambient air quality in the cities but also the indoor air quality in the rural and the urban areas that are causing concern. In fact in the developing world the highest air pollution exposures occur in the indoor environment. These pollutants are also deposited on soil, plants, and in the water, further contributing to human exposure. Air pollutants that are inhaled have serious impact on human health affecting the lungs and the respiratory system; they are also taken up by the blood and pumped all round the body.

During the petroleum process operations, chemicals are either emitted directly to the atmosphere or released from the processing that takes place. Petroleum related air pollutants can have a wide variety of adverse environmental impacts. Chronic exposure may increase the incidence of respiratory and cardiovascular ailments in humans, severely damage many types of vegetation, corrode buildings, and cause unpleasant odours and appearances.

Crude oil is a mixture of hydrocarbons ranging C_1 to C_n where n could be as large as 50 constituting thousands of organic compounds. The hydrocarbons with low number of carbon atoms have high vapour pressure and low boiling point temperature (T_B) resulting into high tendency of evaporation. The hot and arid atmosphere of the State of Kuwait facilitates evaporation of high volatile organic substances, which have low T_B and high vapour pressure resulting into high organic gas/vapour load in the ambient air. Other than VOCs in hundreds, there are primary pollutants, CO, CO_2, SO_2, H_2S, NO_x and $PM_{2.5}$ and

PM_{10}, which are released during various production operations of crude oil (Gas Turbines, Diesel Turbines, Gas Boilers, Gas Engines, Gas/Diesel Engines, Gas Heater Furnaces and Flares consuming different types of fuel and other products from oil industries.

In the crude oil production sectors, there is a need for a thorough knowledge of gaseous emissions resulting from the flaring of associated natural gas of known composition on daily basis through combustion activities under several operating conditions. This can help in the control of gaseous emission from these flares and thus in the protection of their immediate and distant environment against environmental degradation via air pollution.

Oil industries are the major economical strength of the Gulf region; and yet industrial hazards and a fragile environment can have a profound impact on the region. For this reason, environmental issues are becoming a part of day to day life and can no longer be ignored. One of the most visible signs associated with the crude oil production is gas flaring which is widely criticized as substantial volumes of carbon dioxide are emitted [contributes to the greenhouse effect]. It is also viewed by many as wasteful energy that could be better utilized and even can generate revenue.

In Kuwait, the most significant impacts on air quality have been from the oil industries. Oil industry activities emit toxic organic chemicals into the atmosphere.

This chapter provides the background information about Kuwait Oilfields, the history and the environmental concern in the state of Kuwait.

2.2 Kuwait Oil Company History

The first exploration well was drilled at Bahrah. In February 1938, oil was discovered at Burgan. Eight more wells were drilled at Burgan during 1938-1942. Operations, however, remained suspended until the end of the Second World War. On June 30, 1946

the first crude oil shipment was exported. Oil was later discovered at Rawdhatain in North Kuwait in 1955 and at Minagish in 1959.

In 1964, KOC took the first steps to exploit natural gas that now provides substantial additional revenue for Kuwait. In 1974, a participation agreement was ratified by the Kuwait National Assembly giving 60 per cent control of the operations of KOC to the State of Kuwait, the remaining 40 per cent being divided equally between BP and Gulf Oil Corporation. In March 1975, the Kuwaiti Government took over the remaining 40 per cent shares, thus assuming full control of KOC.

Kuwait contains an estimated 94 billion barrels of proven oil reserves, more than 9% of the world total oil reserves. The Neutral Zone area, which the State of Kuwait shares with Kingdom of Saudi Arabia, holds an additional 0.8 billion m^3 (5 billion barrels) of reserves, half of which belong to Kuwait. Most of Kuwait's oil reserves are located in the Greater Burgan area, which comprises the Burgan, Magwa and Ahmadi structures. Greater Burgan is widely considered the world's second largest oil field and accounts to about 11.13 billion m^3 (70 billion barrels). The bulk of Kuwait's oil production occurs at the onshore Greater Burgan field, where Burgan, Magwa, and Ahmadi structures produce roughly 254,380 m^3/day (1.6 million BPD) combined. Most of Kuwait's other producing fields are relatively small and include the 39,747 m^3/day (250,000 BPD) Raudhatain, 25,438 m^3/day (160,000 BPD) Sabriya, 9,539 m^3/day (60,000 BPD) Minagish, and 9,539 m^3/day (60,000 BPD) Umm Gudair fields.

The Burgan Field in the desert of SEK is one of the world's largest and richest oil fields. It is so rich that it is one of the world's easiest production sites, with oil practically flowing to the surface on its own. Burgan has helped Kuwait become one of the largest oil exporters. Greater Burgan was discovered in 1938. All production during the last 40 years has been by its natural pressure. Although natural gas injection has been carried out for some time, no water-flooding has been initiated yet. Recoverable reserves of the field are 13.8 billion m^3 (87 billion barrels) of oil.

There were originally 26 Gathering Centers in KOC operating oilfields prior to invasion of the country. The first center 'GC-1' was commissioned on 7th June, 1946 at Burgan Oilfield and the last center 'GC-26' on September 1980, at the Ratqa oilfield. Presently twenty-one (21) Gathering Centres are operational and receive crude oil from various wellheads located in the producing oilfields. The GCs stabilize the crude oil by multi-stage stabilization process and separate gas and water from the crude oil to meet its quality required for downstream operations.

SEK has 14 Gathering Centres in operation. The overall effective production capacity of the SEK area from these 14 GCs is around 254,380 m^3/day (1600 MBPD). The NK area has three GC's that handle about 103,342 m^3/day (650 MBPD). In the West region, with the recent commissioning of GCs 27 and 28, the output capacity of this area has built up to near 69,955 m^3/day (440 MBPD) from the previous output of 25,438 m^3/day (160 MBPD). Most of the crude oil produced from North, West and SEK areas flows naturally with associated gas and has low viscosity. Very few wells have heavy and viscous crude which require artificial lift systems (i.e. Gas Lift, or Electrical Submersible Pumps) to assist the production.

Kuwait's oil reserves are located in to three productions area's as follows;

- Greater Burgan area located in South East Kuwait (SEK), which comprises the Burgan, Magwa and Ahmadi structures areas, which has 14 gathering centers (GCs) [GC01- 04, GC06 -11, GC19 -22] and 2 booster stations (BS).

- Minagish and Umm Gudair fields located in West Kuwait (WK) have 4 GCs [GC-16, GC-17, GC-27 and 28] and one booster stations (BS).

- Ratqa, Raudatin and Sabiriyah are located in North Kuwait (NK) have 3 GCs [GC-15, GC-23 and GC-25] and one booster station (BS).
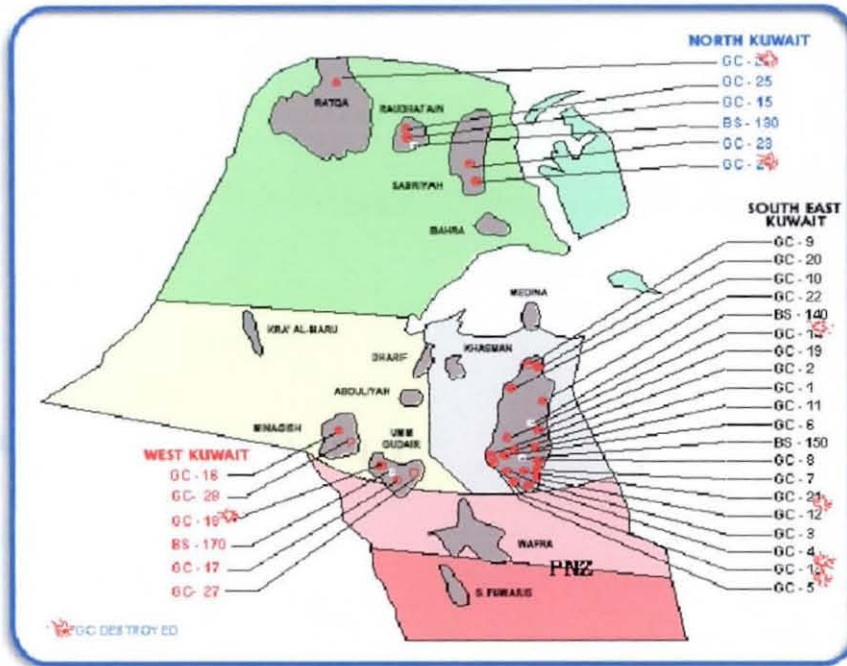
Figure 2.1: Major Oilfields and Gathering Center (GC) in the State of Kuwait

2.3 Kuwait Oil Production Operations Facilities

KOC manages complex and extensive oil production operations including oil wells, gathering centers, booster stations, and tank farms. The crude that is obtained from various wells is separated and stabilized at gathering stations. The stabilized oil fraction is pumped to tank farms while the gas fraction is retained for further separation. The water and crude in the low-pressure gas and high-pressure gas separators are separated. Gas and oil are pumped through booster stations for further refining or transported for marketing. The flare boxes at the site are used to burn the excess gas that is not liquefied by the compressors and excess oil resulting due to emergency shutdowns. Normal operating emissions are due to excess of fuel gas, fuel combustion in hot oil heater. The total emissions of hydrocarbons arise mainly from pipe network, pipe joints, flanges, valves fittings, especially crude oil tank farm, and also from open oil-water treatment pits or spills.

A Gathering Center (GC) is an Oil Production facility having the following functions (See Figure 2.2):

- Incoming flowlines, headers manifolds
- High Pressure (HP) /Low Pressure (LP) Separators
- Wet, Dry and Test Tanks
- Desalter /Dehydration Trains
- Condensate Recovery Units (CRU)
- Transit Pumps
- Gas Scrubbers
- High Pressure / Low pressure gas and Tank Vapor systems
- Chemical Injection system
- Instrument Air System
- Fire water system
- Brackish Water system
- Flares
- Electrical System
- Instrumentation and Control Systems

With reference to the typical configuration the following main processing steps take place in the GC.

- The incoming crude is flashed in the HP Separators at about 18.9 bar (260 psig) and in LP Separators at 5.15 bar (60 psig) and then the crude is routed to the Tanks.

- The gases from the HP / LP Separators are sent to BS for further compression. Tank Vapors are compressed in the CRU to produce condensate and CRU off gas. Condensate is dispatched to the refineries. CRU off gas is routed to the HP system. The HP/LP gas systems are provided with pressure control valves to route the excess gases to the HP/LP Flares when Booster Stations are shutdown or partially available.

- The wet crude from the Wet Tank is fed by pumps to the Desalter/ Dehydration trains to produce crude of quality of less than 0.10% Basic Sediment and Water (BS&W) and 28.5 mg/l 10 Pounds per Thousand Barrels (PTB) of salt.

- The Desalter/ Dehydration trains achieve the product quality by removing salt and water through application of the following:

  - Heating
  - Electrostatic field-2 Stages
  - Mixing with fresh Brackish water (Wash water)
  - Demulsifier Chemicals
  - Settling time

A typical Desalter Train consists of crude / crude heat exchanger, crude preheater, Desalter 1 and 2 stages and the wash water circuit- which includes wash water pumps and wash water heat exchangers. The train has its own chemical injection systems for injecting demulsifier, scale inhibitor, corrosion inhibitor in to crude oil and oxygen scavenger and biocide in to wash water.

- The product crude (Dry Crude) from the Desalter/ Dehydration trains is then sent to dry tanks. The dry crude from dry separator train is routed directly to dry tank. Transit Pumps dispatch dry crude to tank farms through the crude transit network.

- The wet tank provides a large settling time for the oil water separation. Effluent water from the wet tank is disposed off in the water disposal wells by injection or send to disposal pits for natural evaporation.

The HP and LP separated gases from the GCs are transmitted to the Booster Stations via respective HP and LP gas networks. At the Booster Stations, the HP and LP gases are compressed for further transmission to the Liquefied Petroleum Gases (LPG) Plant. The condensate recovered from the compressed and cooled gases in the Booster Stations is

dehydrated and routed to the LPG Plant through dedicated pipelines. Tank Vapours (TV) is locally compressed at the GCs by the Tank Vapour Compressor (TVC).

The gas produced at WK is mostly sour (20,000 to 30,000 ppm H_2S), hence after its compression and dehydration at local stations is first transported to the existing KNPC's Acid Gas Removal Plant (AGRP) for sweetening before being forwarded to LPG Plant. Both Gas and Condensate pipelines are equipped with Pig Launchers and Receivers to facilitate pigging and cleaning of the lines.
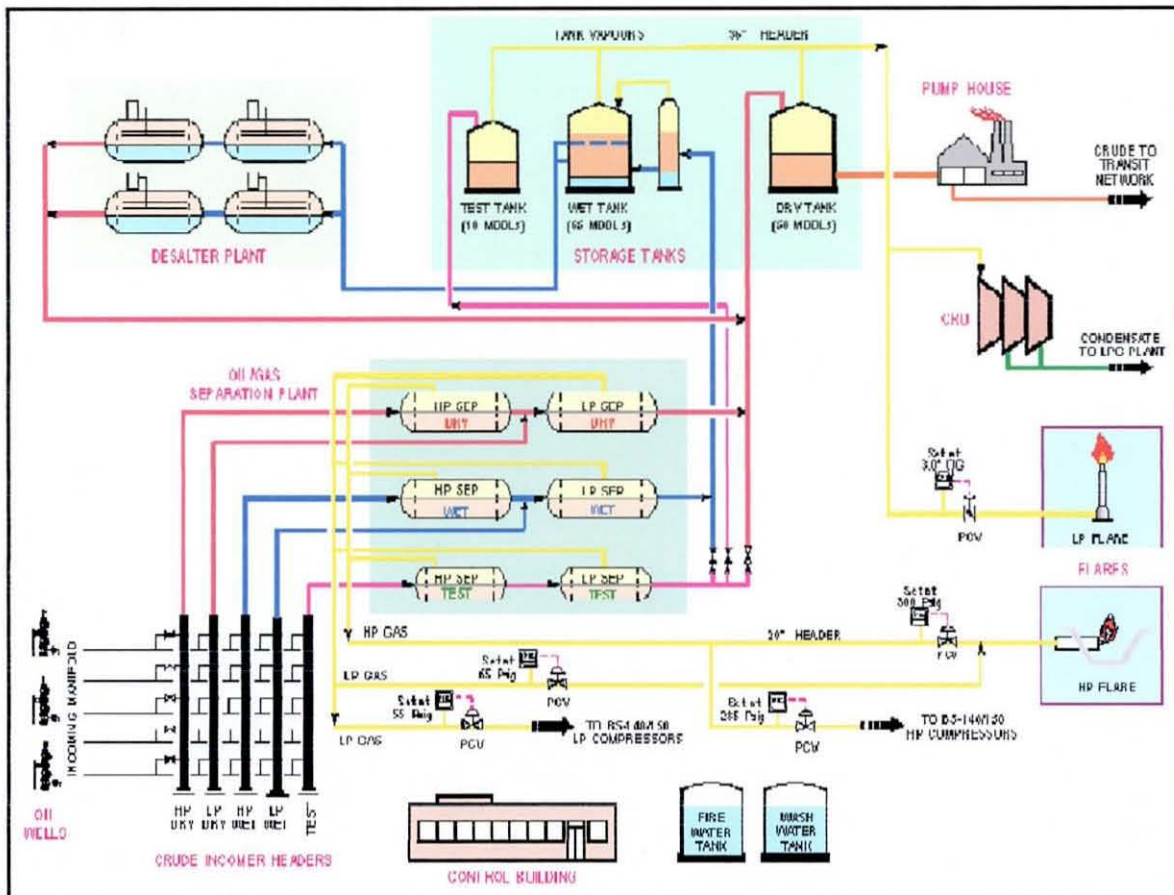
Figure 2.2: Typical Gathering Center (GC) in KOC

2.4 Environmental Concern

The associated problems with this dependence on oil, its production, distribution, trade and use to fuel the world economies is causing extremely damaging effects on the environment either knowingly or unintentionally.

These activities can disrupt the human population, the animal and fish life in the region. Oil waste dumping, production pollution, and spills wreak havoc on the surrounding wildlife and habitat. It threatens the extinction of several plants, and has already harmed many land, air, and sea animal and plant species.

The environmental damage that is a result of oil retraction and production can also directly affect human life in the region. Damage can include pollution of water resources and contamination of the soil.

Oil spills can interfere with the normal working of power stations and desalination plants that require a continuous supply of clean seawater and with the safe operation of coastal industries and ports.

2.5 Environmental Impact of Gulf War

In the aftermath of the Gulf war, scientists calculated that the release of 317,975 m^3/day (two million barrels of oil per day), can generate a plume of smoke and soot which can cover an area of half of the United States. Weather patterns and climactic conditions could have carried such a plume great distances so as to severely hamper agricultural production in remote areas of the world.

Another concern was centered around the effects of the height of such a smoke plume, where upon reaching a specified height 10,668 m to 12,192 m (35,000 to 40,000 feet) and temperature (400 degrees Celsius), such a plume would cause a serious erosion of the ozone layer which could be highly hazardous to plant and animal life.

Scientists attempted to draw attention to the potential effects of acid rain from the Kuwaiti oil fires. Kuwaiti crude contains 2.44% sulfur and 0.14% nitrogen, and it was

estimated that the sulfur dioxide and nitrous oxide emissions were between 0.142 m^3/s and 1.89 m^3/s (750 and 10,000 tons per day), thereby causing inordinate damage to agricultural production in the region.

By November 1991 the last of the burning oil wells had been capped, but the scale of damage to the Kuwaiti economy and ecological environment was just beginning to be assessed. Hundreds of miles of the Kuwaiti desert were left uninhabitable, due to the accumulation of oil lakes and of soot from the burning wells. Indeed, Kuwait is still recovering from the environmental damage it suffered during the Gulf War, [According to Jonathan Lash, the president of the World Resources Institute].

Amin and Hussain [1994] measured the concentrations of gaseous chemicals in the eastern province of Saudi Arabia during 1991, to determine the air-quality impact of the Kuwait oil fires. The data were compared to standards set by the Metrology and Environmental Protection Agency (MEPA) in Saudi Arabia. In most cases, the gaseous concentrations were within the MEPA specified permissible limits, but the concentrations had increased significantly compared to previous years.

However, Kuwait can also point to several successes in cleaning up after the war. The burning oil wells were put out within six months of Kuwait's liberation.

Chapter 3
Emission Inventories

3.1 Introduction

An emissions inventory is a database that lists, by source and the amount the air pollutants discharged into the atmosphere during a given time period. The main objective of an emission inventory is to assess sources of discharges to air. Thus emission inventories are an important component of most air quality management strategies.

The development of a complete emission inventory is an important step in an air quality management process. Emission inventories are used to help determine significant sources of air pollutants establish emission trends over time, target regulatory actions, and estimate air quality through computer dispersion modeling. An emission inventory includes estimates of the emissions from various pollution sources in a specific geographical area. A complete inventory typically contains all regulated pollutants.

Soetjiptono et al.,[1996] have presented methods and procedures to quantify the emissions from the sources in the Duri Indonesia field (process vents, production impoundments and wastewater canals, roads, fugitive emissions, storage tanks, and combustion sources). Emissions of Non-methane hydrocarbons (NMHC) and aromatic hydrocarbons (BTEX, Benzene, Toluene, Ethylbenzene and xylenes), hydrogen sulfide, nitrogen oxides, sulphur oxides, particulate matter (PM),and carbon monoxidethe were addressed. Because of the diverse nature of the sources in the field, a wide range of emission estimating procedures were used including direct measurement methods, empirical methods based on mass transfer principles, and standard emission factors or procedures available from the United States Environmental Protection Agency (U.S. EPA). Millichamp et al., [2001] have prepared report guide to prepare emission inventories in New Zealand.

This step by step guide is presented to prepare emission inventories together with certain information on the process, methodology and application of emission inventory investigations.

3.2 Emission Inventory Objectives

As shown in Figure 3.1 there are strong linkages between the disciplines of monitoring, modelling and emission inventories. In addition, emission inventories play a significant role in the development of an air quality strategy, generally forming the basis of the assessment of the effectiveness of management measures.
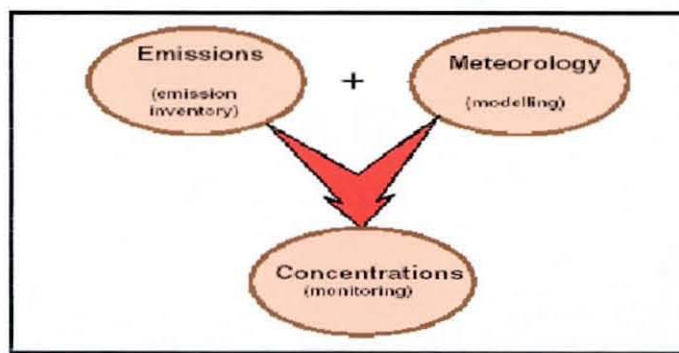
Figure 3.1: Air Quality Management Strategy

An emission inventory is an estimate of the quantity of emissions discharged to air for a given area. It can include a variety of contaminants and should include estimates from all major sources of those contaminants. An inventory of emissions are prepared for a range of areas from a single industrial site with multiple discharge sources, to an assessment of urban, regional or national emissions.

Emission inventories are used in:

- Assessing priorities for air quality monitoring
- Indicating the state of the environment
- Determining any major sources of emissions of which the regulatory authorities are unaware
- Assessing relative contributions to emissions to assist processing of industrial resource consent applications
- Identifying potential policy and regulatory options

3.3 Air Quality Monitoring

Air quality monitoring is an integral component of managing air quality as the need for management intervention that stems from data on concentrations of contaminants. The three main air quality assessment tools are:

1. Ambient monitoring
2. Models
3. Emission inventories/measurement.

The ultimate purpose of monitoring is not merely to collect data, but to provide the necessary information required by scientists, policy makers and planners to enable them to make decisions on managing and improving the environment.

Monitoring fulfils a central role in this process, providing the necessary scientific basis for policy and strategy development, objective setting, compliance measurement against targets and enforcement action.

All three assessment tools are interdependent in scope and application. Accordingly, monitoring, modelling and emission assessments are regarded as complementary components to exposure assessment or in determining compliance with air quality criteria.

3.4 Emission Inventories and Source Studies

Emission inventories can be used to identify sources of emissions and to assist in the assessment of options for managing air quality. They provide an estimate of the quantity of a contaminant emitted by a particular source and the combined emissions from all sources. The basic methodology of an emission inventory is use of an average emission rate for each activity, based on the quantity of material. For some activities actual source data are used.

The potential sources of uncertainty include assessing the level of activity resulting in the discharge. In this regard it is important to note that emission inventories represent

an estimate of the average emissions for a particular time period and are not necessarily indicative of actual emissions for a given day.

3.5 Atmospheric Dispersion Modelling

Atmospheric dispersion modelling is used to assess variations in concentrations of contaminants across a study area. This is done by assessing the impact of meteorology and topography on emissions of contaminants and thus requires detailed meteorological and geographical data across the study area.

Detailed emission inventory data are also a necessary input parameter for atmospheric dispersion modelling. Atmospheric dispersion modelling has a number of uses as an air quality management tool. These include:

- Assessing the extent of an air-shed or the area to which management intervention should be applied

- Assessing the impact of variations in emissions on concentrations of a contaminant

- Estimating concentrations of contaminants in locations where monitoring is not conducted

To estimate concentrations in areas where monitoring is not conducted, has many uses from an air quality management perspective. It provides an indication as to the suitability of monitoring sites and the extent to which concentrations measured at existing sites are typical of the area of interest. It can also be used in assessing the exposure of a population to ambient air concentrations of contaminants and are used as an input parameter to health studies.

Atmospheric dispersion modelling can provide a powerful tool for interpolation, prediction, and optimisation of control strategies if they are validated by real-world monitoring data. It is important, also, that the models utilised are appropriate to local conditions, sources and topography, as well as being selected for compatibility with available emission and meteorological datasets. All models depend on the availability of reliable emission data.

3.6 Managing An Emission Inventory Study

The process of preparing an emission inventory is illustrated below as a task schedule (Figure 3.2). This breaks the process down into eight key components and indicates the relative order in which the tasks should be conducted. Tasks listed in parallel can be carried out simultaneously.
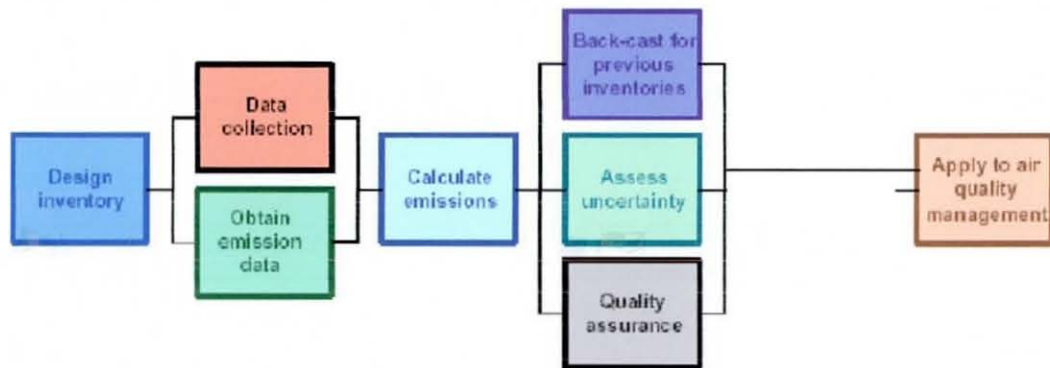
Figure 3.2: The Process of Preparing An Emission Inventory

3.6.1   Emission Inventory Design

The major task in preparing an emission inventory is the design phase. This comprises a number of subtasks, identified below in preferred order of achievement and discussed in the following sections.

3.6.1.1 Identify Key Issues

Identifying key air quality issues in locations where problems exist has four main concerns:

- Assessing the scope and objectives of an emission inventory
- Identifying the sources that are included
- Presenting the report in a meaningful context
- identifying contaminants to be included

3.6.1.2 Identify Contaminants

The main limiting factor in the selection of contaminants to be included is the availability of emissions data. Provided emission factors or other emissions data are available a number of approaches to the selection of contaminants are possible:

- All encompassing collect as much data as possible on all contaminants
- Collect data for any local air quality issues plus data for key indicator contaminants
- Collect data relevant to current and potential future air quality issues

An emission inventory would typically include emission estimates for PM_{10}, CO, SO_x, NO_x, VOCs, and CO_2.

3.6.1.3 Area Selection

Selecting an appropriate boundary for an emission inventory will depend on the purpose of the inventory and its intended application. A major consideration in determining the area to be included is the local topography and meteorology. These characteristics help define an air-shed, which is the area within which emissions travel and influence. Characterisation of an air-shed is beyond the scope of an emission inventory investigation. However, it is necessary when designing the inventory to consider the air-shed concept and the extent to which emissions that occur outside of an urban area may or may not contribute to ground level concentrations.

3.6.1.4 Temporal Distribution

Data are represented for a number of different timeframes including hourly, 24-hourly, monthly, seasonally and annually. These all represent periods during which emissions may vary for a number of reasons. The temporal distributions for the inventory are selected to complement the key air quality issues identified previously and the intended application of the inventory.

3.6.2 Data Collection

An important aspect of collecting data is ensuring adequate representation at the spatial resolution determined during the design of the inventory. Emissions from area sources are estimated for the whole study areas and are generally spatially distributed based on population density. The use of the area source classification, however, can lead to error if population or any other distribution method used is not a good indicator of the actual variation in emissions.

3.6.3 Obtaining Emission Data

Emission data are available in a number of forms, the most common of which are an emission factor. Real data on the emission rate from the activity being assessed are another form of emission data and is preferable to using an emission factor. This data are generally only available for some industrial discharges and relate to testing done at the time of application for consent.

Different methods for obtaining emission data, listed in order of decreasing confidence, include:

- Continuous emissions data – equipment which measures the concentration of pollutants on a continuous basis
- Stack sampling data – involves the insertion of a sampling probe into a stack, the extraction of a sample and the analysis of discharge rate
- Material balance calculations – based on knowledge of the amount of material entering a Process and consumed by the process
- Emission factor – estimate of average emission rate for a particular process
- Published correlations or equations

An emission factor is the rate of emission per unit of activity for a particular process. The unit of activity varies with the discharge type, but would typically be one of the following:

- Hour of discharge occurring (e.g., g/hour)
- Quantity of product produced (e.g., g/tonne of product produced)
- Quantity of product used (e.g., g/tonne)

Emission factors are established based on results of, preferably extensive, emission testing and are intended to represent typical emissions under standard operating conditions. In most cases they are an average of all available data of acceptable quality and are generally assumed to be representative of long-term averages of all facilities in the source category.

3.6.4 Emissions Calculations

Calculating the emissions is in fact one of the prime components of the emission inventory, particularly if purpose designed software or existing calculation spreadsheets can be used.

Different methods for calculating the emissions inventories are available, and the choice of method depends on the availability of data and time. The methods include continuous monitoring to measure actual emissions; extrapolating the results from short-term source emissions tests; and combining published emission factors with known activity levels.

There are numerous approaches to estimate emissions of air contaminants. In the following section, three approaches are discussed including;

- Direct measurement
- Mass balance
- Emission factors and emission models.

3.6.4.1 Direct Measurement

The most accurate way of estimating a source's emissions is directly measuring the concentration of air pollutants in the stack gas. Stack tests and continuous emission monitoring systems (CEMS) are two methods of collecting actual emission data.

The use of source test data reduces the number of assumptions regarding the applicability of emissions data to a source (a common consideration when emission factors are used); as well as the control device efficiency, equipment variations, and fuel characteristics. Even then, the results are applicable only to the conditions

existing at the time of the testing or monitoring. To provide the best estimate of longer-term (e.g., yearly or typical day) emissions, these operating conditions must be representative of the source's routine operations

3.6.4.2 Mass Balance

Mass balance is a method that estimates emissions by analyzing inputs of raw materials to an emission unit and accounting for all of the various possible outputs of the raw materials in the form of air emissions, wastewater, hazardous waste, and/or the final product. As the term implies, one needs to account for all the materials going into and coming out of the process for such an emission estimation to be credible and is illustrated in Figure 3.3.
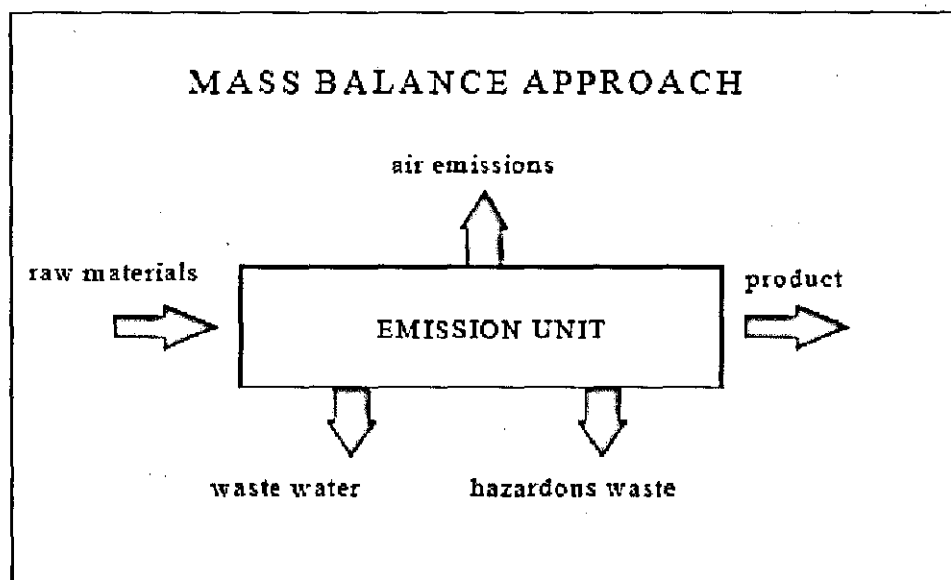
Figure 3.3: Mass Balance

A mass balance approach can provide reliable average emission estimates for specific emission units. For some emission units, a mass balance may provide a better estimate of emissions than an emission test would. In general, mass balances are appropriate for use in situations where a high percentage of material is lost to the atmosphere (e. g., sulfur in fuel, or solvent loss in an uncontrolled coating process).

Mass balances may be inappropriate where material is consumed or chemically combined in the process, or where losses to the atmosphere are a small portion of the total process throughput. As an example, applying mass balances to petroleum product storage tanks is not generally feasible because the losses are too small relative to the uncertainty of any metering devices. In these cases, emission factors can be used

3.6.4.3 Emission Factors and Emission Models

An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. An emission factor is a ratio of the amount of a pollutant emitted per throughput of material (for example, pounds of NOx per gallon of residual oil burned).

Emission factors are founded on the premise that there exists a linear relationship between the emissions of air contaminant and the activity level. A wide variety of sources can use emission factors to estimate their emissions.

An emission factor may be used to estimate emissions when actual emission data are not available. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category. General emission factors are available to the public. However, variations in the conditions at a given facility, such as the raw materials used, temperature of combustion, and emission controls, can significantly effect the emissions at an individual location. Whenever possible, the development of local emission factors is highly desirable.

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e. g., kilograms of particulate emitted per mega gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are

generally assumed to be representative of long-term averages for all facilities in the source category (e.g., a population average). The emission factor is used to calculate the total emission from a source as an input for the emission inventory. The general equation for calculating emissions using an emission factor is:

$$E = A \bullet EF \bullet \left(1 - \frac{ER}{100}\right) \qquad . \qquad (3.1)$$

Where:

    E = emissions

    A = activity rate

    EF = emission factor

    ER = overall emission reduction efficiency

Emission factors can be used to derive estimates of gas emissions based on the amount of fuel combusted or on industrial production levels. The level of precision of the resulting estimates depends significantly on the activity in question.

For combustion processes, both domestic and industrial (excluding generators), emissions for each time period are calculated as follows:

Contaminant emissions (g) = weight of fuel burnt (kg) x emission factor (g/kg)   (3.2)

For most other industrial processes emissions can be calculated using one of the following, depending on the activity specified in the emission factor:

Contaminant emissions (g) = amount of product consumed (kg) x emission factor (g/kg)   (3.3)

Contaminant emissions (g) = amount of product produced (kg) x emission factor (g/kg)   (3.4)

Contaminant emissions (g) = no. of hours of discharge (hr) x emission factor (g/hr)

                                                                      (3.5)

3.6.4.4 Limitations of Emission Factors

Data from source-specific stack tests or continuous emission monitoring systems are usually preferred for estimating a source's emissions because those data provide the best representation of the tested source's emissions. However, test data from individual sources are not always available and, even then, they may not reflect the variability of actual emissions over time. Thus, emission factors are frequently the best or only method available for estimating emissions, in spite of their limitations.

Average emissions differ significantly from source to source and, therefore, emission factors frequently may not provide adequate estimates of the average emissions for a specific source. The extent of between-source variability that exists, even among similar individual sources, can be large depending on process, control system, and pollutant. Although the causes of this variability are considered in emission factor development, this type of information is seldom included in emission test reports used to develop emission factors. As a result, some emission factors are derived from tests that may vary by an order of magnitude or more.

3.6.5 Assessing the Uncertainty

Even the most well conducted emission inventories are subject to uncertainty. Errors are inevitable at the base level of data collection (e.g., the activity data and emission factors). This is because it is not possible to measure and incorporate fuel use, emission factors for all conditions under which these factors may vary. Thus the methodology uses activity data based on average consumption. Similarly, emission factors are based on average values derived from emission testing of often a limited number and variety of activities that discharge to air.

There are a number of options to choose from when deciding how to deal with the uncertainty associated with making estimates of emissions using emission inventory methodologies. These include:

- Ignoring the uncertainty
- Qualitative acknowledgement of the uncertainty
- Certainty rankings

- Quantifying the uncertainty for individual components, where available e.g., sampling error

- Combining the errors for individual components

An emission inventory should contain a discussion detailing sources that have been excluded from the assessment because of lack of data and the potential significance of the exclusion, irrespective of the approach chosen for dealing with uncertainty. Similarly, the numbers of significant values used when reporting the emission estimates are considered, under any uncertainty assessment regime.

3.6.6 Quality Assurances

The purpose of quality assurance is to provide an accurate and consistent emission inventory. Good quality assurance gives confidence in the inventory and any resulting regulatory provisions. Quality assurance is integrated into the process of preparing an emission inventory at all stages. In that sense, it includes the documentation of the process undertaken, the methods used and the assumptions made. Additional quality assurance techniques that are applied at this stage in the process include:

- Checks on the accuracy of data entry
- Identifying outliers
- Peer review of emissions calculations
- Validation of data using consistency checks

Checks on accuracy of data entry and identifying outliers involve checking values are within an acceptable range. Examples of this include:

- Annual fuel use is not greater than daily fuel use times 365
- Daily hours of operation are not greater than 24
- Values for activity data are entered for each industrial process

In addition to this, processes for checking data entry accuracy are developed. These processes depend on the type of software used. Other data handling and transfer errors

are minimised through the development of software that does not duplicate data input requirements and presents outputs in the format required for reporting.

3.6.7 Back Casting for Previous Emission Inventories

"Back-casting" for previous emission inventories means applying the methodology used in preparing the current emission inventory to previous inventories carried out for the same general location. For example, if an inventory were prepared in 1995, then repeated in 2000 with some changes in methodology, the back-cast would apply the changes in methodology to the 1995 data.

The original 1995 inventory are referred to as the "original" and the revised version the "back-cast". The purpose of back-casting is to allow valid comparisons between two emission inventories to assess changes in emissions with time.

The key stages involved in preparing the back-cast include:

1. Identifying the differences in methodology between the inventories
2. Re-evaluating data from the original study in accordance with new methodologies
3. Presenting the results of the back-cast

3.6.8 Apply to Air Quality Management

The final task in the emission inventory process is applying the results to air quality management.

One aspect of the application of an emission inventory to air quality management is the projection of the emission estimates into the future. Such projections are very useful to the management of air quality as they can provide indicators of potential problems and can assist in the assessment of the effectiveness of regulatory options. However, projections rely on predictions of trends and are no substitute for conducting a proper inventory.

3.6.9 Methods for Estimating Air Emissions from Oil and Gas Field Production and Processing Operations

This section describes the procedures approaches for estimating emissions from most oil and gas field production.

3.6.9.1 Process Description

The petroleum industry is organized into the following four broad segments:

- Exploration and production
- Transportation
- Refining
- Marketing

The oil and gas field production and processing operations begin with exploration to locate new sources of crude oil and natural gas. When potential sources are located, wells are drilled to confirm the presence of oil or gas and to determine whether the reserves are economically sufficient to support production.

During production, crude oil and/or natural gas is recovered from wells and prepared for transportation from the field. Trucks, rail cars, barges and tankers are used to transport domestic crude oil to refineries. Domestic crude oil can also be transported from the field to refineries by a complex network of pipelines. Natural gas, which may be produced alone or in combination with crude oil, often must be processed at a gas plant to make it suitable for consumer use.

Oil and gas field production and processing operations are primarily defined by the following types of emission activities:

- Exploration and production
- Processing
- Combustion
- Storage and transport
- Wastewater

3.6.9.2 Emission Source

Emissions from oil and gas field processing operations result from both controlled and uncontrolled sources.

Exploration and Production

Emission sources associated with exploration and production include exploration, well-site preparation, drilling, waste pits, blowouts, well testing, and gas/liquid separation. Fugitive dust and combustion emissions from exploration and well-site preparation result from vehicles, heavy equipment and engines and turbine operation.

Drilling operations are a significant source of short-term air pollutant emissions, which some states consider to be a temporary source. During drilling, gas may seep into the well bore and become dissolved or entrained in the drilling mud. The gases are separated from the mud in a separator or degasser. Gases removed from the mud are either vented to the atmosphere or routed to a flare.

Waste pits storing hydrocarbon laden cuttings may be a source of VOC's and hazardous air pollutants (HAP) emissions. Well blowouts, although infrequent, are considered process upsets and can also be a source of VOC, HAP, and CH_4 emissions. Well testing can result in VOC, HAP and CH_4 emissions.

Emissions from gas/liquid separation processes include fugitive VOC and HAP from valves and fittings and from any operation upsets, such as pressure relief device releases due to overpressure.

Processing (Oil Industry)

Emissions from heater treaters result from fuel combustion and include typical fuel combustion pollutants: CO, CO_2, NO_x, SO_2, particulate matter less than or equal to 10 microns in diameter (PM_{10}), particulate matter less than or equal to 2.5 microns in diameter ($PM_{2.5}$), VOC, lead, and HAPs. Equipment leaks from piping components (e.g., valves, flanges and connectors) also result in fugitive VOC and HAP emissions.

Processing (Combustion)

Boilers and heaters provide local process heat, process steam, steam for electric generation, glycol dehydrator reboilers, and amine reboiler units. Internal combustion engines and gas turbines have many other purposes, such as compression of petroleum gases, compression of refrigerants, electrical generation, and pump and crane operation.

Flares are often used to control VOC emissions and to convert H_2S and reduced sulfur compounds to SO_2. Flares can be used to control emissions from storage tanks, loading operations, glycol dehydration units, vent collection systems, and gas sweetening amine units. Flares can also be used as a backup system for sulfur recovery units.

The pollutants of concern include NO_x , CO, VOC, PM_{10} , $PM_{2.5}$, SO_2 , CH_4 , and CO_2 . HAPs, primarily formaldehyde and acetaldehyde, are also potential pollutants from these combustion sources.

Flares convert potentially hazardous gases into less hazardous emissions. VOC, NO_x , CO, HAPs and CH_4 are the primary pollutants of concern with flares. If flares are used to oxidize H_2S and other reduced sulfur compounds, SO_2 will also be emitted. Depending on the level of conversion achieved, H_2S and other reduced sulfur compounds may also be emitted. Auxiliary fuel combustion is also a source of emissions. Fuel used to fire specific process or control equipment such as flares and incinerators result in additional combustion emissions.

3.6.9.3 Design and Operating Parameters Affecting Emissions

In general, the primary factors affecting emissions and their estimation for sources in oil and gas field processing operations are:

- Oil/gas composition
- Production rate/frequency of operation
- Type of control/recovery, if any

Since the flare/incineration process converts the H_2S to SO_2, the greater the H_2S concentration in the tail gas, the greater the SO_2 for better conversion emissions. Fuel gas can be added to the waste gas to increase the flame's temperature.

3.6.9.4 Description of Emission Estimation Methodologies

There are several methodologies available for calculating emissions from oil and gas field processing operations. The method used is dependent upon available data, available resources, and the degree of accuracy required in the estimate.

In the proceeding sections the methods available for calculating emissions from oil and gas field processing operations are discussed.

Stack Sampling

Stack sampling provides a "snapshot" of emissions during the period of the stack test. Stack tests are typically performed during either representative (e.g., normal) or maximum load conditions, depending upon the requirements of the state.

Samples are collected from the stack using probes inserted through a port in the stack wall, and pollutants are collected in or on various media and sent to a laboratory for analysis. Emissions rates are then determined by multiplying the pollutant concentration by the volumetric stack gas flow rate. Because there are many steps in the stack sampling procedures where errors can occur, only experienced stack testers perform such tests.

Emission Factors

Emission factors are available for many source categories and are based on the results of source tests performed at one or more facilities within an industry. Emission factors are available from various industrial associations such as the American Petroleum Institute (API), the Gas Research Institute (GRI), and the Chemical Manufacturers Association (CMA).

In addition, manufacturers often conduct research to develop emission factors for specific pieces of equipment. For a single facility, stack tests are usually preferable over emission factors, but for estimating emissions across a source category, emission factors can be used and are the only reasonable means of estimating emissions due to the number of sources or lack of individual facility emission estimates.

Calculation Programs

Several calculation programs or theoretical "models" are available for use in estimating emissions from oil and gas field processing operations. Emission estimating programs/models are available for the following types of emission sources:

- Glycol dehydrators
- Gas sweetening units
- Emergency and process vents
- Equipment leaks
- External combustion devices
- Internal combustion engines/gas turbines
- Storage tanks
- Flash losses
- Loading operations

Inputs for programs/models generally fall into the following categories:

- Chemical/physical properties of the material(s) involved (e.g., vapor pressure, vapor molecular weight)
- Operating data (e.g., amount of material processed, operating hours)
- Physical characteristics/properties of the source (e.g., tank color, tank diameter)

Chapter 4
Total Emissions from Flaring

4.1 Introduction

As discussed in the previous Chapter 3, flaring is used extensively in the energy and petrochemical industries to dispose of unwanted combustible gases by burning them in an open flame. The goal of flares is to consume the gases sent to them safely, reliably, and efficiently and through oxidation to produce lower hydrocarbon emissions to the atmosphere than would occur by simply venting the gases. Industrial flares are turbulent combustion systems that are affected by operating conditions, which in turn impact the flare destruction efficiency.

A wide span of air pollutant emissions is generated from the KOC flaring activities. Such emissions include carbon, nitrogen and sulfur oxide gases, methane and non-methane hydrocarbons and suspended particulates as well. The present study involved flare emissions inventory of air pollutant in all KOC area's. The data produced flare air pollution inventory, extent of air pollutant emissions and assessment of the ambient air quality in the sites studied, comparison with local and international standards and identification of major sources for pollution. This chapter present flares emissions, types of flare and flare process description.

4.2 Flaring

Flaring is a volatile combustion control process for organic compound (VOC) in which the VOCs are piped to a remote, usually elevated, location and burned in an open flame in the open air using a specially designed burner tip, auxiliary fuel, and steam or air to promote mixing for nearly complete (> 98%) destruction of VOCs. Completeness of combustion in a flare is governed by flame temperature, residence time in the combustion zone, turbulent mixing of the components to complete the oxidation reaction, and available oxygen for free radical formation.

Abu Dhabi National Oil Company (ADNOC) has adopted new environmental guidelines reported by Tarmoom, [1999] to be followed by all the oil and gas affiliate companies in Abu Dhabi and in particular launched a strong campaign to conserve gas usage and minimize flaring with an ambitious objective of zero flaring. ADNOC established a task force comprising representatives from all Abu Dhabi oil and gas companies in both upstream and downstream sectors of the industry to define, review and study gas flaring and gas conservation.

Amir et al.,[2000] have represented the introduction of the Multiphase Pumps and with the aid of the neutralization systems, Oil flaring was reduced by 38% by end of year 1998 and by 65% by end of year 1999, through the utilization of single-phase oil re-injection pumps. Moreover, Oil flaring was reduced to zero % by February 2000 during the operations where pH neutralization Systems was utilized. Therefore, the introduction of multiphase pumps would lead to achieving zero flaring emission during drilling and work over operations.

Misellati et al., [2006] have presented the zero flaring strategic objective of ADNOC to achieve 95% by the end of 2005. Flare reduction technologies utilized by Zakum Development Company (ZADCO) are presented as part of the path to zero emission flaring that requires a number of technologies and approaches including initial substantial gains through gas re-injection, to later more innovative approaches such as sour gas recovery that require the careful evaluation of project economics and a range of design alternatives.

Flares produce air pollutants through two primary mechanisms. The first mechanism is incomplete combustion of a gas stream, because like all combustion devices, flares do not combust all of the fuel directed to them. The second mechanism of pollutant generation is the oxidation of flare gases to form other pollutants. As an example, the gases that are burned in flares typically contain sulfur in varying amounts. Combustion oxidizes these sulfur compounds to form sulfur dioxide, a criteria pollutant. In addition, combustion also produces relatively minor amounts of nitrogen oxides through oxidation of the nitrogen in flare gas or atmospheric nitrogen in combustion air.

Combustion is complete if all VOCs are converted to carbon dioxide and water. Incomplete combustion results in some of the VOC being unaltered or converted to other organic compounds such as aldehydes or acids. If not properly designed and/or not properly operated, flares produce undesirable by-products including noise, smoke, heat radiation, light, sulfur oxides SO_x, NO_x and CO.

4.3 Atmospheric Flare Emissions

Flare emissions include, at a minimum, NO_x, CO and uncombusted flared gas compounds. In addition, if the flared gas contains sulfur-bearing compounds, emissions will also include H_2S and SO_2.

Products of combustion include NO_x, CO, and SO_2. Flared and pilot gas heat outputs impact emission rates of NO_x and CO. The sulfur content of both flared and pilot gases determines SO_2 emissions.

The flare's destruction efficiency determines what fraction of the flared gas remains uncombusted. The uncombusted flared gas compounds are generally volatile organic compounds, but may also include H_2S, CO, ammonia, and other organic and inorganic compounds present in the flared gas.

4.4 Safety Aspects

The availability of a flare is absolutely necessary in oil and gas production operations. It ensures that safe disposal of the hydrocarbon gas inventory in the process installation is possible in emergency and shutdown situations. Where gas cannot be stored or used commercially, it is essential that the risk of fire and explosion be reduced by flaring.

Even where associated gas is being sold or re-injected, small amounts of gas will still need to be flared or vented for safety reasons. Oil and gas processing and storage equipment is often operated at high pressures and temperatures.

When abnormal conditions occur, the control and safety systems must release gas to the emergency flare or vent to prevent hazards to the employees or public. Good maintenance and operating strategies are the main mechanisms used to keep this already small volume as low as practicable. Emergency flares are normally fitted with pilot systems maintaining a small flame as the ignition source in case the full size flare is activated.

4.5 Environmental Issues

Carbon dioxide and methane (the major component of natural gas) are known as greenhouse gases (GHG) associated with concerns about global warming. Flaring produces predominantly carbon dioxide emissions. The world organizations force the concerned comities to regulate GHG emissions and minimize their environmental impact.

The global warming potential of a kilogram of methane is estimated to be twenty-one times that of a kilogram of carbon dioxide when the effects are considered over one hundred years. When considered in this context, flaring will generally be preferred over venting the same amount of gas in the design of new facilities where sufficient amounts of gas will be produced to run a flare.

While there are still many uncertainties in the understanding of the complex issue of climate change, it makes sense to avoid the unnecessary release of carbon dioxide or methane into the atmosphere, where practicable. These points need to reduce emissions in a reasonably practicable way.

For environmental and resource conservation reasons, flaring should always be minimized as much as practicable, consistent with safety considerations. Flaring can have local environmental impacts, as well as producing emissions which have the potential to contribute to global warming. Available data [International Association of Oil and Gas Productions (OPG), 2000] indicate that, on a worldwide basis, gas flaring contributes only 1% of anthropogenic carbon dioxide emissions, and flaring and venting contribute only 4% of anthropogenic methane emissions.

The emissions concerned and their potential environmental effects are summarised in Table 4.1.

Gaseous emission	Health and environmental effect
Carbon dioxide (CO_2)	CO_2 is a greenhouse gas, meaning that it inhibits the radiation of heat into space, which may increase surface temperatures.
Methane (CH_4)	Methane is a potent greenhouse gas with an effect equivalent to 21 times CO_2 by weight.
Carbon monoxide (CO)	Direct effects upon human health (asphixiant). May contribute indirectly to global warming.
Oxides of nitrogen (NO_x)	NO_2 has direct effects upon human health and vegetation - causes respiratory illness and irritation of the mucous membranes. NO_x acts as a precursor to low-level ozone formation. NO_x contributes to acid deposition (wet and dry) which impacts both freshwater and terrestrial ecosystems.
Sulphur dioxide (SO_2)	SO_2 has direct health effects - causes respiratory illness. SO_2 contributes to acid deposition (wet and dry) which impacts both freshwater and terrestrial ecosystems.
Volatile organic compounds (VOC) (also known as non-methane hydrocarbons (NMHC))	VOC have direct health effects - causes eye irritation and coughing, some are carcinogenic. VOC acts as a precursor to low-level ozone formation.
Nitrous Oxide (N_2O)	N_2O is a potent greenhouse gas with an effect equivalent to 296 times CO_2 by weight
Perfluorocarbons (PFC)	PFC are potent greenhouse gases with an effect equivalent to $5700 - 11900$ times CO_2 by weight.
Sulphur Hexafluoride (SF_6)	SF_6 is a potent greenhouse gas with an effect equivalent to 22,200 times CO_2 by weight.
Hydrofluorocarbons (HFC)	HFC are potent greenhouse gases with an effect equivalent to 12 - 12000 times CO_2 by weight.
Halocarbons	Halons, chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) contribute to stratospheric ozone depletion. The ozone layer provides protection from UV sunlight which can damage human health, animals and plants.

Table 4.1: Health and environmental effects of air pollutants

4.6 Types of Flares

The various flare designs differ primarily in their accomplishment of mixing.

a) Steam-Assisted Flares

Steam-assisted flares are single burner tips, elevated above ground level for safety reasons, which burn the vented gas in essentially a diffusion flame. They reportedly account for the majority of the flares installed and are the predominant flare type found in refineries and chemical plants. To ensure an adequate air supply and good mixing, this type of flare system injects steam into the combustion zone to promote turbulence for mixing and to induce air into the flame.

b) Air-Assisted Flares

Some flares use forced air to provide the combustion air and the mixing required for smokeless operation. These flares are built with a spider-shaped burner (with much small gas orifices) located inside but near the top of a steel cylinder two feet or more in diameter. Combustion air is provided by a fan in the bottom of the cylinder. The amount of combustion air can be varied by varying the fan speed. The principal advantage of the air-assisted flares is that they can be used where steam is not available. However, air assist is not usually used on large flares because it is generally not economical when the gas volume is large.

c) Non-Assisted Flares

The non-assisted flare is just a flare tip without any auxiliary provision for enhancing the mixing of air into its flame. Its use is limited essentially to gas streams that have low heat content and a low carbon/hydrogen ratio that burn readily without producing smoke. These streams require less air for complete combustion, have lower combustion temperatures that minimize cracking reactions, and are more resistant to cracking.

d) Pressure-Assisted Flares

Pressure-assisted flares use the vent stream pressure to promote mixing at the burner tip. Pressure assisted flares generally (but not necessarily) have the burner arrangement at ground level, and consequently, must be located in a remote area of the plant where there

is plenty of space available. These flares have multiple burner heads that are staged to operate based on the quantity of gas being released. The size, design, number, and group arrangement of the burner heads depend on the vent gas characteristics.

e) Enclosed Ground Flares

An enclosed flare's burner heads are inside a shell that is internally insulated. This shell reduces noise, luminosity, and heat radiation and provides wind protection. A high nozzle pressure drop is usually adequate to provide the mixing necessary for smokeless operation and air or steam assist is not required. In this context, enclosed flares can be considered a special class of pressure assisted or non-assisted flares. The height must be adequate for creating enough draft to supply sufficient air for smokeless combustion and for dispersion of the thermal plume. These flares are always at ground level. Enclosed flares generally have less capacity than open flares and are used to combust continuously, constant flow vent streams, although reliable and efficient operation can be attained over a wide range of design capacity. Stable combustion can be obtained with lower Btu content vent gases than is possible with open flare designs, probably due to their isolation from wind effects. Enclosed flares are typically found at landfills.

4.7 Applicability

Flares can be used to control almost any VOC stream, and can handle fluctuations in VOC concentration, flow rate, heating value, and inert content. Flaring is appropriate for continuous, batch, and variable flow vent stream applications. The majority of plants have existing flare systems designed to relieve emergency process upsets that require release of large volumes of gas. These large diameter flares which are designed to handle emergency releases can also be used to control vent streams from various process operations. Consideration of vent stream flow rate and available pressure has been for retrofit applications. Normally, emergency relief flare systems are operated at a small percentage of capacity and at negligible pressure. To consider the effect of controlling an additional vent stream, the maximum gas velocity, system pressure, and ground level heat radiation during an emergency release is evaluated. Further, if the vent stream pressure is

not sufficient to overcome the flare system pressure, then the economics of a gas mover system is evaluated. If adding the vent stream causes the maximum velocity limits or ground level heat radiation limits to be exceeded, then a retrofit application is not viable. Many flare systems are currently operated in conjunction with base-load gas recovery systems. These systems recover and compress the waste VOC for use as a feedstock in other processes or as fuel. When base-load gas recovery systems are applied, the flare is used in a backup capacity and for emergency releases. Depending on the quantity of usable VOC that can be recovered, there is a considerable economic advantage over operation of a flare alone. Streams containing high concentrations of halogenated or sulfur containing compounds are not usually flared due to corrosion of the flare tip or formation of secondary pollutants. If these vent types are to be controlled by combustion, thermal incineration, followed by scrubbing to remove the acid gases, is the preferred method.

4.8 Performance

The parameters that affect flare VOC destruction efficiency are discussed and have the specifications that are presented when flares are used to comply with air emission standards.

The major factors affecting flare combustion efficiency are vent gas flammability, auto-ignition temperature, heating value (Btu/scf), density, and flame zone mixing.

The flammability limits of the flared gases influence ignition stability and flame extinction. The flammability limits are defined as the stochiometric composition limits (maximum and minimum) of an oxygen-fuel mixture that can burn indefinitely at given conditions of temperature and pressure without further ignition. When flammability limits are narrow, the interior of the flame has insufficient air for the mixture to burn.

For most vent streams, the heating value also affects flame stability, emissions, and flame structure. A lower heating value produces a cooler flame that does not favor combustion

kinetics and is also more easily extinguished. The lower flame temperature also reduces buoyant forces, which reduces mixing.

The density of the vent stream also affects the structure and stability of the flame through the effect on buoyancy and mixing. By design, the velocity in many flares is very low; therefore, most of the flame structure is developed through buoyant forces as a result of combustion. Lighter gases therefore tend to burn better. In addition to burner tip design, the density also directly affects the minimum purge gas required to prevent flashback, with lighter gases requiring more purge.

Poor mixing at the flare tip is the primary cause of flare smoking when burning a given material. Streams with high carbon-to-hydrogen mole ratio (greater than 0.35) have a greater tendency to smoke and require better mixing for smokeless flaring. For this reason one generic steam-to-vent gas ratio is not necessarily appropriate for all vent streams. The required steam rate is dependent on the carbon to hydrogen ratio of the gas being flared. A high ratio requires more steam to prevent a smoking flare.

At too high an exit velocity, the flame can lift off the tip and flame out, while at too low a velocity, it can burn back into the tip or down the sides of the stack. The US EPA requirements for steam-assisted flares used to comply with air emission standards state.

For gas streams the maximum permitted velocity (Vmax, in ft/sec) is determined by the following equation:

$$\log_{10}(V_{MAX}) = \frac{B_V + 1,214}{852} \qquad (4.1)$$

Where B_v is the net heating value in Btu/scf.

- No visible emissions. A five-minute exception period is allowed during any two consecutive hours.

- A flame present at all times when emissions may be vented. The presence of a pilot flame shall be monitored using a thermocouple or equivalent device.

- The net heating value of the gas being combusted being (300 Btu/scf) or greater.

In addition, operators must monitor to ensure that flares are operated and maintained in conformance with their design.

4.9 Measuring Quantities of Gas Flared

The major requirement involved in addressing environmental aspects of flaring is identifying the total amount of gas is being released. All oilfields contain associated gas. The associated gas that is released when oil is brought up from the deep rock strata in which it is found. The proportion of associated gas to oil (GOR or Gas/Oil Ratio) can vary significantly between oilfields. Moreover, in some oilfields, the GOR increases as more and more oil is produced, while in others it can reduce with time. Consequently, the amount of gas which must be dealt with can vary dramatically from year to year between oilfields and even within a specific oilfield.

A major difficulty in managing flaring is identifying exactly how much gas is coming from the various sources that are contributing to the overall volume flared and vented. It is not possible to measure gas flow rates accurately under such varied conditions with the measuring devices presently available on the market.

Therefore, the only way to obtain consistent data is to base it on estimates and calculations.

4.9.1 Flaring Efficiency

The flaring efficiency directly affects the quantities of unburnt hydrocarbons emitted (methane and VOC's). It is assumed that production flares are 98% efficient and well test flares, which may carry substantial liquids and aqueous content, 95% efficient. Both estimates are likely to be conservative but there is a lack of definitive information at present. If further data becomes available, the efficiency of flaring, including well tests conducted using green burners, can be revised.

Ozumba et al.,[2000] have represented combustion efficiency measurements of flares made on eight representative flares of varying designs and flow rates across the company, to determine their minimum combustion efficiencies using the open-path infrared technique. Unburned methane and carbon monoxide were not detected in the individual flare exhausts studied and, therefore, minimum combustion efficiencies were calculated by considering the potential quantities of gas that is present and yet remained undetected in the plume. Combustion efficiencies based on maximum methane and carbon monoxide levels in the exhaust gases of typical flares were measured to be in excess of 0.98.

4.10 Flare Process Description

The elements of an elevated steam assisted flare generally consist of gas vent collection piping, utilities (fuel, steam, and air), piping from the base up, knock-out drum, liquid seal, flare stack, gas seal, burner tip, pilot burners, steam jets, ignition system, and controls.

4.10.1 Gas Transport Piping

Process vent streams are sent from the facility release point to the flare location through the gas collection header. The piping (generally schedule 40 carbon steel) is designed to minimize pressure drop. Ducting is not used as it is more prone to air leaks. Valving are kept to an absolute minimum and are "car-sealed" (sealed) open. Pipe layout is designed to avoid any potential dead legs and liquid traps. The piping is equipped for purging so that explosive mixtures do not occur in the flare system either on start-up or during operation.

4.10.2 Knock-out Drum

Liquids that may be in the vent stream gas or that may condense out in the collection header and transfer lines are removed by a knock-out drum. The knock-out or

disentrainment drum is typically either a horizontal or vertical vessel located at or close to the base of the flare, or a vertical vessel located inside the base of the flare stack.

Liquid in the vent stream can extinguish the flame or cause irregular combustion and smoking. In addition, flaring liquids can generate a spray of burning chemicals that can reach grouped level and create a safety hazard. For a flare system designed to handle emergency process upsets this drum is sized for worst-case conditions (e.g., loss of cooling water or total unit depressuring) and is usually quite large.

For a flare system devoted only to vent stream VOC control, the sizing of the drum is based primarily on vent gas flow rate with major consideration given to liquid entrainment.

4.10.3 Liquid Seal

Process vent streams are usually passed through a liquid seal before going to the flare stack. The liquid seal can be downstream of the knockout drum or incorporated into the same vessel. This prevents possible flame flashbacks, caused when air is inadvertently introduced into the flare system and the flame front pulls down into the stack. The liquid seal also serves to maintain a positive pressure on the upstream system and acts as a mechanical damper on any explosive shock wave in the flare stack. Other devices, such as flame arresters and check valves, also sometimes replace a liquid seal or are used in conjunction with it. Purge gas also helps to prevent flashback in the flare stack cause by low vent gas flow.

4.10.4 Flare Stack

For safety reasons a stack is used to elevate the flare. The flare is located so that it does not present a hazard to surrounding personnel and facilities. Elevated flares are self supported (free-standing), guyed, or structurally supported by a derrick. Flares are generally used for lower flare tower heights 9.2-30.5 m (30-100 feet) but are designed for

up to 76 m (250 feet). Guy towers are designed for over 91.5 m (300 feet), while derrick towers are designed for above 61 m (200 feet).

Free-standing flares provide ideal structural support. However, for very high units the costs increase rapidly. In addition, the foundation required and nature of the soil must be considered.

Derrick-supported flares can be built as high as required since the system load is spread over the derrick structure. This design provides for differential expansion between the stack, piping, and derrick. Derrick-supported flares are the most expensive design for a given flare height.

The guy-supported flare is the simplest of all the support methods. However, a considerable amount of land is required since the guy wires are widely spread apart. A rule of thumb for space required to erect a guy-supported flare is a circle on the ground with a radius equal to the height of the flare stack.

Chapter 5
Emission Inventory Results

5.1 Introduction

The development of a complete emission inventory is an important step in an air quality management process. Emission inventories are used to determine significant sources of air pollutants establish emission trends over time, target regulatory actions, and estimate air quality. This is carried out using computer dispersion model.

A detailed literature search has been conducted to collect relating average monthly emissions of various air pollutants; NO_x, SO_2, CO_2, particulate matter and hydrocarbons; from oil production operations facilities in the world. Smog, high ozone concentrations and health risk due to air pollution in mega cities have been focus of the research of many Environmental experts to quantify the nature of problem by determining the total organic load of ambient air. A detailed report has been published by Dennison et al.,[1983] for emission characteristics of crude oil production operation in California showed that 18% of the CO, 3% of NOx, 2% of SO_2 and over 3% hydrocarbon and less than 1% of particulate emissions were accounted for oil production in the South Coast Air Basin alone based on 1979 statistics.

Dahl and Kuralbayeva [2001] have presented the exploitation of the energy resources for Kazakhstan and their associated inherited environmental problems, methane emissions from aging gas infrastructure and coal mines, soil and Caspian Sea pollution due to oil products and thermal and particulate problem due to energy production. They have outlined the environmental laws for environmental protection and made recommendation technical and legal improvements to provide safer and clean environment in the country.

A comprehensive impact assessment report by Villasenor et al., [2003] has been published to account all emissions from the offshore operations of the oil and gas

exploration and production by Mexico industry in the states of Tabasco and Compeche in southeast Mexico. The emission inventory include 174 offshore platforms, the compression station at Atasta, Dos Bocas Marine terminal for storage and treatment of crude oil and the transhipment station at Cayo Arcas. The total mass of air pollutants emitted into ambient air was calculated as nearly 660,000 tons per year. CALPUFF dispersion model was used to assess the impact of SO_2 emissions from offshore operations.

In chapter 3, the details has been presented step by step guide for preparing emission inventories. It contains information on the purpose, process, methodology and application of emission inventory investigations.

This chapter presents estimates of total emissions of primary pollutants associated with flaring activities from Kuwait Oilfield. An inventory records the monthly emissions of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons: resulting from oil production operations. The emissions are generated from various sources and aggregated to give total pollutants load of ambient air, which are associated with all production operations and processing in the Oilfields (e.g. GC, BS, Tank areas and other production related activities).

This emission inventory data are a necessary input for the atmospheric dispersion model. ISCST3 model has been adopted in the present work to predict the impact of methane, non-methane hydrocarbons and SO_2 over the surrounding areas near oilfields in Kuwait.

5.2 Description of the Study Area

As stated in chapter 2, the bulk of Kuwait's oil production is onshore from Greater Burgan field, where Burgan, Magwa, and Ahmadi. Most of Kuwait's other producing fields are relatively small and includes Raudhatain,, Sabriya, Minagish, and Umm Gudair fields.

The area under study covers all the Kuwait's oil reservoirs which are located in three productions area's as follows;

- Greater Burgan area located in SEK.

- Minagish and Umm Gudair fields are located in WK.

- Ratqa, Raudatin and Sabiriyah are located in NK.
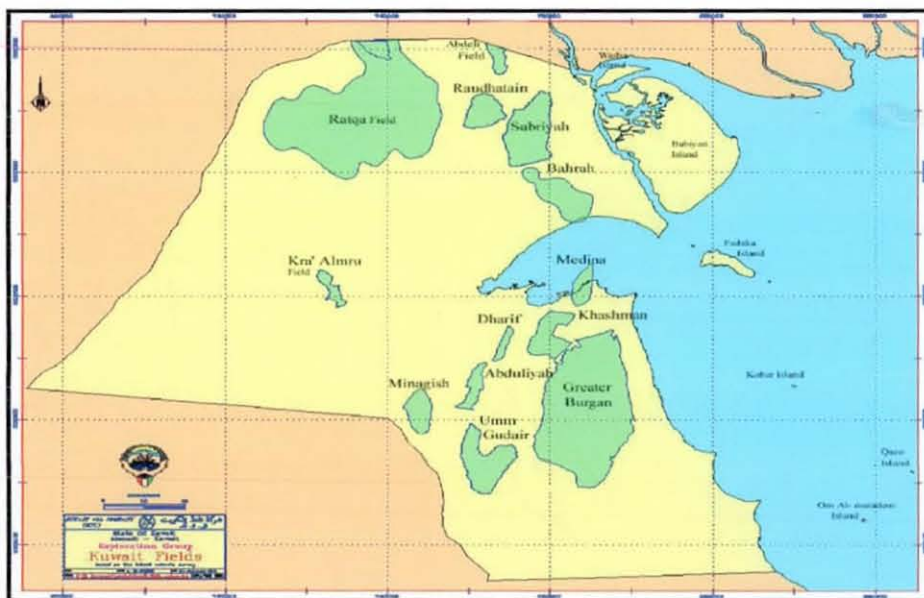
Figure 5.1: Major Oilfields in the State of Kuwait

The present work covers all operational facilities and relevant sites where workers are exposed to ambient air quality that is effected by various pollutants emissions (e.g. apportioned emissions related to utilities production). The facilities that contribute to emission inventories are:

- Production wells and interconnecting pipelines

- Gathering Centers

- Booster Stations

It is not practical to estimate or calculate the emissions of every substance which is a potential hazardous compound, given the diverse range of chemical species encountered

in crude oil production. Thus, a set of pollutants is proposed covering the most relevant and significant substances, based on known pollutants from the oil industry. The present study is insured on exact evaluation of inventories of the following pollutants:

- Carbon Dioxide (CO_2)

- Carbon Monoxide (CO)

- Sulphur Dioxide (SO_2)

- Nitrogen Oxides (NO_2 & NO & N_2O)

- Methane (CH_4)

- Volatile Organic Compounds (VOCs)

5.3 Programme and Methodology

The basic approach used in this inventory programme is to locate and identify emission sources, apply suitable emission factors to compute and then categorize as aggregated the air pollutant emissions to include many individual emissions. Various techniques can be used to complete existing information from which emissions are determined.

The inventory is prepared using Excel from Microsoft office 2003 which provides a template for calculating pollutant emissions for year 1997 and subsequent years. The inventory follows the normal industry standard approach, which is not based on measured emissions, but uses emission factors to calculate emissions in tonnes per year for each major pollutant, in broad agreement with the internationally recognised Exploration and Production Forum Tier 3 methodology (AP42).

The primary objective of the inventory is to complete emissions of the six criteria pollutants, NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons. Proper representation of oil field characteristics and operations are incorporated in the sampling process, oil fields are grouped according to specific parameters. Representative Fields from each group are then selected for inventory. The inventory procedures are further

refined by inventorying specific leases at each field. The lease is the lowest level on which data are compiled.

Excel spreadsheet was used to complete emission inventories and aggregated the emissions from each of those sources by field. Emissions calculated by the programme were expressed as metric tons per year.

5.4 Emission Inventory

It is practical to directly measure emissions from all environmental sources continuously every year. Thus it is necessary to produce estimates of total emissions that can be derived from other continuously monitored activity data, such as fuel usage or product throughput. With sufficient knowledge of the operational conditions and the level of activity, it is now accepted practice to apply emission factors.

For the exact calculations, the latest Microsoft office Excel 2003 Software was used to host all of the input data, emission factors and estimates of the emissions. Excel workbooks were set up for every major KOC facility (e.g. gathering centers, booster stations, etc.).

The combustion of hydrocarbons produces many gases which when released into the atmosphere such gases as CO_2, CO and NO_X affect the natural balance that exists in the atmosphere. Upon combustion, each mole of carbon atom is converted to one mole of CO_2. This means that one mole of CH_4 yields one mole of CO_2 when complete combustion occurs. Similarity one mole of Ethane (C_2H_6) results in to two moles of CO_2. Incomplete combustion can also occur if insufficient air is supplied. The following reactions are typical in the flaring system during combustion of hydrocarbons;

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$
$$C_2H_6 + 3.5\,O_2 \longrightarrow 2CO_2 + 3H_2O$$
$$C_3H_8 + 5\,O_2 \longrightarrow 3CO_2 + 4H_2O$$
$$C_nH_{2n+2} + \frac{3n+1}{2}O_2 \longrightarrow nCO_2 + (n+1)H_2O$$

Complete Combustión

$$CH_4 + 1.5\,O_2 \longrightarrow CO + 2H_2O$$
$$C_2H_6 + 2.5\,O_2 \longrightarrow 2CO + 3H_2O$$
$$C_3H_8 + 3.5\,O_2 \longrightarrow 3CO + 4H_2O$$
$$C_nH_{2n+2} + \frac{2n+1}{2}O_2 \longrightarrow nCO + (n+1)H_2O$$

Incomplete Combustión
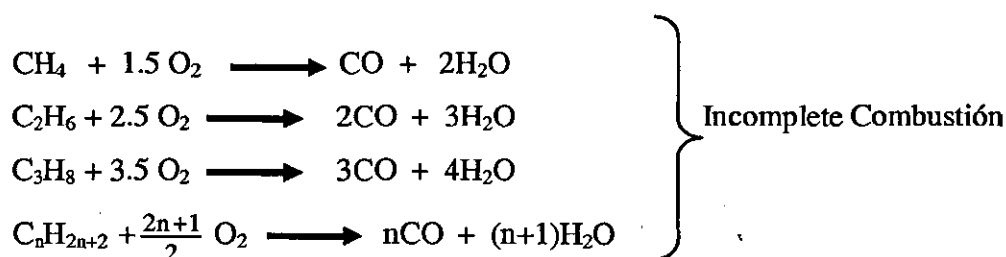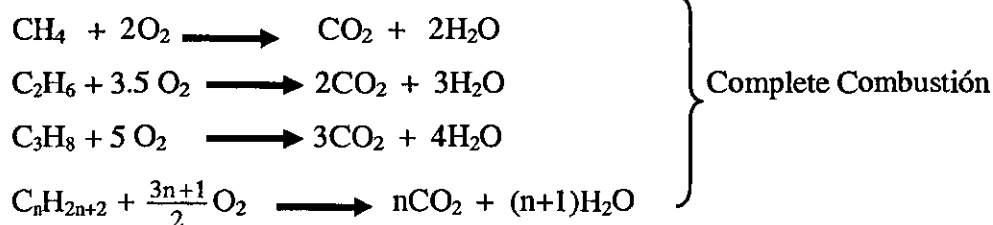
Therefore, with known composition and amount of each hydrocarbon the total moles of CO_2 can be calculated. Emission factors are well documented and well investigated. An emission factor is applied as follows:

$$PE = LA \times EF \tag{5.1}$$

PE: Pollutant Emission in Tonnes

LA: Level of Activity

EF: Emission Factor

Emission factors have been derived for a large number of pollutants and industrial facilities, particularly those related to combustion processes. Emission factors, take into account variations in fuel composition, crude oil properties, ambient air temperature and fuel/air ratio etc.

For methane greater than 70% by volume, flaring efficiency of 95% has been assumed. For VOC volume Percent composition, 95% flaring efficiency is also considered that resulted into very low factor in conversion to wt%. The presence of H_2S and its high concentration in West Kuwait area can result into erroneous values of SO_2 emissions in the flaring.

There are a number of established sets of emission factors applicable to oil exploration and production facilities, which are recognized internationally.

- US EPA AP42 factors [1997], which are applicable to a wide range of industries, and thus must be used carefully to ensure applicability to the equipment and the planned use

- E and P Forum factors [1994] which are based on AP42 or other international factors, based specifically on oil and gas production operations

- UKOOA factors [1995], which have a similar basis to the E and P Forum factors but provide complimentary advice and quantification of different classification of typical North Sea production facilities

The factors employed in year 1997 for KOC oil related operations are based on the E and P Forum protocols, with some input from the UKOOA guidelines.

5.4.1 E and P Forum Combustion Emission Factors

The environmental Division concerns at the time related to global warming as well as regional or local air quality. E&P Forum [1994] in a study involving Brown and Root Environmental introduced a tiered approach to emissions estimation primarily based on emission factors. The factors were derived from previous measurement studies in a number of countries particularly the USA, Canada, Norway and the UK.

Factor Units = tonnes emission / tonne gas burned	Carbon Dioxide (CO_2)	Nitrogen Dioxide (NO_2)	Carbon Monoxide (CO)	Sulphur Dioxide (SO_2)	Methane (CH_4)	Non Methane VOCs
Flaring - Rich Gas	2.8595	0.0015	0.0087	0.0006	0.035	0.0015

Table 5.1: E and P Forum Emission Factors

It is assumed that most of the flares burn gas with negligible fine particulate emissions.

Figure 5.2: Flare at GC 22 viewed from Al Tameer, Ahmadi

5.5   Results and Discussion

Al-Hamad and Khan [2007] have presented a detailed emission inventories for oil production facilities in Kuwait. The Environmental Pollution Inventory data for years 1997- 2006 have been collected for flaring events from all oil production facilities in Kuwait. This inventory focuses primarily on air emissions. The inventory estimates the amount of each of the flaring pollutants generated by KOC operations on an annual basis, the analysis was repeated for the next year, and the results are compared and validated with preceding year known emissions.

The first inventory has been completed for year 1997 and is therefore an appropriate baseline for the incoming year's inventories. The inventory is based on the best estimates of actual operational data but where operational data is not available, typical industry values are substituted.

The Excel spreadsheet used to collate the input data and calculate the estimated emissions has been greatly improved and updated for the later years.

South and East Kuwait gathering centers are fairly similar in size in terms of throughput and power consumption, which are emphasized by the lack of variation in combustion gas emissions such as NO_x.   Gathering centers in West and North Kuwait are generally larger, with greater capacity and hence have larger power consumption.   The further expansion of drilling activities in these two areas gives rise to higher levels of emissions in these regions as compared to the South East Kuwait.

5.5.1   1997 Flare Inventory Results

Figures 5.3, 5.4a and 5.4b depict a breakdown mainly in 3 major production areas of KOC.   With the exception of SO_2 exclusively in West Kuwait, it can be observed that there is a fairly even spread of emissions across the operations.   The larger number of facilities present in SEK as explained in accounts for the slightly higher NO_x emissions, whilst the proportionately higher North and West emissions of CO_2 resulted from higher levels of flaring of excess gas.

The quantity of gas flared for each area in the year 1997 is shown graphically in Figure 5.3.   Very high levels of gas flaring occurred in North and West Kuwait, together accounting for over 70% of the total emissions in the state of Kuwait in that year.
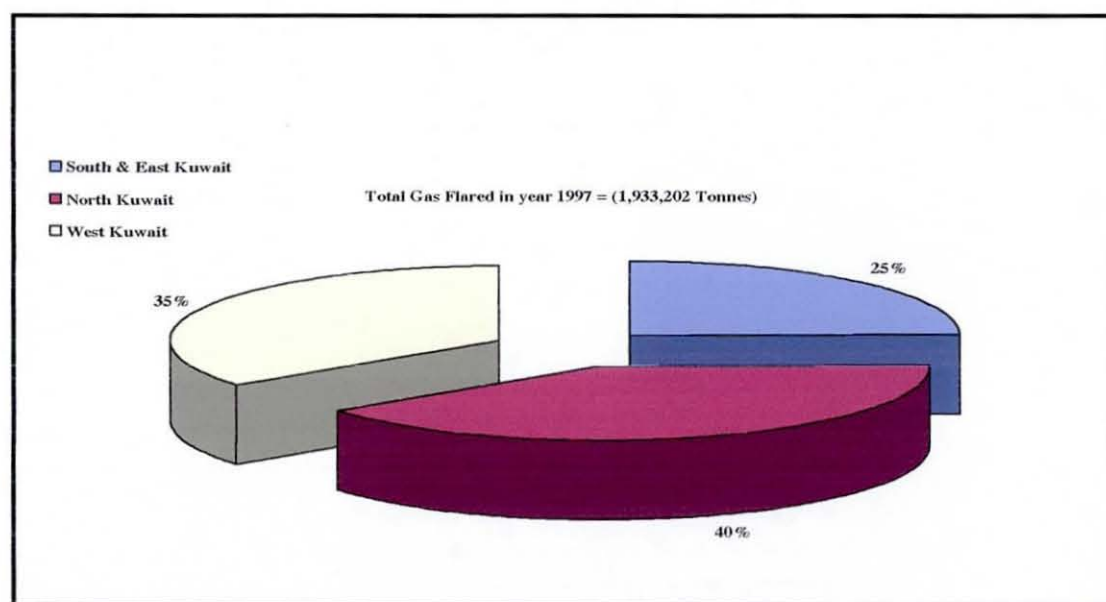
Figure 5.3: Total Gas flared from different oilfields in the State of Kuwait in Year 1997.

The results of total emissions from flaring at each area are represented graphically in Figures 5.4a and 5.4b. Very high levels of gas flaring occurred in North and West Kuwait.
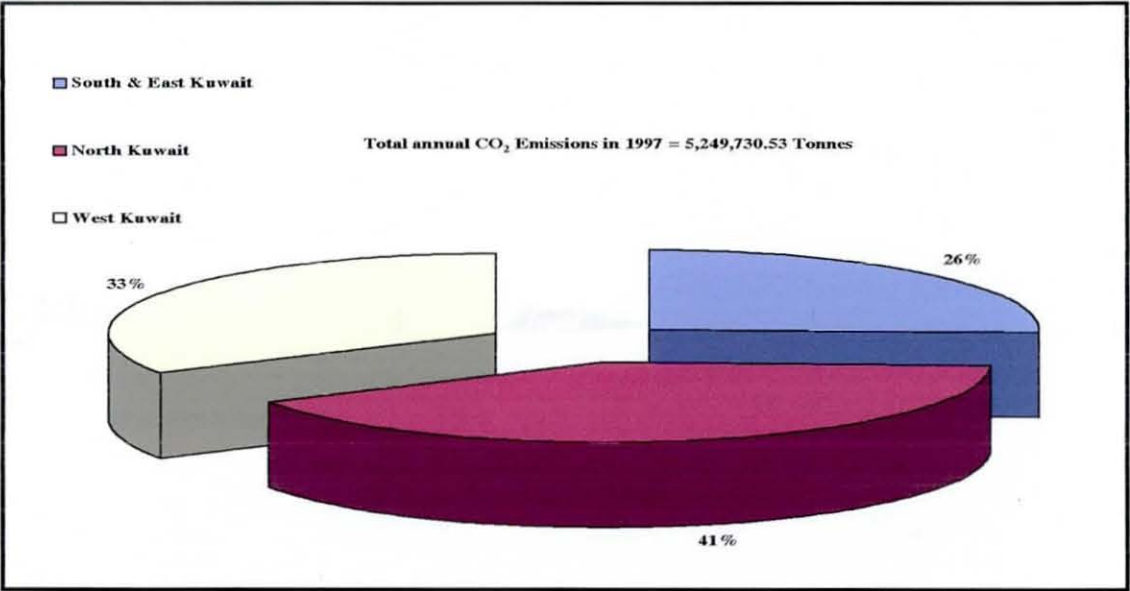
Figure 5.4a: Percentage of Total annual CO_2 emissions from various Oilfields in Kuwait in Year 1997
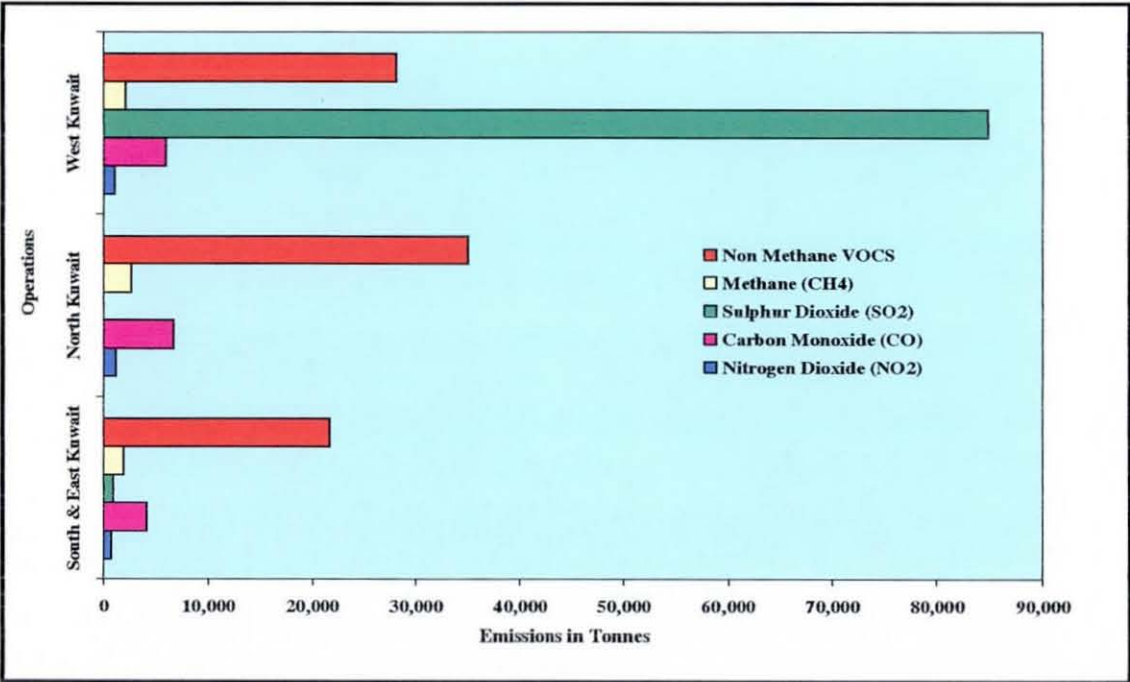
Figure 5.4b: Total emissions of different pollutants from various Oilfields in year 1997.

5.5.2 Total Emissions to Air from Flaring

Figure 5.5 shows overall total crude and gas production and Figure 5.6 presents quantity of gas flared for years 1997-2006. It is clear that there is an obvious decrease in atmospheric emissions since 1997 to 1999. This reduction is mainly due to apparent decrease in production over the same period providing less excess gas/oil to be flared.
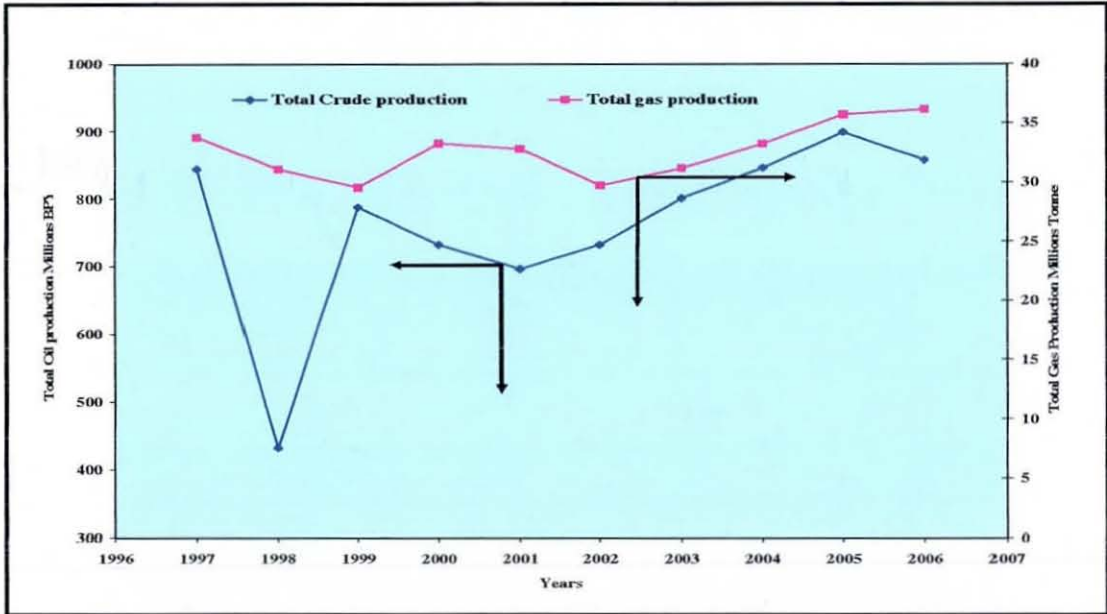
Figure 5.5: Total Annual Oil and Gas Production in the State of Kuwait
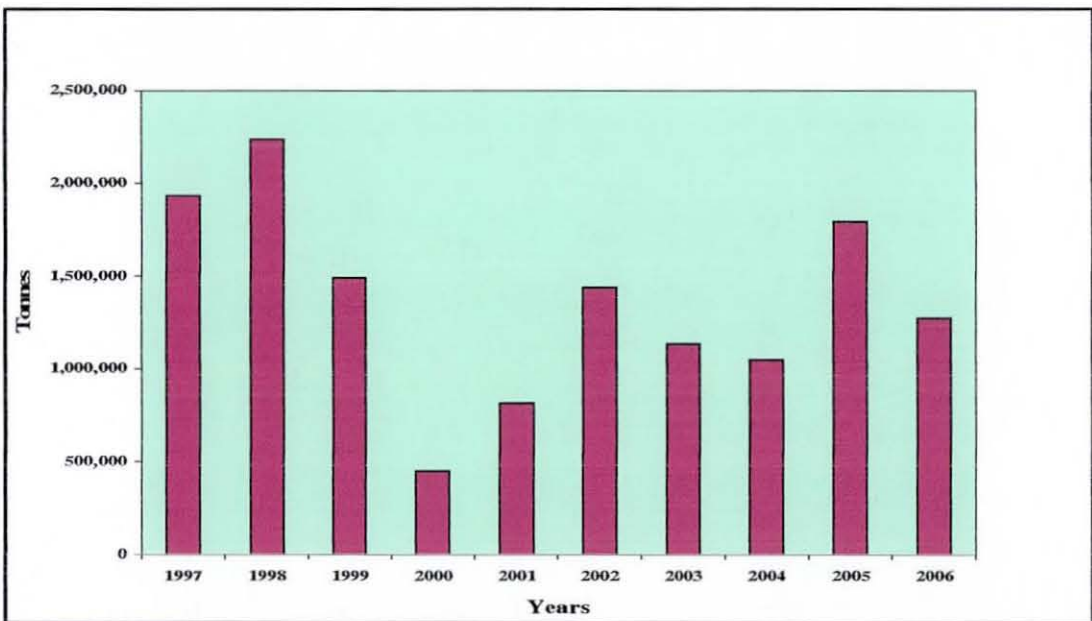
Figure 5.6: Total annual amount of Gas flared from the State of Kuwait.

Figures 5.7a and 5.7b provided graphically the results of the total emissions from flaring at each area in KOC for years 1997-2006. Very high levels of gas flaring occurred in North and West Kuwait for the year 1998, although these were substantial reduction in the following year.
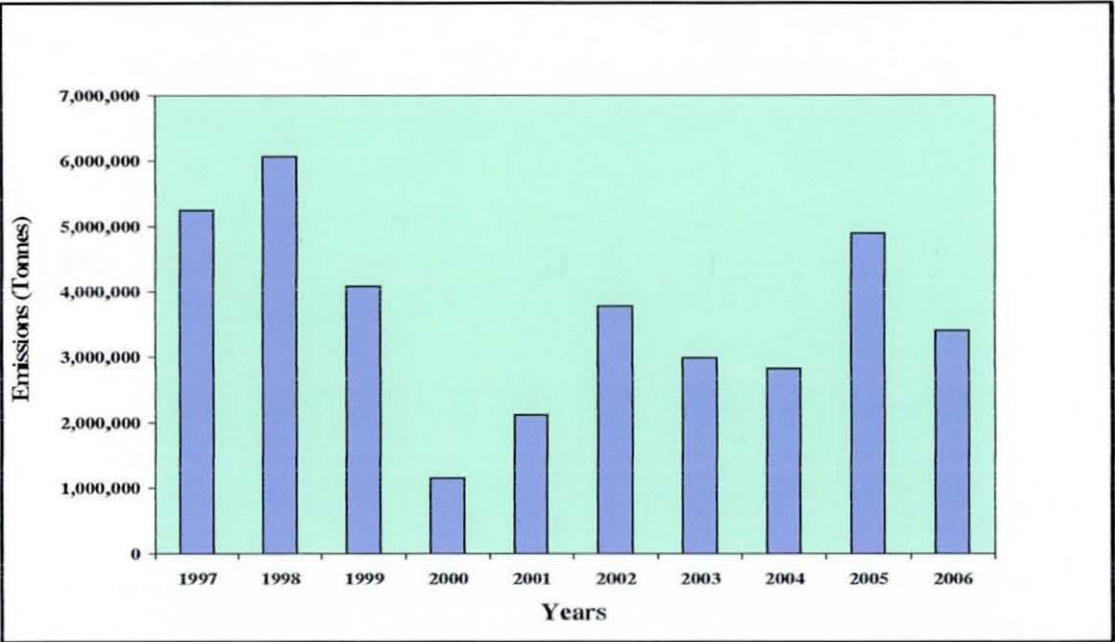
Figure 5.7a: Total annual CO_2 emissions (Tonnes) from all Oilfields in Kuwait
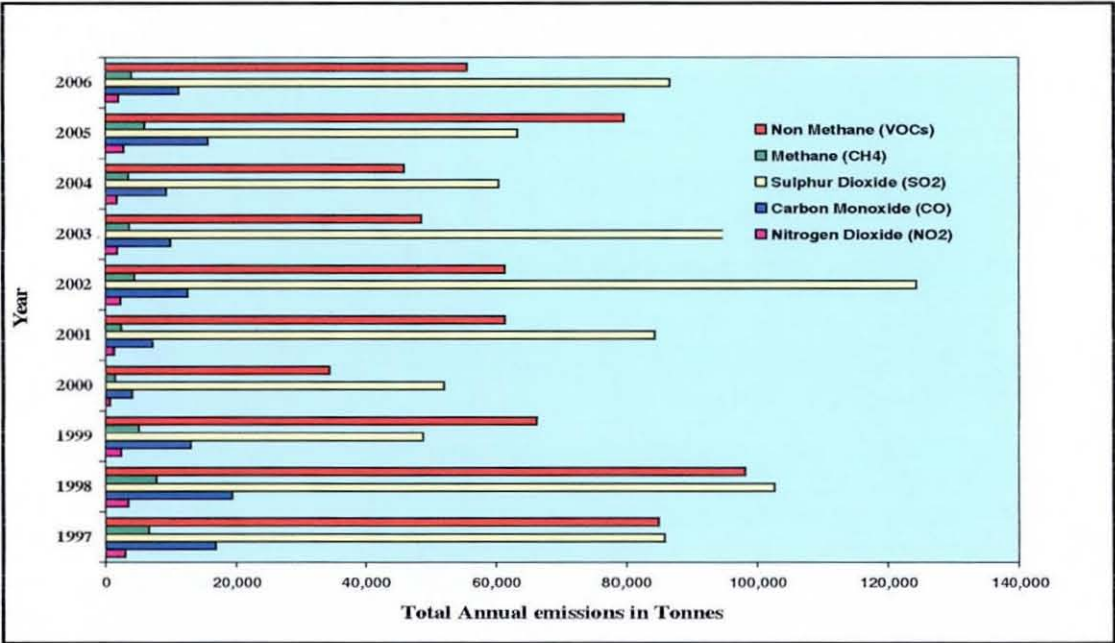
Figure 5.7b: Total annual emissions of different Pollutants (Tonnes) from all Oilfields in Kuwait.

The major reasons for the increased flaring per KOC Area's during 1998 are as follows:

- Condensate Recovery Unit frequent shutdowns
- Shortage of gas compression facilities
- Booster Stations malfunction

The percentage of gas flared has increased in 1998 due to the above mentioned reasons and the subsequent increased volume of flared gas in West Kuwait.

In line with the KOC flaring reduction goals, emissions from flared gas have reduced in year 1999 below year 1997 levels, despite a significant increase in 1998. Flaring emissions increased during year 1998 but have decreased by about 10% over the 3 year period.

All KOC assets have introduced measures to reduce the quantity of gas flared in year 2000. These measures include:

- Compression of vapors from the storage tanks, enabling them to be fed into the gas export line.
- Installation of new high pressure separators at Burgan and Magwa.
- Linking drilling sites to gathering centers so that any gas produced during drilling operations can be further processed.

Therefore, emissions from flared gas have reduced significantly in years 2000 and 2001 even less than the 1999 levels.

The quantity of gas flared has increased slightly in year 2002 due to the frequent shutdowns of Condensate Recovery Unit and shortage of Gas Compression facilities and the subsequent increased volume of flared gas in North Kuwait.

Monitoring carried out in between years 2003 and 2004 showed that emissions from flared gas have reduced to below year 2002 levels.

The quantity of gas being flared in KOC was about 14% of the total gas produced in 2002 that flared fraction reduced to 10% in year 2003, despite substantial increase in the amount of gas being produced as shown in Figure 5.5.

As in the case of CO_2 emissions, releases of all other pollutants have fallen gradually from years 2002 to 2003 and year 2004 in line with the decrease in the quantity of gas flared as shown in Figure 5.7a.

Efforts continued to reduce the quantity of gas flared. Although the amount of gas produced increased substantially from previous years, the amount of gas flared or lost only increased slightly from year 2003 and quantified to 8% of the total gas production compared with 14% in year 2002 and 10% in year 2003.

There was a large increase in gas flaring in year 2005 compared with previous years as shown in Figures 5.7a and 5.7b. This was almost entirely due to events in North Kuwait. These included:

- A breakdown of the condensate pump
- A major survey of the Condensate Recovery Unit
- The complete shutdown of the compressor

The cumulative effect of these events resulted in very high levels of flaring at the respective gathering centers.

Because of the problems in North Kuwait, the amount of gas flared, as a percentage of production, was about increase consider double that of the previous year as shown in Figure 5.8a and 5.8b.

The increase in gas flared in year 2005 inevitably resulted in a similar increase in most atmospheric emissions. The exception to this was sulphur dioxide emissions, which remained almost unchanged from the previous year as show in Figure 5.7b. This was mainly due to flaring of sour gas (rich in H_2S and mercaptans) at West Kuwait contributing to high levels of sulphur dioxide emissions.

To observe the influence of crude production to the associated gas and fraction being flared, total annual Emissions (Tonnes) of different pollutants per Millions barrel of crude produced are shown in Figures 5.9 and 5.10. There has been decrease in flaring volumes in years1997 to 1999 with the exception of year 1998 and the least emissions in year 2000 followed by slight gradual increase to year 2005.

As shown in Figures 5.8a and Figure 5.8b, in 2006 gas flaring decreased to 9.94% compared to the 17.6% in 2005 and this was achieved because KOC took several initiatives as follows:

- Construction of new Booster Station which is handling all gas produced from North Kuwait and reduced gas flaring to the minimum.
- Coordination with Kuwait National Petroleum Company (KNPC) and West Kuwait for synchronizing the shutdown of Mina Al-Ahmadi Refinery (MAA) – AGRP with the shutdown of GC 27 and GC 28
- Coordination with NK Assets to reduce downtime of machinery, rescheduling pigging operations, etc.
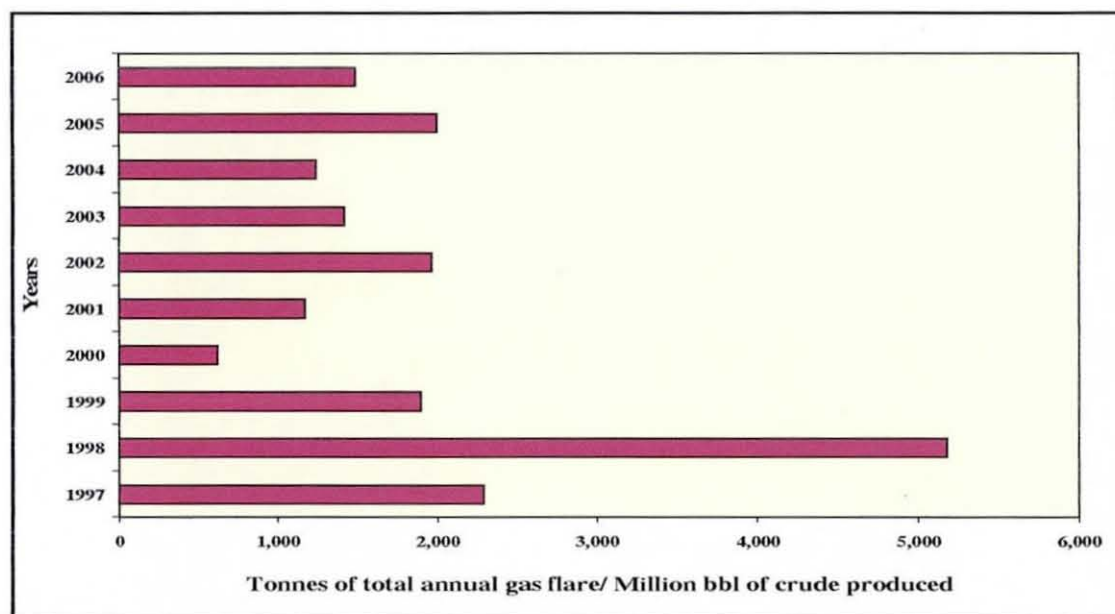
Figure 5.8a: Total annual amount of Gas flared per million tones of Crude produced from all Oilfields in Kuwait.
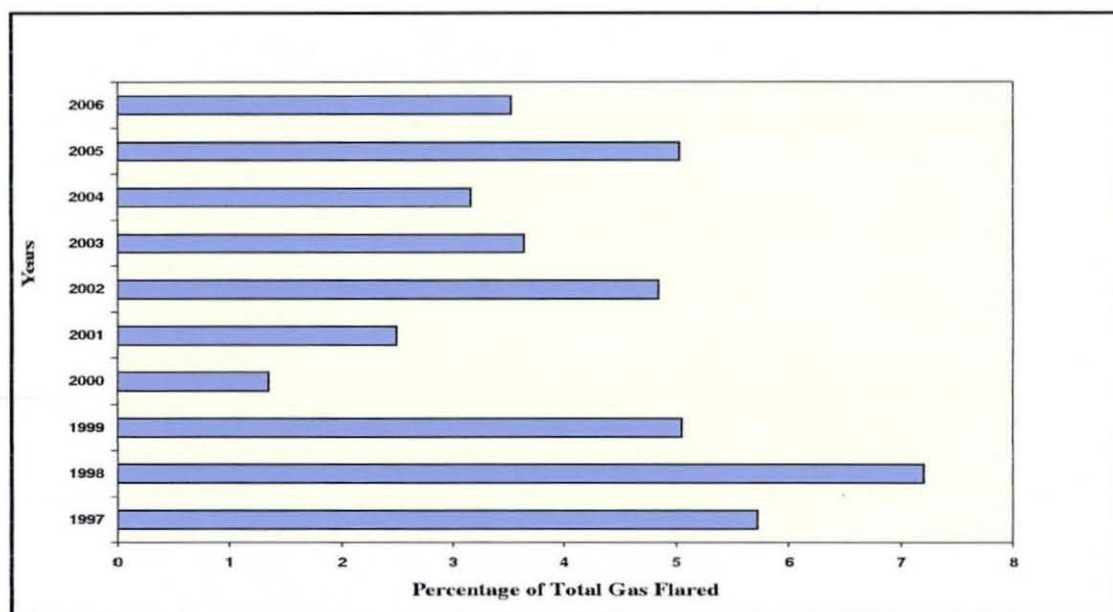
Figure 5.8b: Percentage of Total Gas flared annually from all Oilfields in Kuwait

Due to the significant decrease in Gas Flaring during year 2006 across KOC Assets, almost all Pollutants decreased to near by 30% as shown in Figures 5.9 and 5.10. Only Sulfur Dioxide increased, which was due to regular shut down of Shuaiba AGRP, MAA-AGRP and CRU's of GC-16 and GC 17. In addition to this complete shutdown of GC 27 and 28 for survey, has contributed in increase of flare as well as the pollutants.

The influence of crude production and associated gas depends on the crude Gas-Oil ratio. The influence of gas production was assessed and is shown in Figures 5.11 and 5.12.
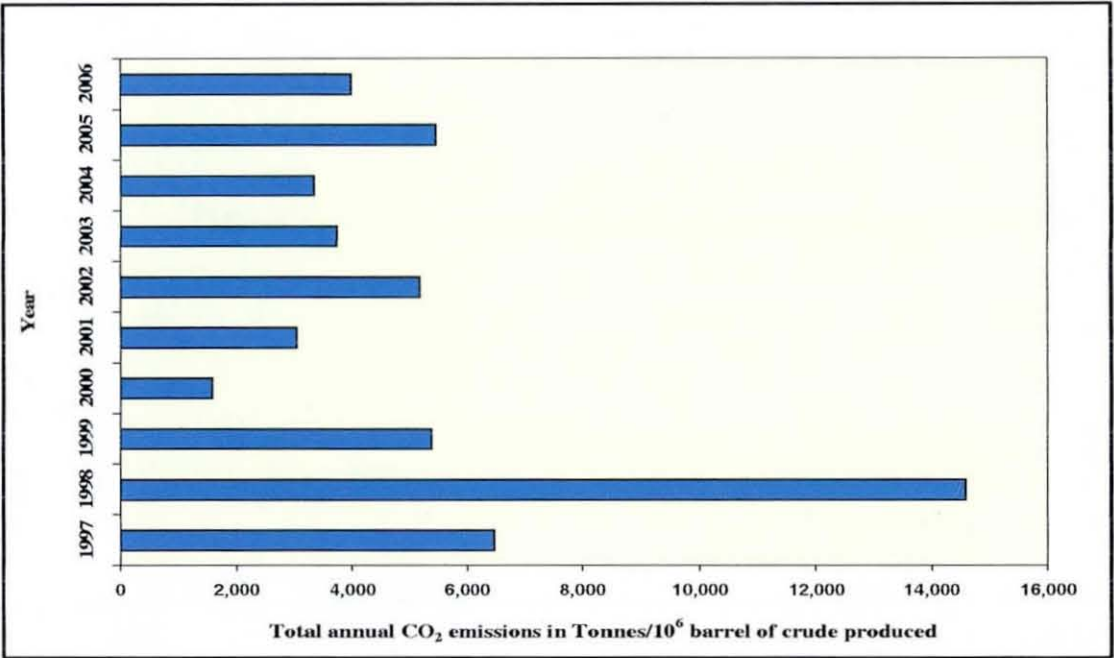
Figure 5.9: Total Annual CO_2 emission (Tonnes) per million barrels of crude produced
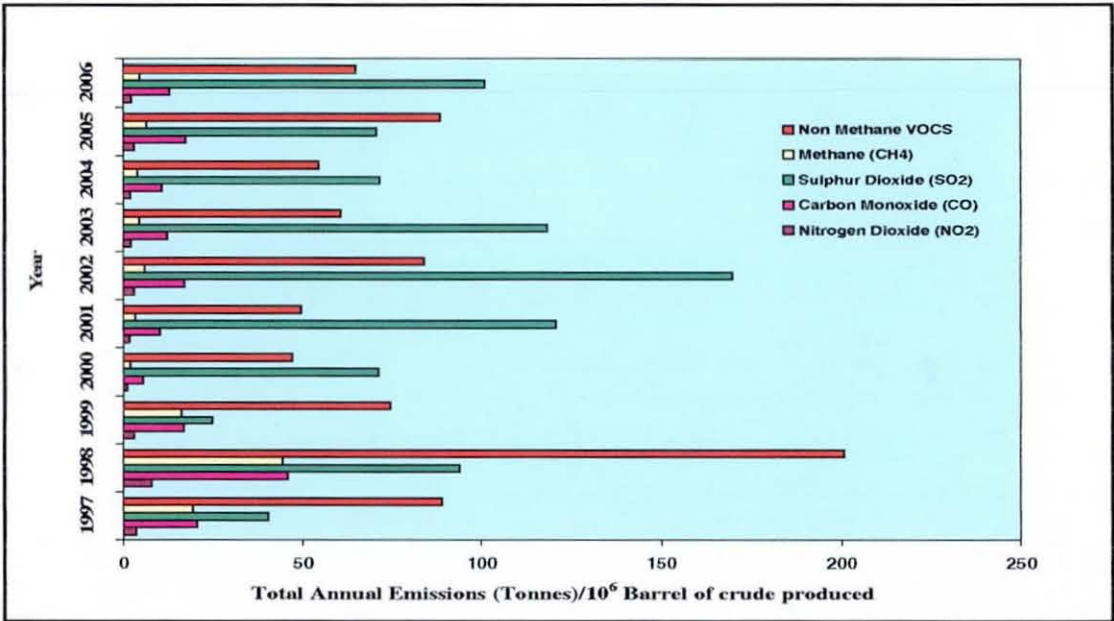
Figure 5.10: Total Annual emissions (Tonnes) per million barrels of crude produced

Figures 5.11, 5.12 show the total emissions (Tonnes) per million tonnes of annual gas produced. There has been decrease in flaring volumes from 1997 to 1999 and further decrease in year 2000. There was gradual increase in coming years 2002 to 2005.
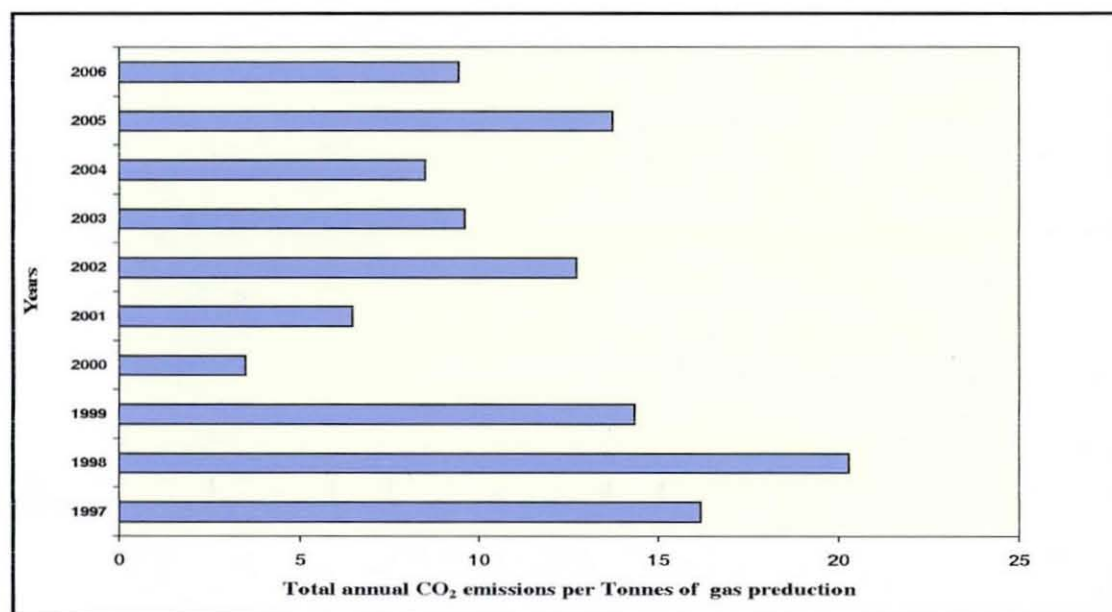
Figure 5.11: Total annual CO_2 emission (Tonnes) based on million Tonnes of Total Gas Produced
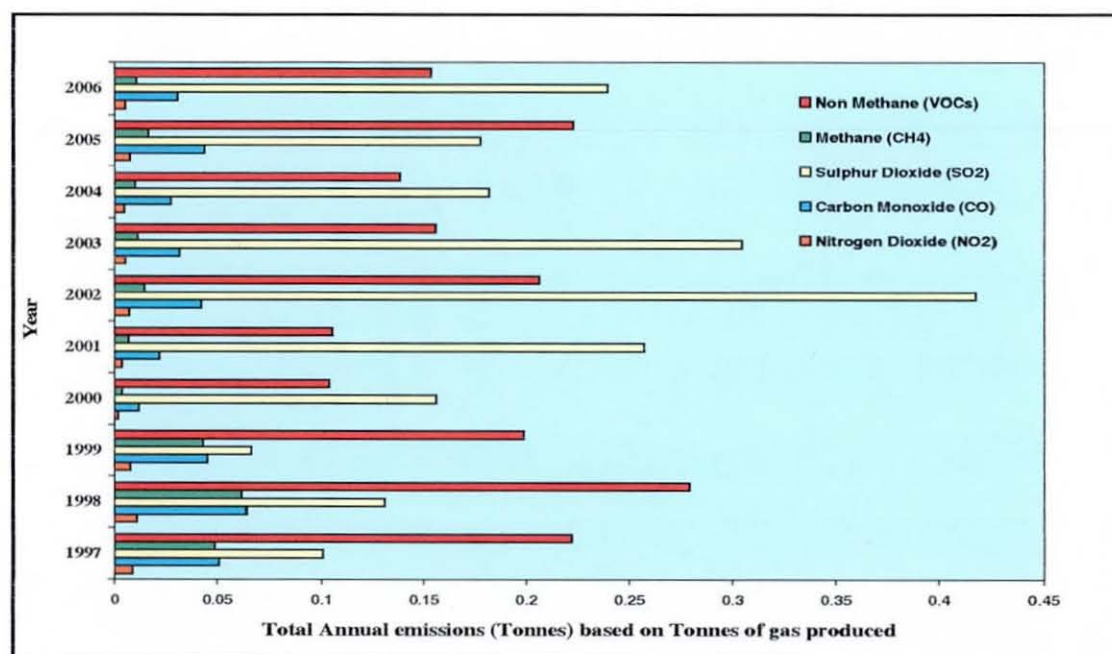
Figure 5.12: Total annual emissions (Tonnes) based on 10^6 Tonnes of Gas Produced

5.6 Emission Inventory Application

The inventory is prepared based on best estimates of actual operational data but where operational data is not available, typical industry values are substituted.

The inventory provides reasonably detailed information for each facility while allowing the total emissions for all KOC to be reviewed and understood.

The current knowledge in the inventory represents a valuable first step in understanding KOC's impact on the environment and the benefits which can be achieved by emission abatement measures.

Chapter 6
Air Pollution Dispersion Model

6.1 Introduction

The impact of flaring emissions from all of the Kuwait oil production facilities has been assessed using the dispersion of the methane, non-methane hydrocarbons and SO_2 pollutants. The predicted concentrations of methane, non-methane hydrocarbons and SO_2 are used to assess the impact of SO_2, methane and non-methane hydrocarbons released on the neighbouring areas near oil production facilities.

Soetjiptono et al., [1996] have discussed the dispersion modelling methods that were used to estimate the ground level concentrations in the surrounding areas using the data developed in the emission inventory. This study was a proactive step to better understand the emissions into the atmosphere from the various sources in some areas of the Duri field and their influence on the air quality. The results could be used to develop cost effective control strategies for the facility.

Evaris et al.,[1994] have described mathematical-models and the difficulties met in their application. They have also described how recent advances in understanding of vapour cloud explosions might help in designing safer installations in the future.

Jadidi, [2003] has presented a computer simulation of Air Pollution in Dalan Refinery which is located in Farashband area at 200 km from southwest of Shiraz city. Pollutant components from the dehydration units in Dalan refinery pollute the surrounding environment. The main pollutant components are aromatic hydrocarbons such as benzene, toluene, ethyl benzene, propyl benzene, TEG and hydrogen sulfide. All the refining operations are simulated by the PROII software. Then Gaussian Plume model was used with plant data for obtaining the concentration gradient of pollutant components.

An overview of the present state of air quality modelling and the applications to total flaring emissions from Kuwait Oilfields to predict ground level concentrations of selective pollutants are discussed. From these predicted concentrations compared to the monitoring data from selected site used as receptors discrete in the model and Kuwait Ambient Air Quality Standards (KAAQS) resulted in categorizing the most affected area by pollutants emissions for Kuwait Oilfields. The results are also used to assess control strategies and determine emission limits.

Guassian Dispersion Model is the most widely used techniques for estimating the impact of non-reaction pollutant where the effect of topography is minimal. Thus ISCST3 model was used to calculate ground level concentration of selected primary pollution and compared with the monitoring data from selected sites used as receptors discrete in the model.

6.2 Atmospheric Dispersion Models

Air quality modelling is the necessary substitute for ubiquitous air quality monitoring, which is impracticable. Air quality models are used to predict the impacts from a potential emitter, which is useful for permitting new sources. Models are also used to determine the relative contributions from different sources as a tool for tracking trends, monitoring compliance, and making policy decisions.

Atmospheric dispersion modeling is the mathematical simulation of air pollutants dispersion in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms, which simulate the pollutant dispersion. The dispersion models are used to predict the downwind concentration of air pollutants emitted from sources such as industrial plants and vehicular traffic.

Air dispersion modelling is a way to show the transport of air pollutants, which is performed mathematically using a computer program. By using information such as meteorology and source emissions, models calculate the pollutant concentrations in the air such as:

- SO$_2$

- CO

- NO$_2$

- PM$_{10}$ (Particulate matter smaller than 10 microns in diameter or about 1/7 the thickness of human hair)

- Total Suspended Particulate (TSP)

These models also generate estimates of secondary formation of pollution by incorporating atmospheric chemistry into the model. Dispersion models are used to determine the source contribution on selected area and source review for evaluation of emission reduction plan.

The available dispersion models vary in their complexity. At a minimum, most of the models require meteorological data, emissions data, and details about the facilities in question (such as stack height, gas exit velocity, etc). Some of the more complex models require topography information, individual chemical characteristics and land use data. The output from this type of model is a prediction of the concentration of the pollutant in question throughout the appropriate region (which depends on the model chosen).

The Air dispersion model is used for three major reasons.

1. Modeling can be used in predicting pollutant concentration estimates at most locations where there are no air monitors.

2. Models can predict the potential impact of new sources before they are built as well as how new pollution control devices will affect the outcome of the pollutant.

3. Influence of meteorological conditions on dispersion of contaminations.

Dispersion models are used to predict ambient concentrations and receptor (or source apportionment) using ambient data to determine the sources. They differ in:

1. The required model inputs (e.g., meteorological data)

2. The spatial scale (global; regional-to-continental; local-to-regional; local)

3. The temporal scale (episodic models, long-term models)

4. The treatment of the transport equations (Eulerian, Lagrangian models);

5. The treatment of various processes (e.g., chemistry, wet and dry deposition)

6. The complexity of the approach. The choice of the appropriate model depends on the available data and the purpose of execution.

6.2.1 Types of Air Pollution Dispersion Models

There are five types of air pollution dispersion models, as well as some hybrids of the five types:

1. Box Model

The Box model is the simplest of the model types. It assumes the air shed (e.g., a given volume of atmospheric air in a geographical region) is in the shape of a box. It also assumes that the air pollutants inside the box are homogeneously distributed and uses that assumption to estimate the average pollutant concentrations anywhere within the air shed.

2. Gaussian Model

The Gaussian model is the oldest (Circa, 1936) and the most commonly used model. It assumes that the air pollutant dispersion has a Gaussian distribution. Gaussian models are normal probability distribution, buoyant air pollution plumes originating from ground level or elevated sources. Gaussian models are also used for predicting the dispersion of non-continuous air pollution plumes. The primary algorithm used in Gaussian modeling is the Generalized Dispersion Equation for a Continuous Point-Source Plume.

3. Lagrangian Model

The Lagrangian dispersion model mathematically follows pollution plume parcels (also called particles) as the parcels move in the atmosphere and they model the motion of the parcels as a random walk process. The Lagrangian model then calculates the air pollution dispersion by computing the statistics of the trajectories of

a large number of the pollution plume parcels. A Lagrangian model uses a moving frame of reference as the parcels move from their initial location.

4. Eulerian Model

The Eulerian dispersions model is similar to a Lagrangian model in that it also tracks the movement of a large number of pollution plume parcels as they move from their initial location. The most important difference between the two models is that the Eulerian model uses a fixed three-dimensional Cartesian grid as a frame of reference rather than a moving frame of reference.

5. Dense gas Model

The Dense gas models are models that simulate the dispersion of dense gas pollution plumes (i.e., pollution plumes that are heavier than air).

Apart from the above models, there are various other models available. The details of the same is given in Appendix D.

6.3 Parameters Influencing Pollutant Dispersion

There are two types of parameters which influences pollutant dispersion:

- Source parameters

For source parameters, concentrations are proportional to the amount of pollutant which is emitted. If dust is concerned, the particle diameter has to be known to determine sedimentation and deposition of the material.

- Meteorological parameters.

Meteorological parameters which influence pollutant dispersion are wind speed and direction as well as vertical thermal stratification. The pollutant concentration is proportional to the reciprocal of wind speed. This is mainly due to the accelerated

transport. Moreover, turbulent mixing increases with growing wind speed. As so-called inversions (i.e., situations where temperature is increasing with height) hinder turbulent mixing, maximum surface concentrations are observed during highly stable stratification. On the contrary, convective situations intensify vertical mixing and therefore show the lowest concentration values.

6.4 Factors Affecting Air Dispersion Model

Transport and dispersion of pollutants are subject to the effect of the parameters of meteorology (e.g., winds, turbulence and temperature in the atmosphere). These meteorological parameters affecting the transport and dispersion of pollutants include cloud cover, relative humidity and radiation to or from earth's surface and used to model variations in pollution levels throughout the whole year. However, in the near field that is less than 29km from the source, atmospheric chemical reactions and removal process can usually be neglected except for selected pollutants such as fluorine, H_2S, and photochemical oxidants. In the far field (e.g., greater than 100 km from the source), chemical reactions and removal process become increasingly important (De Nevers, 2000; Seibert, et al. 2000; Zlatev and Havasi, 2002).

6.4.1 Effects of Wind Speed

Wind in the planetary boundary layer, the layer of roughly 1 km height above the earth's surface, is influenced by surface roughness and atmospheric temperature profile (Referred to as the lapse rate of temperature as discussed later). However, movements of air near the earth's surface are hindered by frictional effects which proportional to the surface roughness. This relationship between wind speed and surface roughness changes with height. Thus, wind speed will be greater farther from the ground surface. One of the effects of wind speed is to dilute continuously released pollutants at the point of emission. This dilution takes place in the direction of plume transport and at the top of the stack. As a result, wind speeds used in estimating plume dispersion are generally estimated at stack top. The variation of wind speed with altitude is frequently described using the power law:

$$u_z = u10 * \left(\frac{z}{z10} \right)^p$$

(6.2)

Where:

u_z is wind speed at height, z above the ground in (m/s), u_{10} is wind speed at 10 m height, z_{10} is the height measurement specified by the World Meteorological Organization for meteorological stations in m, and p is exponent depending upon the atmospheric stability and the characteristics of the underlying surface (varies from about 0.1 to 0.3). In addition, wind speed affects the plume rise in a way that fast wind bends the plume faster and increases the rate of dilution. Therefore, wind speed work in two opposite directions. First, increasing wind speed decreases plume rise, thus increasing the ground level concentrations. Second, increasing wind speed increases mixing rate, consequently decreasing the ground level concentrations.

6.4.2 Effects of Wind Direction

Wind direction is certainly the most important parameter affecting the dispersion of pollutants especially from point sources more than any other parameter. The initial direction of transport of pollutants from their sources is determined by the wind direction at the source. If the wind is blowing directly toward a receptor, a shift in direction of as little as 5° causes concentrations at the receptor to drop about 10% under unstable conditions, about 50% under neutral conditions, and about 90% under stable conditions (Stern, et al. 1984). The direction of plume transport is very important in assessing source impact assessment where there are sensitive receptors or two or more sources, and in trying to assess the performance of a model through comparison of measured air quality with model estimates. Pollutant dispersion is also affected by variability in wind direction. Thus, if the wind direction is constant the area will be covered by high level of pollutant concentrations. However, direction is constantly shifting then will be there dispersion over a larger area, which will lower the concentration levels over any given

area (Abdul-Wahab, et al. 2002). Wind direction and frequency for a given period can be determined by constructing a wind rose.

6.4.3 Effects of Turbulence

Turbulence is the highly irregular motion of the wind. It is the most important mixing process in the atmosphere, which causes the dispersion of air pollutants. Sometimes, it is called eddy diffusion. The size and influence of these eddies on the vertical expansion of continuous plumes is affected by the vertical temperature. The level of turbulence in the planetary boundary layer increases with increased wind speed, surface roughness, and instability. Therefore, turbulence is produced by two specific processes;

1. Thermal turbulence (buoyancy) resulting from atmospheric heating, usually dominant on clear sunny days.
2. Mechanical turbulence (shear and surface friction), usually dominant on windy nights with neutral atmospheric stability.

6.4.4 Effects of Temperature

The temperature normally decreases with increasing altitude at a rate of -6.5°C/ Km, because of the decrease in pressure with height. This phenomenon is known as the Normal Lapse Rate of temperature (NLR). This temperature profile (e.g., the variation of temperature with altitude) has an important effect on wind structure and turbulence in the planetary boundary layer. The temperature profile that observed for a parcel of dry air as it moves upward in the atmosphere and expands slowly to lower pressure with no gain or loss of heat is the Dry Adiabatic Lapse Rate (DALR). DALR describes the adiabatic cooling at a rate of 10°C/ m or 1°C/100 m. If such a profile exists in the atmosphere, a parcel of air at any height is in neutral equilibrium; (e.g., it has no tendency either to rise or fall). This situation is taken as a reference profile, although it is very rare when the atmosphere is in such a state of equilibrium. Due to the influence of surface heating as well as local weather influences the temperature profile is usually different from this

reference profile. If the temperature decreases faster with height than the reference profile, air parcels at any height are unstable. Such a condition is referred to as unstable. On the other hand, if the temperature decreases more slowly with height than the reference profile (or even increases), air parcels arc would be inhibited from either upward or downward motion and the situation is referred to as stable. The stability condition of the atmosphere plays an important role in determining the rate of dispersal of pollutants. The Lapse Rate graph is typically will be as an indication of dispersion characteristics. If the slope of the graph is to the left of the DALR, dispersion characteristics are good to excellent. However, if it is to the right of the DALR, dispersion characteristics are not good.

6.4.5 Effects of Atmospheric Stability

The amount of turbulence in the ambient air has a major effect upon the rise and dispersion of air pollutant plumes. The amount of turbulence can be categorized into defined increments or "stability classes". The most commonly used categories are the Pasquill stability classes A, B, C, D, E and F (De Nevers, 2000; Turner, 1994). Class A denotes the most unstable or the most turbulent conditions and class F denotes the most stable or the least turbulent conditions.

6.5 Overview of the ISC Models

The Industrial Source Complex ISC Model is a computer model used to predict concentrations of a pollutant at specified locations as it is transported through the air. It is especially designed to support the EPA's regulatory modelling programs. This model is a steady-state Gaussian dispersion model with a number of options available to the user. These options include the use of stack-tip downwash, buoyancy-induced dispersion, final plume rise (except for sources with building downwash), a routine for processing averages when calm winds occur, and default values for wind profile exponents and for the vertical potential temperature gradients. The user may select either rural or urban dispersion parameters, depending on the characteristics of the source location.

The ISC model can predict the concentration of a pollutant downwind from a source or groups of pollutant sources. The ISC model estimates how much of the chemical a person is likely to be exposed to by considering a variety of factors. Many factors could affect exposure but are only focused on the ones that are affecting the amount of exposure due to inhalation. The factors listed below are used to calculate the average daily dose of a pollutant that a person is exposed to:

1. Concentration of the contaminant in inhaled air ($\mu g/m^3$)

2. Body weight (kg)

3. Inhalation rate (m^3 / day)

4. Type of physical activity; resulting volume of air inhaled with each breath

5. Exposure duration (days)

6. Averaging time (days) for non-carcinogenic effects or (lifetime, 70 years) for carcinogenic or chronic effects

It is important to note that there are two different types of ISC models. The short-term ISCST3 model can calculate the concentration or deposition of a pollutant for time periods of 1, 2, 3, 4, 6, 8, 12, and 24 hours. The long-term ISCLT3 model uses statistical summaries of meteorological data to provide estimates of annual average concentrations of a pollutant in the atmosphere. Figure 6.1 reveals a brief structure of Dispersion model.
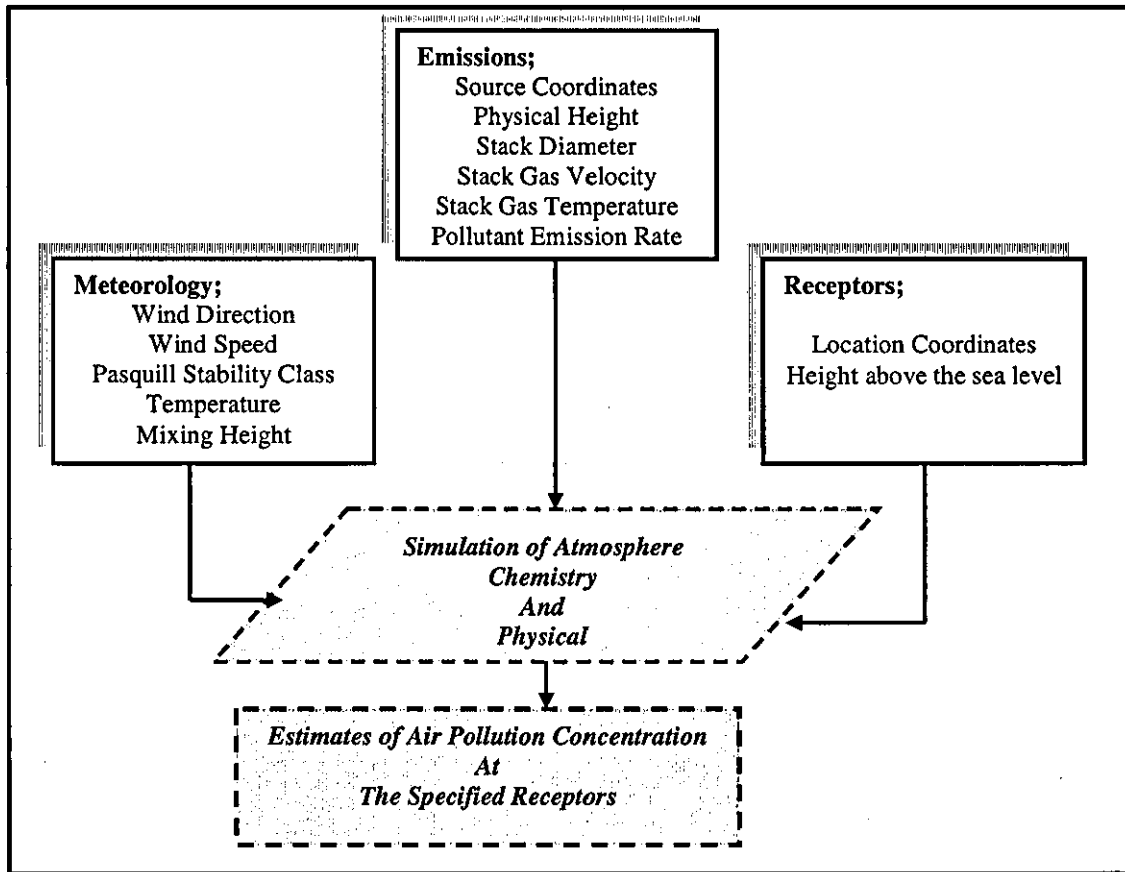
Figure 6.1: The Dispersion Model Structure

6.5.1 Industrial Source Complex Short Term Model (ISCST3)

In this study, the ISCST3 model are used to calculate ground level concentration of selected primary pollution and compare it with the monitoring data from a selected site used as receptor in the model. The ISCST3 model is the latest version of the series of the ISC models, which was originally developed in the 1970's. The ISCST3 model utilizes hourly meteorological data that have been pre-processed using the PCRAMMET program for National Weather Service (NWS) data, and the Meteorological Processor for Regulatory Models (MPRM) for on-site data. There are various publications that discussed the applications and verifications of the ISCST3 model.

The ISCST3 model is capable of :

- Modelling continuous and non-continuous contaminant emissions from many sources.

- Handling multiple sources, including point, volume, area, and open pit. Line sources may also be modeled as a string of volume sources or as elongated area sources.

- Enabling source emission rates to be treated as constants or varied by month, season, hour-of-day, or other optional periods of variation. These variable emission rate factors may be specified for a single source or for a group of sources.

- Accounting for the effects of aerodynamic downwash due to nearby buildings on point source emissions.

- Containing algorithms for modelling the effects of settling and removal (through dry deposition) of large particulates and for modelling the effects of scavenging precipitation for gases or particulates.

- Specifying receptor locations as gridded and/or discrete receptors in a Cartesian or polar coordinate system.

- Using real hourly meteorological data to account for the atmospheric conditions that affect the distribution of air pollution impacts on the modelling area.

- Producing results that can be output for concentration, total deposition flux, dry deposition flux, and/or wet deposition flux.

The ISCST3 models do not contain a terrain pre-processor. As a result, receptor elevation data must be obtained through alternative means. The use of an inverse distance algorithm for interpolating representative receptor elevations is an effective method.

The accuracy of the model is evaluated through comparisons between statistical parameters and standard deviation of the predicted and observed concentrations. An investigation of the performance of the ISCST3 model under the prevailing meteorological conditions in Kuwait was conducted by M.S. Al-Rashidi, et al. [2005]. Statistical evaluation of the model performance based on comparison between the indexes of agreement (IA) and NMSE of all Kuwait EPA monitoring stations to indicate

the model accuracy had been presented. The IA varies from 0 to 1 (poor to perfect agreement between predicted and observed values). The value IA should be close to one and NMSE should be close to 0 for a good model performance. The statistical results show that the index of agreement (IA) and NMSE vary respectively between 0.60-0.94 and .28-2.86, at the monitoring stations. The overall conclusion of this comparison is that the model predictions are in good agreement with the observed data with accuracy of 60-94% at six monitoring stations used by Kuwait EPA. Figure 6.2 shows overview of program elements in the ISCST3 modelling system.
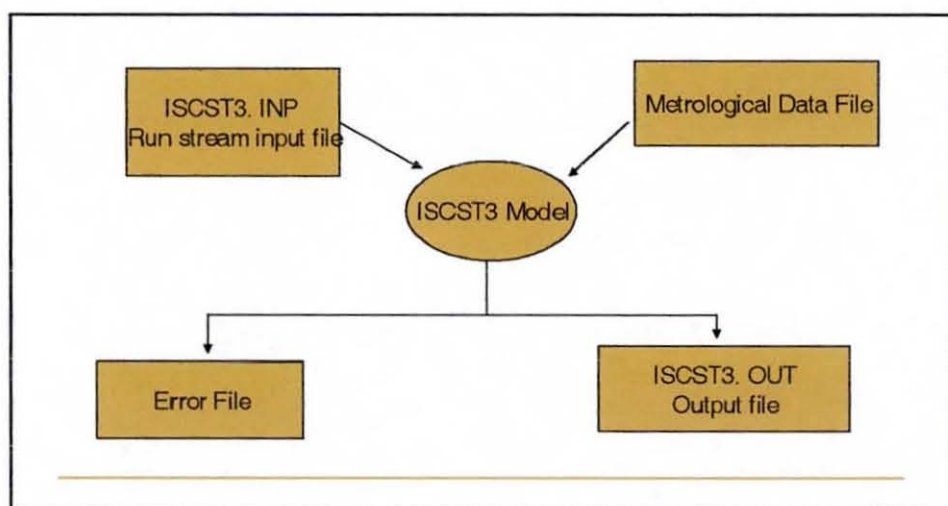
Figure 6.2: Overview of the program elements in the ISCST3 modelling system

6.5.2 The ISCST3 Dispersion Model Equations

The short term concentration model for pollutant sources uses the steady-state Gaussian plume equation for a continuous elevated source. For each source and each hour, the origin of the source's coordinate system is placed at the ground surface at the base of the source. The x-axis is positive in the downwind direction, the y-axis is crosswind (normal) to the x-axis and the z-axis extends vertically. The fixed receptor locations are converted to each source's coordinate system for each hourly concentration calculation. The hourly concentrations calculated for each source at each receptor are summed to

obtain the total concentration produced at each receptor by the combined source emissions.

The hourly concentration at downwind distance x (meters) and crosswind distance y (meters) is given as follows:

$$C(x,y,z) = \frac{Q}{(2\pi)\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \tag{6.3}$$

Where:

Q	=	pollutant emission rate (mass per unit time)
σ_y, σ_z	=	standard deviation of lateral and vertical concentration distribution (m)
u	=	mean wind speed (m/s) at release height
H	=	source height (m)
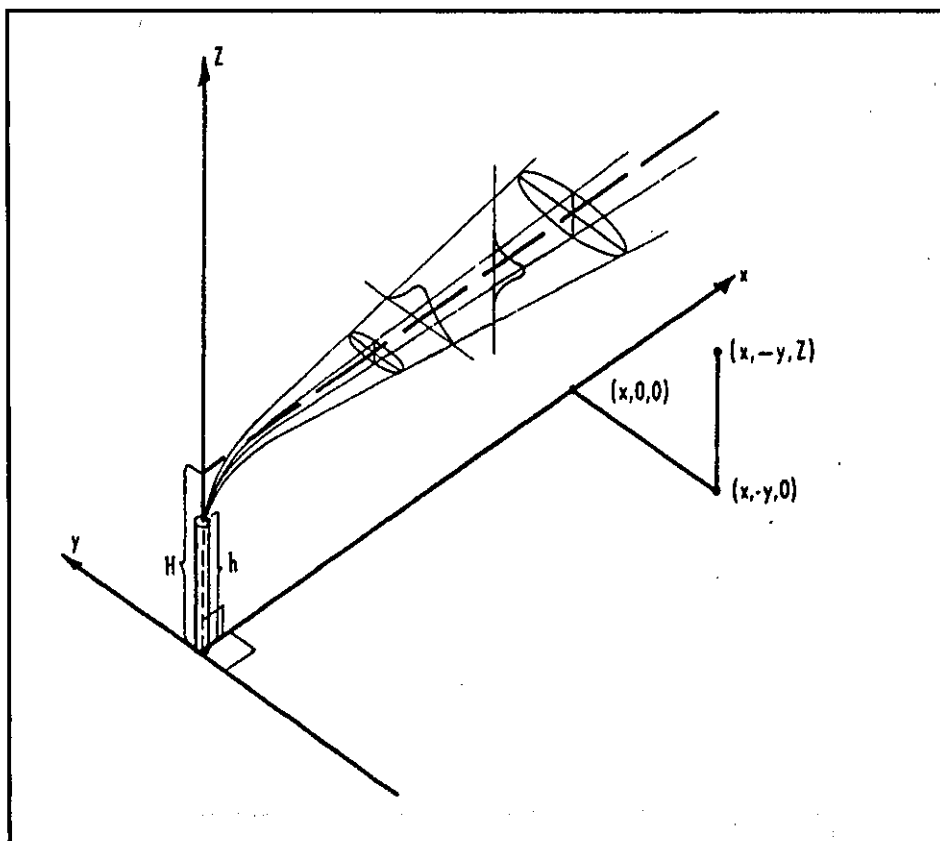
Figure 6.3: Coordinate system of the Gaussian theory

6.5.3 The ISCST3 Model Basic Data Requirements

The ISCST3 View interface uses the five pathways that compose the ISCST3 run stream file as the basis for its functional organization. These pathways are:

- Control Pathway (CO): specify the modelling scenario and the overall control of the modelling run.

- Source Pathway (SO): define the sources of pollutant emissions. In this pathway it must specify the location of the source and source parameters, (e.g., emission rate, physical stack height, stack gas exit velocity, etc). Optional inputs include source elevation, building dimensions, variable emission rates, particle size distributions, scavenging coefficients, etc.

- Receptor Pathway (RE): define the receptors to determine the air quality impact at specific locations. Input requirements are the location and optional ground elevation for each receptor.

- Meteorology Pathway (ME): define the atmospheric conditions of the area being modelled so that it can be taken into account when determining the distribution of air pollution impacts for the area.
- Output Pathway (OU): define which (e.g., output results are necessary to meet the needs of the air quality modelling analyses. Various types of output files can be produced. It can choose to output concentration, dry deposition flux, wet deposition flux or total deposition flux). ISCST3 View comes with a postprocessor that can plot these results for you automatically.

6.5.4 The ISCST3 Model Source Options

The types of air pollutant emission sources are commonly characterized as point, line, area, flare or volume sources.

- **Point Sources**

Point sources are typically used to model releases from sources like stacks and isolated vents.

- **Area Sources**

Area sources are used to model low level or ground level releases where releases occur over an area (e.g., landfills, storage piles, slag dumps, and lagoons).

- **Volume Sources**

Volume sources are used to model releases from a variety of industrial sources such as building roof monitors, fugitive leaks from an industrial facility, multiple vents, and conveyor belts.

- **Line Sources**

The ISCST3 model handles LINE sources as VOLUME sources.

- **Flare Sources**

Flare sources are used as control devices for a variety of sources. Flare sources can be modelled similar to point sources, except that there are buoyancy flux reductions associated with radiative heat losses and a need to account for flame length in estimating plume height. Input requirements are similar to those for a point source, except that the release height must be calculated as an effective release height and stack parameters need to be estimated to match the radiative loss reduced buoyancy flux.

Due to the high temperature associated with flares, the effective release height of the plume is calculated as follows:

$$H_{sl} = H_s + 4.56 \times 10^{-3} \bullet \left[\frac{H_r}{4.1868} \right]^{0.478} \tag{6.4}$$

Where:

H_{sl} = effective flare height (m)

H_s = stack height above ground (m)

Hr = net heat release rate (Joules per sec, J/s)

The net heat release rate is computed as follows:

$$H_r = 44.64 \bullet V \bullet \sum_{i=1}^{n} f_i H_i \bullet (1 - F_r)$$

(6.5)

Where:

V = volumetric flow rate of the flare (m³/s)

fi = volume fraction of each gas component

Hi = net heating value of each component (J/g-mole)

Fr = fraction of radiative heat loss

The fraction of radiative heat loss depends on the burning conditions of the flare. If there is information specific to the flare, then that fractional loss shall be used. As a default, a heat loss of 25% shall be used, as recommended by Alberta Environment. The stack parameters can be estimated by matching the buoyancy flux from the flare. The buoyancy flux from the flare is:

$$F = \frac{g \bullet H_r}{\pi \bullet \rho \bullet T \bullet C_P} = \left(8.8 x 10^{-6}\right) \bullet H_r$$

(6.6)

Where:

g = acceleration due to gravity (m/s²)

ρ = density of air (kg/m³)

T = air temperature (°K)

Cp = specific heat of dry air constant (J/(Kg °K)

Buoyancy flux for stack releases is:

$$F = g \bullet V_s \bullet r_s^2 \bullet \left(\frac{T_S - T}{t_s}\right)$$

(6.7)

Where:

Vs = exit velocity (m/s)

r_s = stack inner radius (m)

T_s = stack exit temperature (°K)

Using an estimated stack gas exit temperature (1,273 °K) and the actual exit velocity to the flare, an effective stack radius shall be calculated for input.

6.5.5   The ISCST3 Model Receptor Options

The ISCST3 models have considerable flexibility in the specification of receptor locations. The user has the capability of specifying multiple receptor networks in a single run, and may also mix Cartesian grid receptor networks and polar grid receptor networks in the same run. This is useful for applications where the user may need a coarse grid over the whole modelling domain, but a denser grid in the area of maximum expected impacts.

There is also flexibility in specifying the location of the origin for polar receptors, other than the default origin at (0,0) in x,y, coordinates. The input can elevate receptor heights in order to model the effects of the terrain above (or below) stack base, and may also specify receptor elevations above ground level to model flagpole receptors.

6.5.6   The ISCST3 Model Meteorology Options

The Short Term model includes a dry deposition algorithm and a wet deposition algorithm. The dry deposition algorithm requires additional meteorological input variables, such as Monin-Obukhov length and surface friction velocity that are provided by the PCRAMMET and MPRM pre-processor. The wet deposition algorithm in the Short Term model also needs precipitation data, which is optionally available in the PCRAMMET pre-processed data. When using the dry deposition or wet deposition algorithms in ISCST3, the meteorological data must be a formatted ASCII file.

6.5.7 Preparing Meteorological Data for ISCST3 Dispersion Modelling

The ISCST3 models require actual hourly meteorological conditions as inputs. These models require pre-processed meteorological data that contains information on surface characteristics and upper air definition. This data is typically provided in a raw or partially processed format that requires processing through a meteorological pre-processor. The ISCST3 models make use of a pre-processor called PCRAMMET.

6.5.8 PCRAMMET and the ISCST3 Models

The PCRAMMET program is a meteorological pre-processor which prepares NWS data for use in the various US EPA air quality dispersion models. The operations performed by PCRAMMET include:

- Calculating hourly values for atmospheric stability from meteorological surface observations;

- Interpolating the twice daily mixing heights to hourly values; Optionally, calculating the parameters for dry and wet deposition processes

- Outputting data in the standard (PCRAMMET unformatted) or ASCII format required by regulatory air quality dispersion models.

The input data requirements for PCRAMMET depend on the dispersion model and the model options for which the data is being prepared as show in Figure 6.4. The minimum input data requirements for PCRAMMET are:

- The twice-daily mixing heights and upper air data, also known as mixing height data, are required for pre-processing meteorological data required to run the ISCST3 model.

- The hourly surface observations of wind speed, wind direction, dry bulb temperature, opaque cloud cover, and ceiling height.
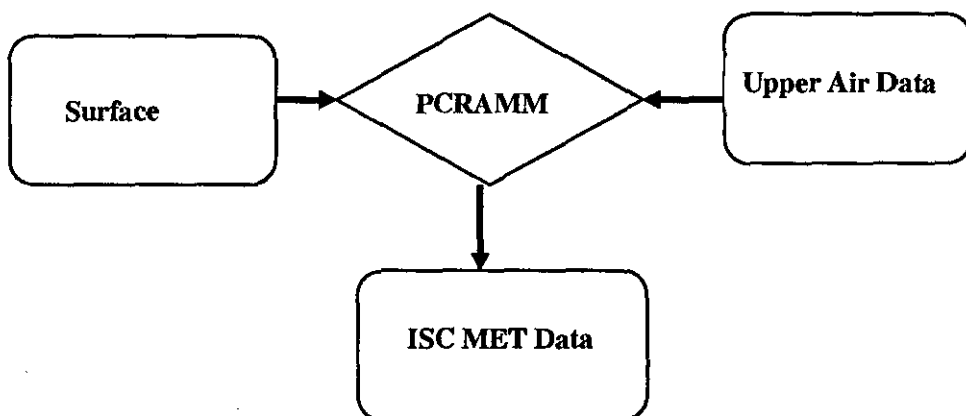
Figure 6.4: Meteorological data pre-processing flow diagram for the EPA ISC Models

For dry deposition estimates, station pressure measurements are required. For wet deposition estimates, precipitation type and precipitation amount measurements for those periods are required. Regulatory default settings of the model do not consider deposition. The surface and upper air stations shall be selected to ensure they are meteorologically representative of the general area being modeled.

6.5.9   ISCST3 Output Options

The basic types of printed output available with the Short Term model are:

- Summaries of high values (highest, second highest, etc.) by receptor for each averaging period and source group combination.

- Summaries of overall maximum values (e.g., the maximum 50) for each averaging period and source group combination.

- Tables of concurrent values summarized by receptor for each averaging period and source group combination for each day of data processed. These "raw" concentration values may also be output to unformatted (binary) files.

Chapter 7
Meteorological Conditions and Data Analysis for State of Kuwait

7.1 Introduction

Pollution problems arise from the confluence of atmospheric contaminants, adverse meteorological conditions, times and certain topographical conditions. Because of the close relationship that exists between air pollution and certain atmospheric conditions, it is necessary to have a thorough understanding of meteorology. Meteorological conditions play a major role in the dispersion model of pollutants emitted to atmosphere.

As discussed in Chapter 6, in order to conduct air dispersion modelling using ISCST3, it is needed to process the meteorological data to be representative of the general area being modelled. The collected meteorological data is not always in the format supported by this model, therefore, the meteorological data needs to be pre-processed using the U.S. EPA PCRAMMET program.

One year hourly record of the surface and upper air meteorological data for the year 2006 obtained from Kuwait International Airport (KIA) weather station was used in the present study for simulation of the dispersion of methane, non-methane hydrocarbons and SO_2 emitted from flaring in all Kuwait Oilfields areas (NK, SEK, WK).

7.2 Meteorology

Meteorology is the interdisciplinary scientific study of the atmosphere that focuses on weather processes and forecasting. Meteorological phenomena are observable weather events which illuminate and are explained by the science of meteorology. Those events are bound by variables that exist in Earth's atmosphere. Such variables are temperature, pressure, water vapour, and the gradients and interactions of each variable, and how they change in time. Accurate measurement is very important in meteorological studies.

Meteorological conditions obviously affect the transport of pollutants and the movement of a plume. Many different meteorological factors are important in the transport of pollutants.

One important factor is caused by changes that occur from day to night (diurnal differences). During the day, heat from the sun causes the mixing of air, while at night, when cooling occurs, the air subsides (settles down) and becomes stratified (arranged in layers). Figures 7.1a and 7.1b reveal the situation.

$$\frac{\textit{Layer} \text{ of warm air}}{\text{Layer of cold air}}$$
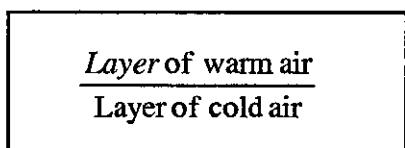
Figure 7.1a: Stable environment – layers of air do not mix – Night times

$$\frac{\textit{Layer} \text{ of cold air}}{\text{Layer of warm (hot) air}}$$
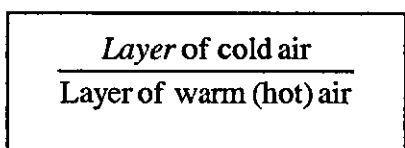
Figure 7.1b: Unstable environment – Convection currents mix layers of air (summer)

Another important concept that also needs to be understood is the mixing height of the air. The lowest layer of the atmosphere is the troposphere. The troposphere is made up of two parts: the planetary boundary layer (PBL) and the free atmosphere. The PBL extends from the earth surface to between 100 meters and 3,000 meters, depending on meteorological conditions. A special mixing height program has been developed that uses surface and upper air data to calculate the mixing height at any given time.

The PBL is higher during the daytime than at night. The PBL also changes with seasons. On average, the PBL is lower in the winter and higher in the summer. To summarize, the mixing height of the PBL is another important factor that the ISC model incorporates.

Meteorological conditions combine with pollutant emissions to influence air quality. Because of this relationship, air quality models require meteorological data to correctly predict ambient pollutant concentrations.

The requisite meteorological inputs can vary by air quality model, but typically involve information including wind vectors, vertical mixing, temperature, and atmospheric moisture.

7.2.1   Meteorological Data and Processors

Air quality models solve for the change in pollutant concentrations over time and space, and thereby require certain meteorological inputs that, in part, determine the formation, transport, and destruction of pollutant material. The requisite meteorological inputs vary by air quality model, but usually include information regarding wind speed and direction, vertical mixing, temperature and atmospheric moisture. While inputs for these air quality models are often derived from ambient measurements, it can be advantageous to use meteorological models to provide the necessary data.

7.2.2   Observational Meteorological Data

Observed meteorological data for use in air quality modelling consist of physical parameters that are measured directly by instrumentation (temperature, dew point, wind direction, wind speed, cloud cover, cloud layer(s), ceiling height, visibility, current weather, and precipitation amount). These data are used in air quality models to capture the atmospheric conditions occurring at a source and/or receptor location, and therefore, play an important role as they effect the concentration of pollutants at receptors of interest.

7.2.3   Surface and Upper Air Databases

There are two types of meteorological data; Surface data and Upper air data.

Surface data are meteorological data that are measured at the earth's surface (technically, somewhere between the ground level and 10m). This data contains physical parameters

that are measured directly by instrumentation, such as temperature, dew point, wind direction, wind speed, cloud cover, cloud layer(s), ceiling height, visibility, current weather, and precipitation amount. In current study, surface data are reported by the Kuwait International Airport weather station for each hour.

Upper air data are meteorological data that are measured in the vertical layers of the atmosphere. Upper air data are usually measured by twice daily radionsonde soundings, taken at 00 and 12Z (Greenwich Time). There are other collection methods for gathering upper air data, though radiosonde soundings are the method usually employed for local-scale dispersion modelling.

7.3   PCRAMMET

PCRAMMET is a meteorological pre-processor used for preparing National Weather Service (NWS) data for use in the Agency's short term air quality dispersion models. PCRAMMET is a PC version of the original RAMMET program. Output from PCRAMMET is commonly used as input to ISCST3 as stated in chapter 6, section 6.5.8.

As explained in previous chapter, the input data requirements for PCRAMMET depend on the dispersion model and the model options for which the data are being prepared. For concentration estimates for which the effect of settling and removal processes of dry and wet deposition are not required, the necessary data are:

- Wind direction
- Wind speed
- Dry bulb temperature
- Opaque cloud cover
- Cloud ceiling height
- Morning mixing height
- Afternoon mixing height

The mixing heights are based on NWS upper air soundings at 1200 GMT and 0000 GMT, respectively.

7.3.1   Mixing Height Data

The mixing height records input to PCRAMMET must contain the morning and afternoon mixing heights for the day being processed.   The morning and afternoon mixing height estimates are determined based on the method described by Holzworth [1972] and Hanna[1969]. In addition, mixing heights based on accelerometer and temperature measurements made with a light aircraft during daytime have been found by McCaldin and Sholtes [1970] to be in good agreement with heights calculated as indicated herein.

As show in Figure 7.2, Mixing height can be estimated by plotting maximum surface temperature and drawing a line parallel to the dry adiabatic lapse rate from the point of maximum surface temperature to point at which the line intersects the ambient lapse rate early morning.
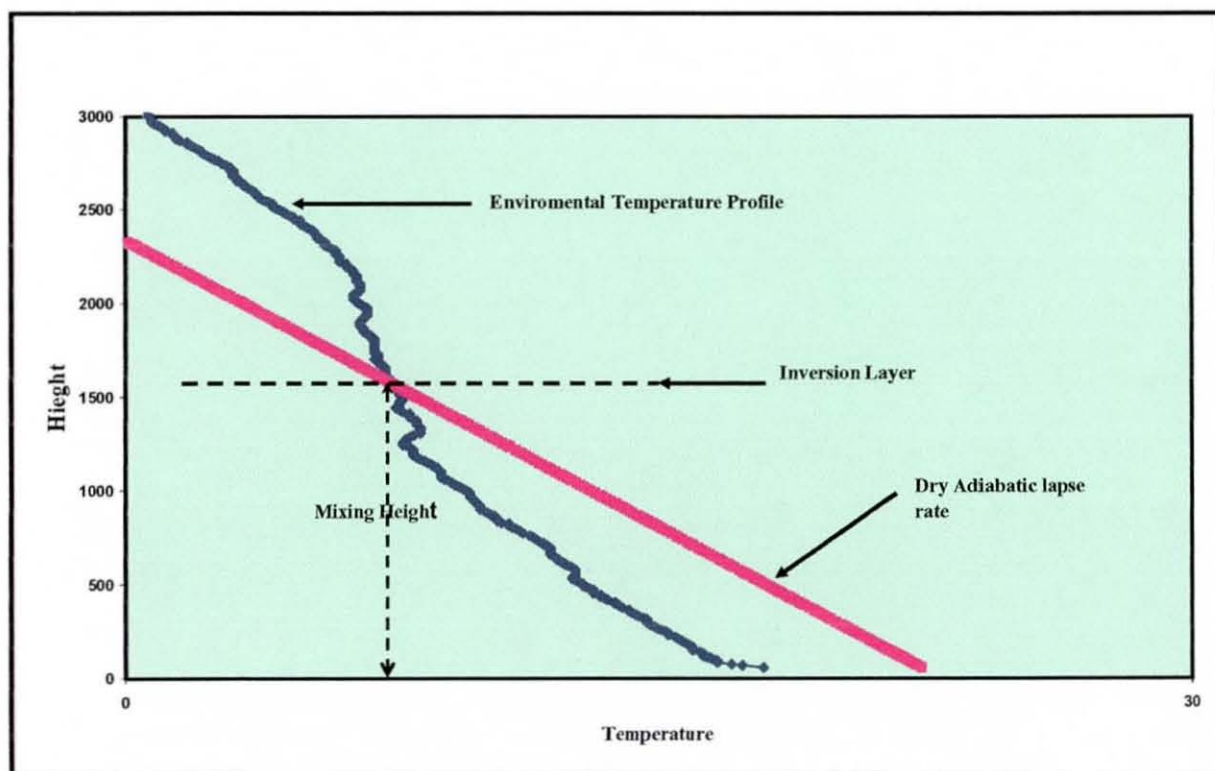
Figure 7.2: Upper air temperature profile and formation of the temperature inversion

Operations likely to produce significant amount of air pollution be limited to those areas in which atmospheric dispersion process are most favourable. A determination of the mixing height of an ambient environment could help establish whether an area is a proper site of contaminant causing human activities.

7.4 Analysis of Meteorological Data

The meteorological data that are input to and output from PCRAMMET were compared. Input data included wind speed, wind direction, cloud cover, ceiling height, and ambient temperature. Output data included Pasquill Gifford (PG) stability category and rural and urban mixing heights. Two sets of input to PCRAMMET were examined:

1. Cloud cover, ceiling, winds, temperature, and pressure from conventional observations;

2. All meteorological variables from Kuwait International Airport weather station. In the former, the effects of cloud cover and ceiling are isolated without the effects of winds and temperature.

Meteorological data quality is of critical importance, particularly for reliable air dispersion modelling using models. Meteorological data shall be collected, processed and analyzed throughout the entire creation phase for completeness and quality control. Wind roses showing the wind speed and directions shall be provided with the modelling assessment. If wind direction dependent land use was used in deriving the final meteorological file, the selection of the land use must be described.

7.5 Meteorological Data of the State of Kuwait

Meteorological conditions play a major role in the dispersion model of pollutants emitted to atmosphere. The understanding of the physical and chemical behaviour of pollutants in the atmosphere necessaries the knowledge of Meteorological conditions of the area under study. Therefore, a one year hourly record of the surface and upper air meteorological

data for year 2006 obtained from the KIA weather station is used in the present work for simulation of the dispersion of methane, non-methane hydrocarbons and SO_2 emitted from flaring in all Kuwait Oilfields areas (NK, SEK, WK).

The major aim here is to report on real meteorological data being measured and recorded so that a clear picture can be withdraw about the climate in the State of Kuwait and it is affect air pollution.

7.5.1   Geography of the State of Kuwait

Kuwait is shaped roughly like a triangle, surrounded by land on its northern, western and southern sides and sea on its eastern side, with 195 kilometers of coastlines. Kuwait has an area of about 17,818 square kilometers.   At its most distant points, is about 200 kilometers north to south and 170 kilometers east to west.   Kuwait lies at the northwest between latitudes 28° and 30° north and between longitudes 46° and 48° east. Most of the Kuwaiti mainland is a flat sandy desert, gradually sloping down from the extreme west towards the sea level in the east. Dust and sand storms are persistent problem in Kuwait, especially during the seasonal transactions. The bulk of the Kuwaiti populations live in the coastal area of Kuwait. Smaller populations inhabit the nearby city of Al-Jahrah. (See Figure 7.3).

Figure 7.3: Geography of Kuwait Map

Kuwait has a typical desert climate, hot and dry most of the time. Rainfall varies from seventy five to 150 millimeters a year across the country, however, rainfall ranging from twenty-five millimeters a year to as much as 325 millimeters have also been recorded.

In summer (April to October) , average daily temperatures range from 42°C to 46°C, the highest recorded temperature has been 51.5°C. The summers are relentlessly long, punctuated mainly by dramatic dust storms in June and July when northwesterly winds cover the cities in sand. In late summer, there is slight increase in humidity that ditches the temperature by a few degrees. Winters (November through February) are cool with some precipitation and average temperatures around 13°C (56°F) with extremes from -2°C to 27°C. The spring season (March) is warm and pleasant with occasional thunderstorms. Surface coastal water temperatures range from 15°C (59°F) in February to 35°C (95°F) in August. The winter months are often pleasant, featuring some of the region's coolest weather, with daytime temperatures hovering around 18°C (64°F) and nights being genuinely chilly. Sandstorms occur throughout the year but are particularly common in spring.

7.5.2   Meteorological Data Analysis for year 2006 for the State of Kuwait

The meteorological data required for the model are anemometer height (m), wind speed (m/s), wind direction (degree) clockwise from the north, air temperature, total and opaque cloud cover (%), stability class at the hour of measurement (dimensionless) and mixing height (m). The anemometer height, wind speed, wind direction, air temperature and cloud cover are usually obtained from direct measurements. For the present study, average hourly measurements of wind speed, wind direction, air temperature and clouds were obtained from routine measurements at the Kuwait International Airport weather station for year 2006.

The most important meteorological factors that strongly affect continuously the behavior of the pollutants trends during a day are the mixing height and depth of the mixing layer. The estimation of mixing heights from upper air meteorological data is a critical parameter for understanding the formation, dispersion and transfer of ozone and precursors during pollution episodes. The upper air meteorological data (Appendix B)

are obtained from routine measurements at the KIA weather station for the year 2006. These data were used to calculate the mixing heights (Figure 7.2) as discussed in the previous section and to investigate the effects of upper air meteorological data in the diurnal behaviors of ozone and its precursors.

The stability class was defined on the basis of Pasquill categories, which are mainly a function of the hour of measurement, wind speed and sky cover (i.e., the amount of clouds). Based on temperature profile measurements, the mixing height was estimated by the model.

In general, the prevailing wind direction is along the north westerly quadrant throughout the year, but it is more so in summer. Figure 7.4 shows detailed wind rose plots for the main two seasons in Kuwait for year 2006. Figure 7.4a presents the wind rose plot for winter (November-March) where calm conditions are about 19.11% of the total time and an average wind speed of 4.35 m/s. Figure 7.4b provides the wind rose plot for summer (April -October) where calm conditions are about 10.92% of the total time and an average wind speed of 4.92 m/s. This indicates that there is no marked seasonal variation in the wind direction throughout the year. Moreover, there is no significant diurnal variation in the prevailing wind direction during the day and night times. This tends to minimize the effect of any land or sea breeze in the dispersion of the pollutants in the urban areas of Kuwait.

Figure 7.5 illustrates the frequency distribution of the winds for year 2006. The highest wind higher than 11.1 m/s (about 0.7% of wind speed record), the range of 8.8 to 11.1 m/s was 3.7%, 5.7 to 8.8 m/s was 19.4%, 3.6 to 5.7 m/s was 32.2%, 2.1 to 3.6 m/s was 17.5% and 0.5 to 2.1 m/s was 26.4%. The recording and monitoring of wind speed and wind direction can indeed play an important role in the outcome of the strength of any possible air pollution.

As shown in the detailed wind rose plots (Figures 7.4a and 7.4b), the main prevailing wind direction in North West (NW) is more frequent than other directions (e.g., N, NNW

and W). In addition and as shown in Figure 7.6 that the NW wind direction prevails with high wind speed in respect to other directions.

The effect of the wind speed is a very important parameter in the dispersion of pollutants as the relationships between the wind speed and the concentrations of pollutants downwind a source is of inverse proportional. This means when the wind speed reaches its highest level, it actually helps in reducing the concentration of any air pollution, thus reducing its hazardous effects on the residential area. On other hand, slow wind can be considered as disadvantage since it allows for the formation high concentrations of pollutants moving slowly over residential area, and hence increasing on their hazardous effects.
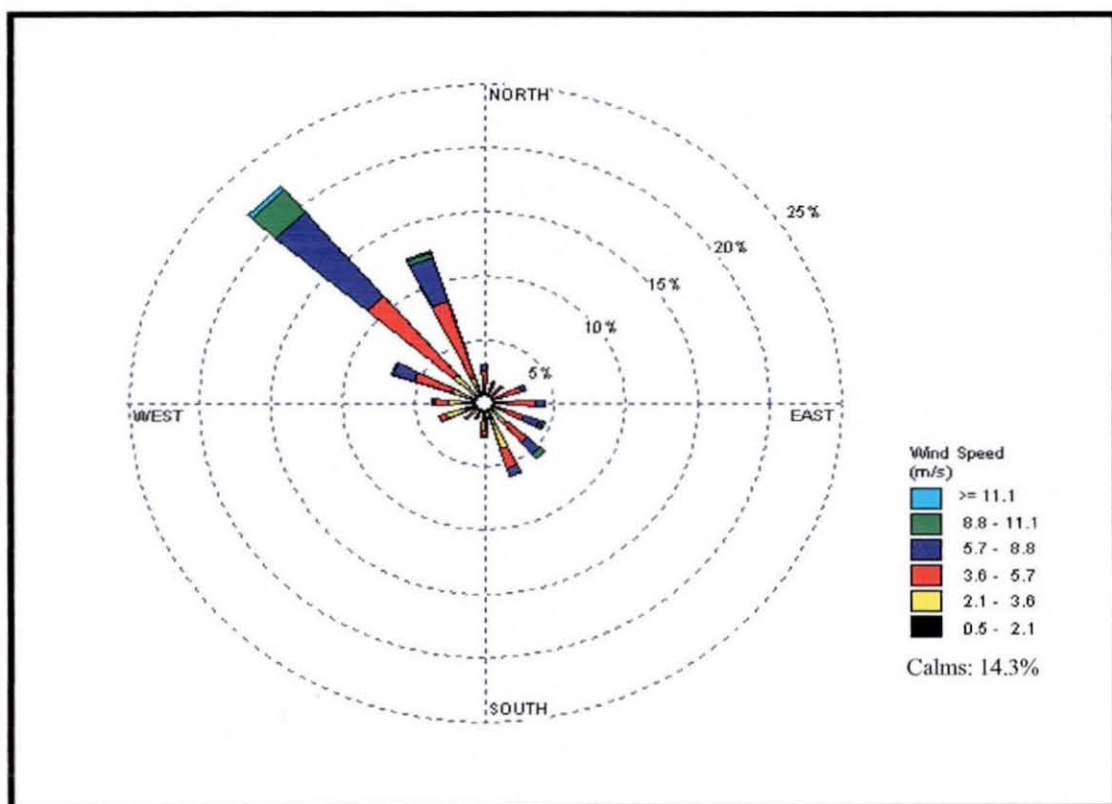
Figure 7.4: Wind Rose Plot for the year 2006
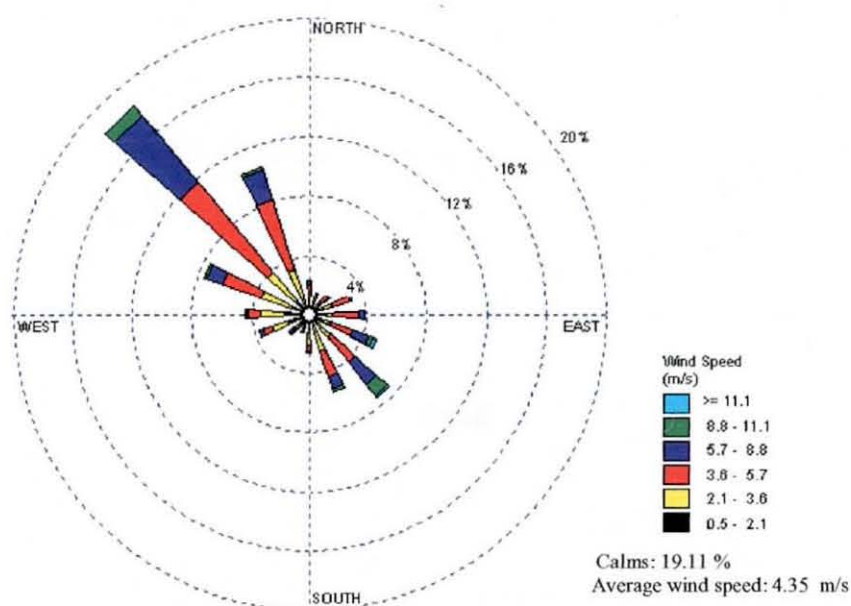
Figure 7.4a: Wind rose plot for winter (November - March)
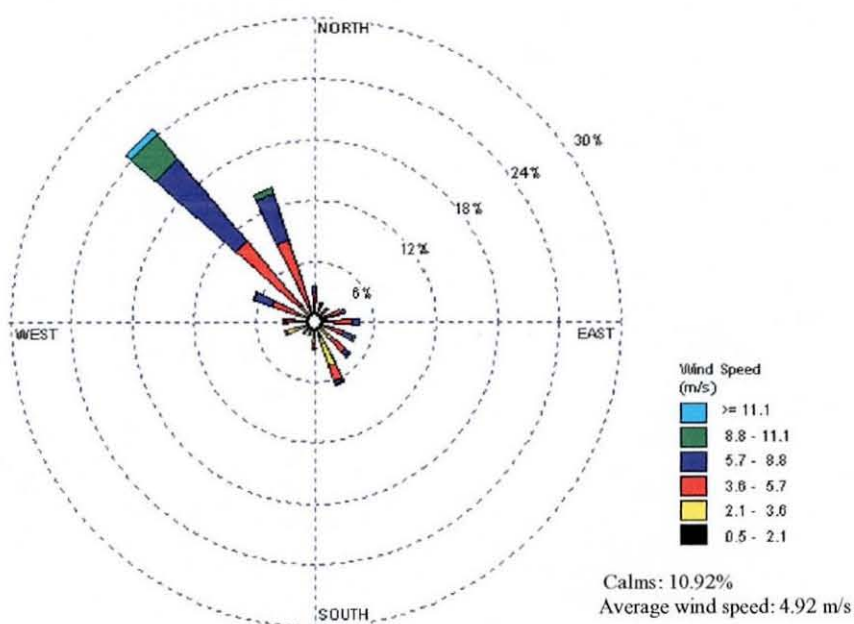
Figure 7.4b: Wind rose plot for summer (April - October)
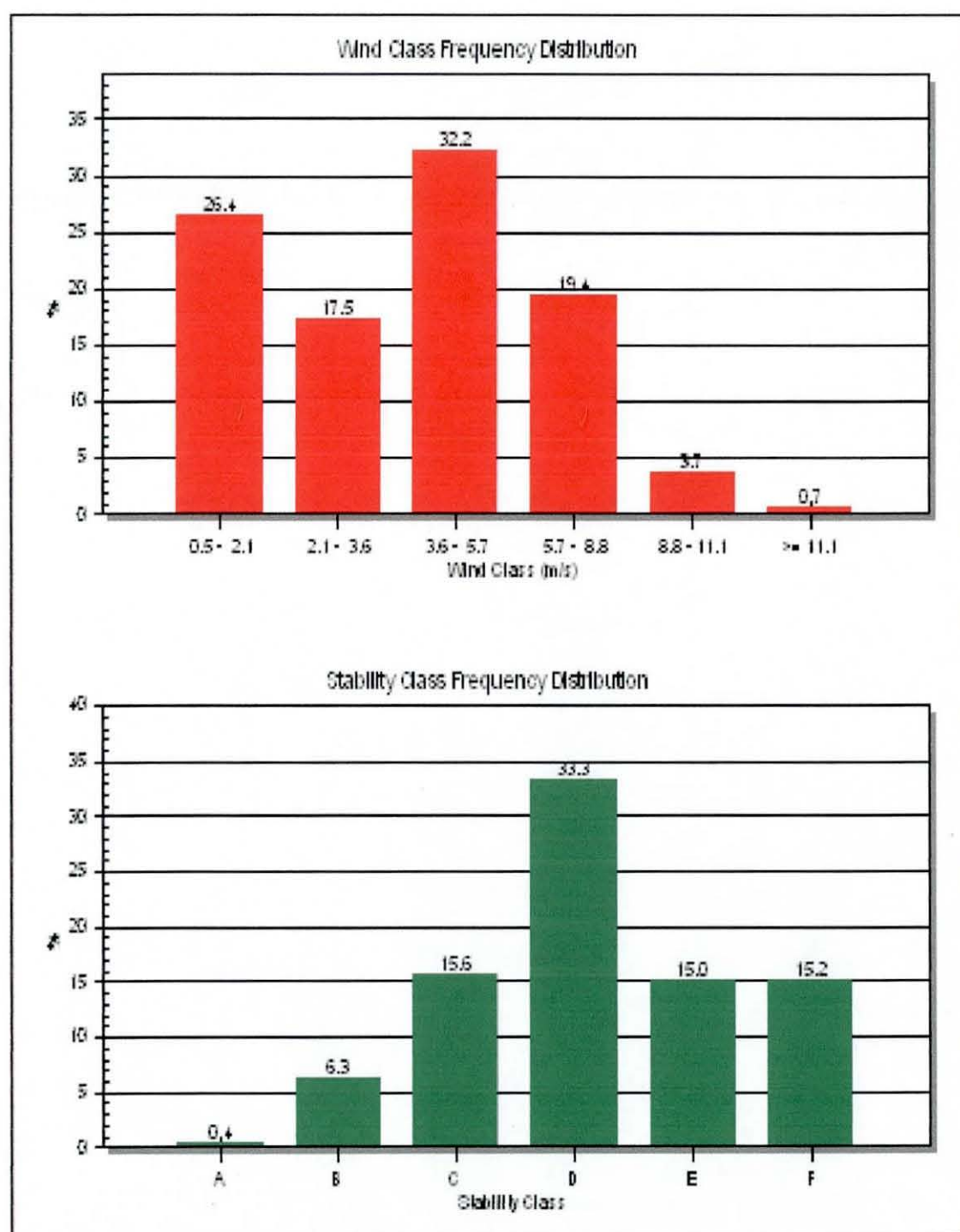
Figure 7.5: Frequency Distribution of the Wind Speed Class during the year 2006
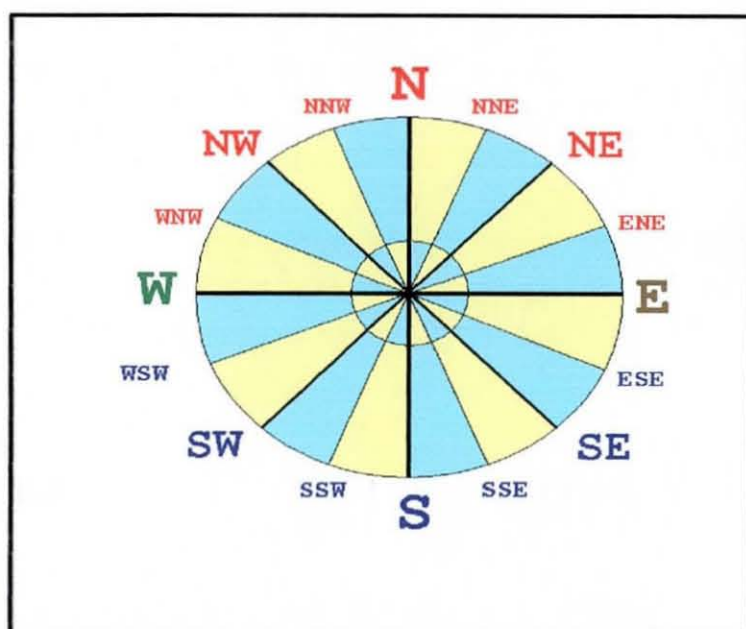
Figure 7.6: Wind Rose Wind Direction Plot

Wind moves in three dimensions. The wind speed determines the travel time from a source to receptor and the total area over which the plum will be dispersed. Whereas, the wind direction determines the path of the effluents will take or the area to which the plum will be directed.

The wind in the State of Kuwait results from the influence of the pressure systems, which dominate the area during the season. In general, the prevailing winds are from the northwesterly quadrant throughout the year, but they are more frequency in summer, about 60% of the time, the prevailing wind in summer is northwesterly.

Table7.1, presents the Mean Monthly Wind Speed (MMWS) and the Mean Monthly Ambient Temperature (MMAT) for 2006. These mean monthly meteorological data were computed from the hourly records during each day of 2006. The annual mean wind speed in 2006 is low being only 4.04 m/s, while MMWS reaches its highest in June (5.23 m/s) and in July (6.07 m/s), and its lowest in January (3.18 m/s). The annual mean temperature was 27°C where the lowest MMAT recorded during the year was 11.6°C in December and the highest MMAT was 40°C in July.

Figure 7.7 shows the MMAT, maximum and minimum temperatures recorded for each month. The maximum temperature in summer ranges from 40 to 51°C. This variation of temperatures and wind speeds has serious consequences on dispersion the level of air pollutants, and hence the air quality, especially in residential areas close or downwind of NK Oilfields. Appendix B presents meteorological data for year 2006 for each month.

Month	Mean Wind Speed (m/s)	Mean Ambient Temperature (°C)
January	3.18	13.50
February	3.73	15.94
March	4.10	21.17
April	4.01	26.30
May	4.27	34.25
June	5.23	38.52
July	6.07	40.04
Auguest	3.75	39.34
September	3.66	34.41
October	3.76	30.18
November	3.43	19.58
December	3.33	11.61
Average	4.04	27.07

Table 7.1: Mean Monthly Meteorological Conditions for year 2006
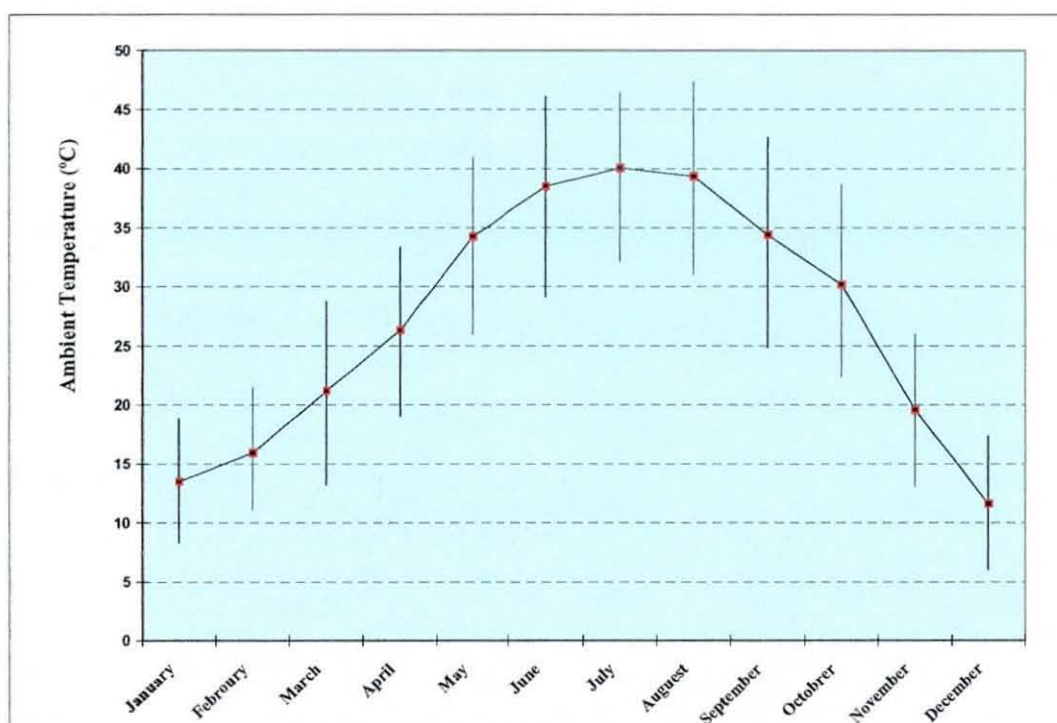
Figure 7.7: The mean monthly, maximum and minimum record of ambient air temperature for year 2006.

Table 7.2 presents the frequency distribution count for the wind direction under a specify winds speed class for year 2006. The frequency of the calm winds was 14.3% of the 8736 hourly record data. The wind direction is considered as the direction from which the wind is blown and, therefore, a NW wind will move pollutants to the South East (SE) of the source. As such, this consideration was taken in to account in gathering the information as given in Table 7.2 and the wind rose plot as shown in Figure 7.4 to make the analysis of the wind data more consistent with the modelling results.

Wind Direction	Wind Speed Class in (m/sec)						Total
	0.5 - 2.1	2.1 - 3.6	3.6 - 5.7	5.7- 8.8	8.8 - 11.1	>= 11.1	
N	33	43	144	47	0	0	267
NNE	21	54	74	10	0	0	159
NE	30	40	85	6	1	0	162
ENE	32	61	154	28	0	0	275
E	35	82	204	60	1	0	382
ENE	34	79	156	106	25	5	405
SE	77	122	161	106	42	6	514
SSE	126	205	150	48	8	2	539
S	97	95	35	11	2	0	240
SSW	59	38	21	12	1	0	131
SW	69	36	31	23	2	0	161
WSW	132	112	42	9	1	0	296
W	114	109	77	20	0	3	323
WNW	76	132	247	136	17	2	610
NW	78	174	697	753	193	38	1933
NNW	47	144	536	324	33	6	1090
Total	1060	1526	2814	1699	326	62	7487

Frequency of Calm Winds :14.3% out of Calm wind Hours : 8736

Average Wind Speed : 4.7 m/s

Table 7.2: Frequency Distribution Counts for the Wind Direction in year 2006.

In general, clear sky, high temperature and airborne dust is the feature of the summer season whereas mild to relatively cold with light rain is the feature of the winter season. These two contrasting weather conditions would have opposite effects on the dispersion of the pollutants and the concentrations levels through the processes of transport and reaction in the atmosphere. In the winter season, the presence of the cloud cover results in the reduction of the solar energy, ambient temperature and wind speed. These conditions decrease the photochemical reactions for the formation of ozone and increase the incidence of the surface based inversion that results in lower mixing height. Thus, these meteorological conditions during winter season would tend to increase the concentrations of the primary pollutants.

Chapter 8
Air Quality Monitoring Stations in the State of Kuwait

8.1 Introduction

In order to create a strategy to control air pollution or an impact assessment study for such industrial activities, it is imperative to have a thorough knowledge of the spatial and temporal variations of the pollutants concentrations.   This knowledge initiated through the understating of the diurnal and seasonal variations of the air pollutants within the residential areas. Moreover, it is important to establish the role of weather conditions in the dispersion of the pollutants in Kuwait. Such a role can be determined through the investigation of the relationships between the measured pollutants concentrations and the relevant meteorological parameters. For these purposes, measurements of the air pollutants concentrations and meteorological parameters made available and then collected from the air quality monitoring network established in 1995 by the Kuwait EPA.

8.2 Air Quality Monitoring Network

Air quality monitoring networks (AQMN) are an essential tool to monitor and control the atmospheric pollution. The ultimate objective of monitoring is to collect data that can be used to make informed decisions about how best to manage and improve the environment by providing the scientific basis for developing policies and strategies, for measuring compliance with local guidelines values and tracking progress towards environmental goals or targets.

8.3 State of Kuwait Air Quality Monitoring Network

The government of Kuwait established the Kuwait EPA in 1995, to safeguard the environment from air pollution due to heavy industrialization. Kuwait EPA established a number of fixed monitoring stations, to be updated with the air quality in the urban areas, through a monitoring network. These stations continuously measure the levels of pollutants such as SO_2, NO_2, CO, NO, CO_2, H_2S, O_3, and TSP (total suspended particles) in the air, the increasing levels of which effect human health, apart from eroding materials.

The hourly air pollutants concentrations were measured continuously by fixed ambient air stations located over the State of Kuwait. The Kuwait EPA air quality-monitoring network consists of eight monitoring stations to measure the values of the air pollutants concentrations in the state of Kuwait. These are as follows:

- **Al-Jahra monitoring station**

  Al-Jahra of population equal 100,000 is located about 35 km west downtown. Al-Jahra monitoring station Located on Latitude 29° 20' N to Longitude 47° 41' E. Al-Jahra is an urban residential and commercial area situated in the northern side of Kuwait. It is 22 km northwest of Rabia. Al-Jahra is having Doha Power plant on its Northwest; Rawdatain oil fields in the North. Moreover, Sulaibiya Industrial Area and sewage plant are in the south of Al-Jahra which contributing to the atmospheric contamination. The station is fixed on the top of Al-Jahra hospital.

- **Rabia monitoring station**

  Rabia is an urban area, situated 11 km southwest of Mansoriya. It has pollution impact from Kuwait Airport as well as the Ardiya sewage plant close to Rabia. Moreover, the Al - Ray Industrial area is located to the north of Rabia. The monitoring station is functioning on the top of the polyclinic medical center near the Rabia cooperative stores.

- **Mansoriya monitoring station**

  Al- Mansoriya is a typical urban residential and commercial area, close to Kuwait City, bounded by the heavy traffic from the first and second ring roads. It is surrounded by Al Megwa oil field to the southwest, Al-Doha power plant to its northeast and Al Subiya power plant to its northwest. Al- Mansoriya is close to Kuwait Bay and Arabian Gulf, where wind plays a major role in the intensity of pollutants.

- **Riqqa monitoring station**

Reqqa is semi coastal urban area. It is 18 km South of Rabia as shown in Figure 8.1. The air monitoring station is located on the medical centre in the center part of Reqqa, near the cooperative stores. Being a major commercial area, car parking is also provided. Pollution from vehicles is a concern to the air quality. Petroleum refineries at Ahmadi are to the Southeast of the station. On the West side, there is Al-Reqqa sewage plant and Subhan Industrial Area. In the Southwest part of Reqqa there is the multi-reservoir Greater Burgan field. To its east there is Arabian Gulf. The pollutants are influenced by the sea breeze being a coastal area. Reqqa is a major suburb 25 km South of Kuwait City with a major regional hospital. Riqqa monitoring station is located on Latitude 29° 08' N to Longitude 48° 07' E with population equal 100,000.

- **Fahaheel monitoring station**

Fahaheel is the major coastal city just North of the Shuaiba Industrial Area. It has several workshops. Fahaheel monitoring station is located on Latitude 29° 06' N to Longitude 47° 08' E with population equal 200,000.

- **Ali Al-Salem monitoring station**

Ali Al-Salem is a coastal urban region situated in the southern part of Kuwait. It is surrounded by oil wells, petrochemical and oil industries as well as other industries. On the west side of Ali Al-Salem is the Wafra field and the multi-reservoir Greater Burgan field, the second largest oil field in the world. Al Meqwa oil field is located 42 km in its Northwest. On its east side there is the Mina Abdullah Port which is just 2 km away. Mina Abdullah port industrial area lies 2 km on its Northwest. The Shuoiba industrial area and Al-Ahmadi port are to the Northeast that is just 6 km away.

- **Umm Al-Aish monitoring station**

Umm AL-Aish is along the Abdalli Highway, 35 km North of Mutla Ridge Deseret area. Located on Latitude 29° 41' N to Longitude 47° 40' E.

- **Rumaithiya monitoring station**

It is important to mention that all of the above monitoring stations are generally considered as urban stations distributed within the residential areas except for Umm Al-Aish monitoring station, which is located in the north part of the country far away from the residential areas and considered a rural station. Figure 8.1, shows the area map and the locations of Kuwait EPA air quality monitoring sites.

Figure 8.1: Location of the Air Quality Monitoring Network in the State of Kuwait

These monitoring stations are equipped with an automatic analyzer and meteorological sensors. All the pollutants are measured in 'ppm' except PM_{10} is $\mu g/m^3$. Figure 8.2a, 8.2b, 8.2c and 8.2d, indicates Al-Jahra, Umm Al-Aish, Fahaheel and Riqqa monitoring stations with the automatic analyzer and meteorological sensors. The measurements parameters are recorded simultaneously every five minutes, and they are stored in a computer at each station. Measurements of 10 parameters have been collected over a period of one year starting from January 2006 for the pollutants concentrations and the meteorological data from each station.

The air pollutants measured include sulphur dioxide (SO_2), nitrogen oxides (NOx = NO+NO_2), carbon monoxide (CO), ozone (O_3) and non-methane hydrocarbon. The meteorological parameters monitored include wind speed and (direction, air temperature, relative humidity and solar radiation.
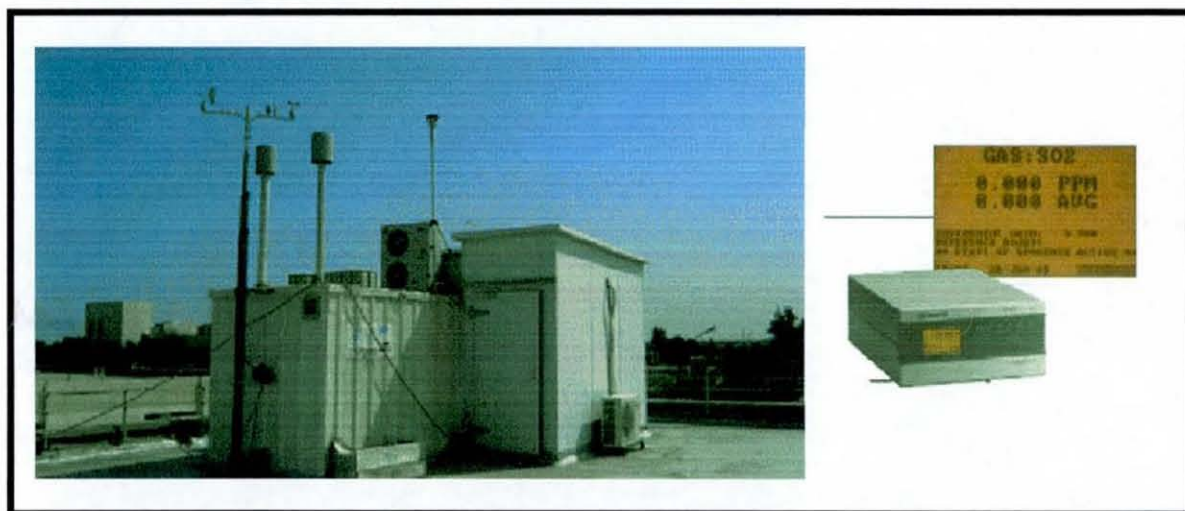
Figure 8.2a : Digital images of AL-Jahra Monitoring station with the automatic analyzer and meteorological sensors
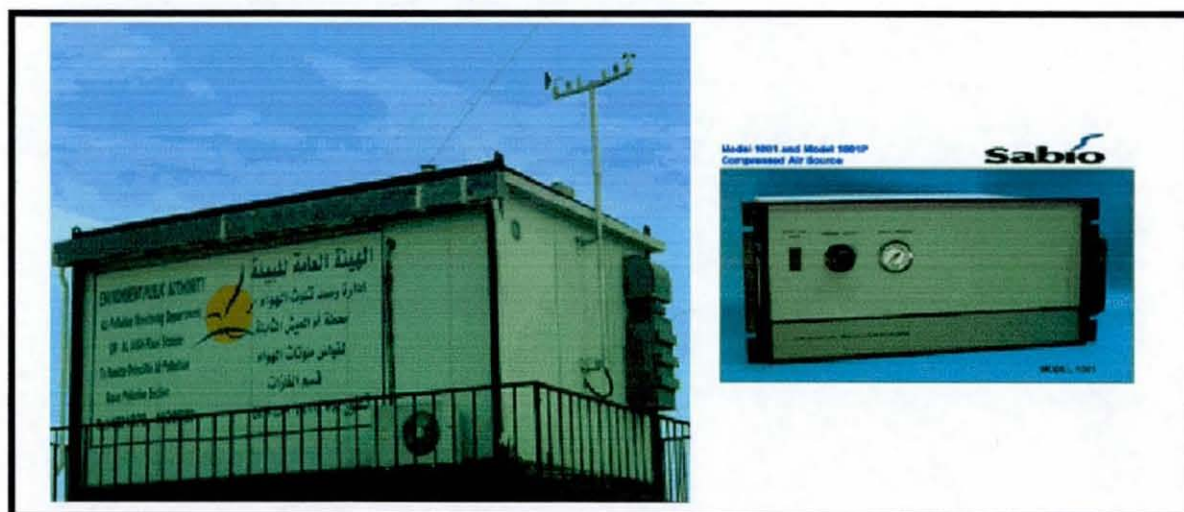
Figure 8.2b : Digital images of Umm Al-Aish Monitoring station with the automatic analyzer and meteorological sensors
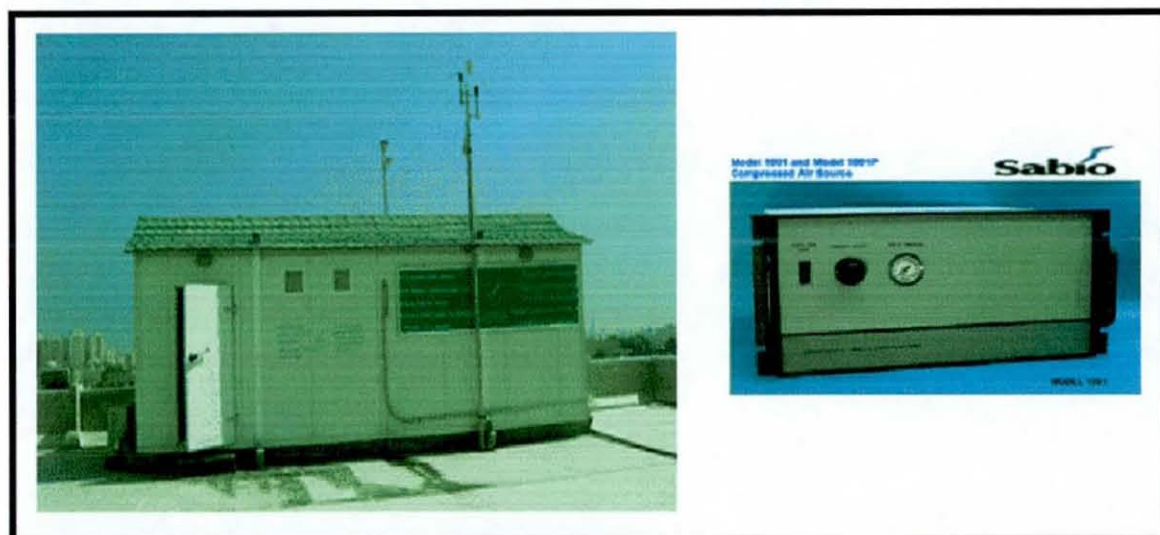
Figure 8.2c : Digital images of Fahaheel Monitoring station with the automatic analyzer and meteorological sensors
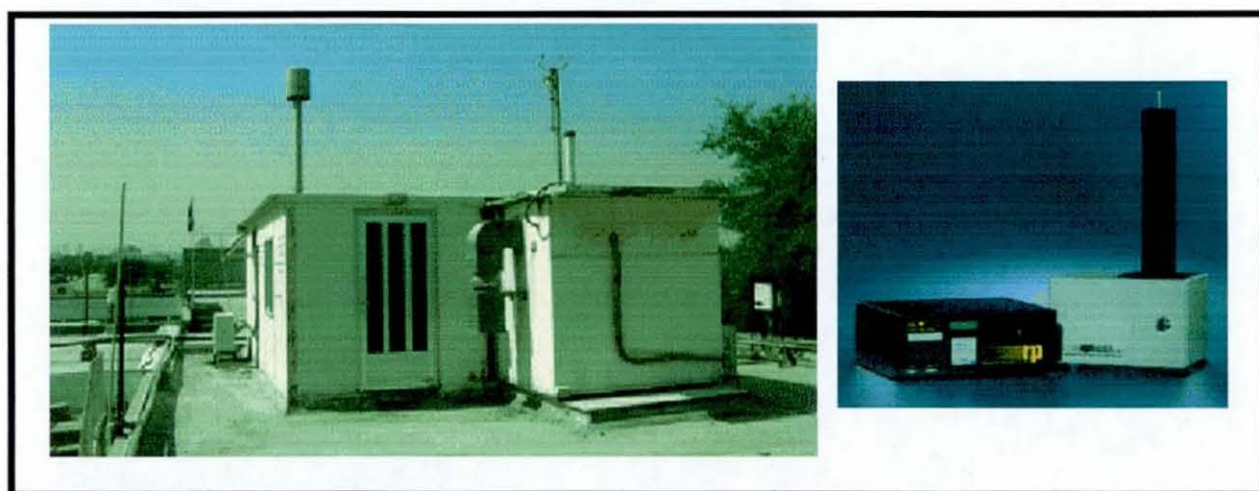
Figure 8.2d : Digital images of Riqqa Monitoring station with the automatic analyzer and meteorological sensors

8.4 State of Kuwait Environmental Standards

The executive regulations of the law of establishing the Kuwait EPA is quoted from three American authorities: Environment Public Authority (US-EPA), Occupational Safety and Health Organization (OSHA), and Association of Occupational Health Practioners (ACGIH). Also, the supplements of the maximum limits permitted in the executive regulation of law of establishing the K-EPA, (supplements no. 3, 4, 5, 6, 7, 8 and 9) in respect of occupational exposure to the chemical substances, noise, non-

ionized rays, temperature, light and oscillation, are a guideline placed by the ACGIH. This association is an occupational, not a governmental censoring authority. It placed its measurements in 1968 for preserving the health of laborers, and it's not correct that those guidelines criteria would be placed as environmental measurements and stipulations.

Industrial Areas				
Compound	Ambient Air Standard (ppb)			
	1 hr	8 hr	24 hr	1 year
Ozone (O3)	80	60		
Ammonia (NH3)	800			140
Sulfur Dioxide (SO2)	300		200	65
Hydrogen Sulfide (H2S)			130	
Nitrogen Dioxide (NO2)	100		50	
Nitric Oxide (NO)				
Carbon Monoxide (CO)	30,000	10,000	8000	
Carbon Dioxide (CO2)				
CH4				
n-CH4 Hydrocarbons			0.24	
Dust			350 (ug/m3)	90 (ug/m3)
Residential Areas				
Compound	Ambient Air Standard (ppb)			
	1 hr	8 hr	24 hr	1 year
Ozone (O3)	80	60		
Ammonia (NH3)	800			140
Sulfur Dioxide (SO2)	170		60	30
Hydrogen Sulfide (H2S)	140		30	6
Nitrogen Dioxide (NO2)	100		50	30
Nitric Oxide (NO)				
Carbon Monoxide (CO)	30,000	10,000	8000	
Carbon Dioxide (CO2)				
CH4				
n-CH4 Hydrocarbons			0.24	
Dust			350 (ug/m3)	90 (ug/m3)

Table 8.1: Ambient Air Quality Standards Reported by EPA Kuwait, 2001

Chapter 9
Dispersion Model Results

9.1   Introduction

The impacts of methane and non-methane hydrocarbons emissions emitted from flaring activities at oil production facilities at Kuwait Oilfields have been assessed through a screening study using, for instance, records of flaring operations taken at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources. In the present work the ISCST3 model is used to calculate the ground level concentrations of methane and non-methane hydrocarbons emitted due to flaring at Kuwait Oilfields. Moreover, an air quality screening study was performed to assess the impacts of SO_2 emissions emitted by flaring in WK Oilfields. The meteorological wind and temperature fields were generated with the ISCST3 model, a diagnostic meteorological model that used surface observations and upper air soundings from one year hourly record data for year 2006 obtained from the KIA weather station.

Model validation is based on the comparison of the 50 highest daily measured values and their respective predicted concentrations of methane and non-methane hydrocarbons from NK flaring activities at Al-Jahra monitoring station used by Kuwait EPA. It is noticed that the model predictions are in good agreement with the observed data with an error bond of ± 50 %.

Overall, the present chapter provides the description of study area, emission inventory of methane, non-methane hydrocarbons and SO_2 from Kuwait Oilfields flaring activities, meteorological conditions and modelling results of the ground level concentrations of methane and non-methane hydrocarbons from flaring over the State of Kuwait and SO_2 from WK Oilfields. Also, evaluating the ISCST3 model, by comparing the model

prediction with the observed concentration of methane and non-methane hydrocarbons obtained from the monitoring sites.

9.2 Emission Inventory

As discussed earlier in Chapter 5, a comprehensive emission details from Kuwait Oilfields has been established. It provides a complete account and estimates of all the emissions of primary pollutants emitted due to flaring activities in the Kuwait Oilfields. This comprehensive emission detail records the emissions of primary air pollutants: NO_X, SO_2, CO, CO_2, methane and other hydrocarbons done monthly. Emissions done from various sources in and around the oil fields are aggregated to obtain total pollutants load in the ambient air. These emissions of air pollutants include flaring done during various operations in the oilfields. In this study, data of SO_2, methane and other hydrocarbons emissions for year 2006 has been used as the necessary input for the ISCST3 model.

9.3 Mathematical Model

As discussed in Chapter 6, ISCST3 dispersion model has been used in this study. The ISCST3 algorithm is based on a Gaussian plume dispersion model and calculates short-term pollutant concentrations from multiple point sources at a specified receptor grid on a particular level or gently sloping terrain. The ISCST3 model includes a wide range of options for modelling impacts of pollution sources on air quality, which makes it a popular choice for the modelling in a variety of applications.

9.3.1 The main inputs data requires in the ISCST3 model

The ISCST3 model implementation requires three main inputs as discuss in Chapter 6 as follows:

I. Source Information

The model was set to simulate the pollutant ground level concentration resulting from all the flares at each GC in KOC areas. The amount and composition of each gas that goes to the flare are known as it collected from flaring activities from Kuwait Oilfields. Then

the amount of heat release, heat of combustion can be calculated depending on composition of hydrocarbon being released.

As shown in Figure 2.2 where crude enters the GC through the header then diverted to the HP separator where HP gas is separated, then the crude continues to the LP separator where LP gas is separated, and finally the crude is diverted to the tanks. Some vapors are released from crude oil in these Tanks. The tank vapors are then compressed by the compressor. Although not show in Figure 2.2, Oil is pumped to the Tank Farm, several tanks erected to store oil.

If the Gas (HP and LP) compressors inside the GC are not available TV is flared, and in case the BS is not available then some or all of the gas is flared including TV. And if the LPG is down which is the worst-case scenario, then all the gas is flared. This is due to the fact that the production of the gas cannot stop without stopping the oil production, since the gas is associated with the crude.

Two parallel flare systems are provided (High and Low Pressure) for each GC to afford safe disposal of excess gases. A spare flare is also provided for each system to ensure operational flexibility. The flares are located 'off-site' and remote from the GC, approximately 1500 meters away from the GC and 250-500 meters away from any oil well installation. The flares are located so that the prevailing wind direction helps in the dissipation of flare gases away from the GC.

Figure 9.1: Flare facilities, LP stack and HP flare (open pit)

In general, two to three types of flares are provided 'off-site' the GC. These are:

- The elevated flare.   (20 meter high)
- The ground flare.   (0 meter)
- The burn pit flare.   (0 meter)

Elevated Flares are used for disposing heavy light-end gases (heavier than air) and toxic gases, which have highly toxic combustion products.

Ground Flares are used for 'clean' gases and where noise pollution is a critical factor.

Burn Pit Flare is used for disposing hydrocarbon liquids as well as vapors. Its use is limited due to dense smoke emissions.

The oil production facilities (21 GC's) are recognized as the potential emitters and the major pollutant sources within the area under study. The flare stacks and open pits are considered as the main emission sources.

One open pit at each gathering center provide in the area under study. A total of 10,000 m^2 to 62,500 m^2 emission area (based on supplied information at each GC from KOC) with different emission rate was utilized.

The source parameters required for the ISCST3 model are pollutant emission rate (g/s), location coordinates (UTM), source height (m), exit inner diameter (m), exit gas speed (m/s), and exit gas temperature (°C). The required information on all the location coordinates, the respective emission rates and stacks characteristic (height, diameters), flue gas velocity and temperature at the discharge have been obtained from all flaring activities from all Kuwait Oilfields area. (See Appendix C)

A total of 18 stacks were used with total emission rate for methane and non-methane hydrocarbons equal to 1084 g/s and 16884 g/s contributed by WK Oilfields, A total of 28 stacks were used with total emission rate for methane non-methane hydrocarbons equal to 85.11 g/s and 847 g/s contributed by SEK Oilfields and A total of 12 stacks were used

with total emission rate for methane non-methane hydrocarbons equal to 2909.08 g/s and 218.32 g/s contributed by NK Oilfields were used as input sources in the model.

II. Receptor Information

The ISCST3 model have considerable flexibility in the specification of receptor locations, has the capability of specifying multiple receptor networks in a single run, and may also mix Cartesian grid receptor networks and polar grid receptor networks in the same run.

Two different kinds of Cartesian coordinate receptors were used as an input to the ISCST3 model, these are;

- The course mesh for WK Oilfields covers approximately 40 km by 40 km with 441 receptors superimposed with two finer meshes of 25 km by 26 km and 10 km by 10 km and SEK Oilfields covers approximately 40 km by 40 km with 441 receptors superimposed with two finer meshes of 17 km by 38 km and 5 km by 5km and NK Oilfields covers approximately 40 km by 40 km with 441 receptors superimposed with two finer meshes of 26 km by 18 km and 21 km by 14 km. The three meshes implemented to facilitate accurate using interpolation in evaluation of ground level concentrations results. The grid base elements are a square with side length of around 1 km x 1 km.

- Discrete Receptors points correspond to the location of the major population centers and the existing monitoring stations in the State of Kuwait. This means that concentrations in each point in the grid, which is 1km apart, are estimated in addition to the discrete point of the population centers and existing monitoring stations. The matrix of concentrations is plotted as a contour map for the selected meteorological data file.

These receptors are selected based on actual sites in UTM location coordinate of Kuwait map. Figures 9.2-9.4 describe the grids used in this study.   These Figures show the uniform grid receptors where the concentration is calculated using the ISCST3 model.
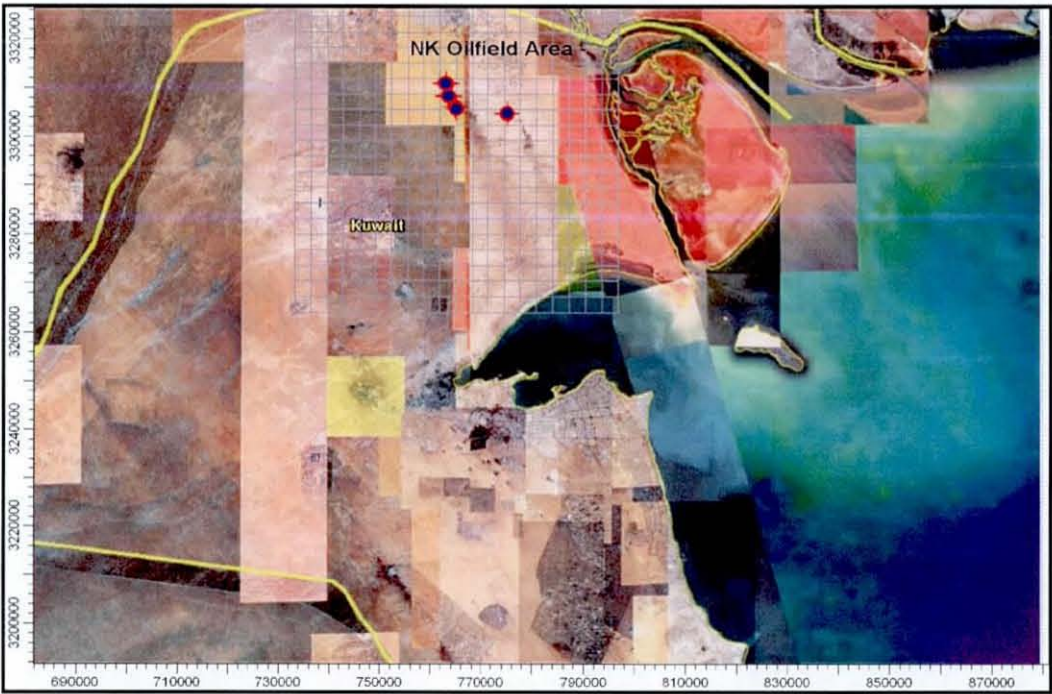
Figure 9.2: The first grid area (NK Oilfields Area) under study
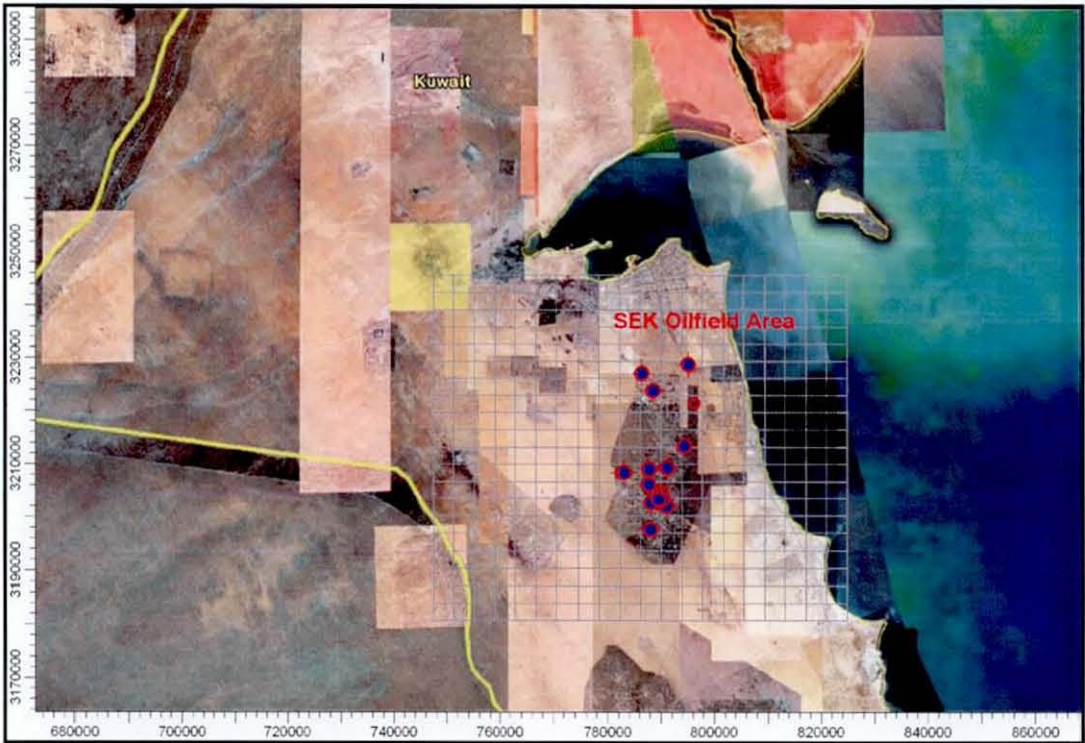
Figure 9.3: The second grid area (SEK Oilfields Area) under study
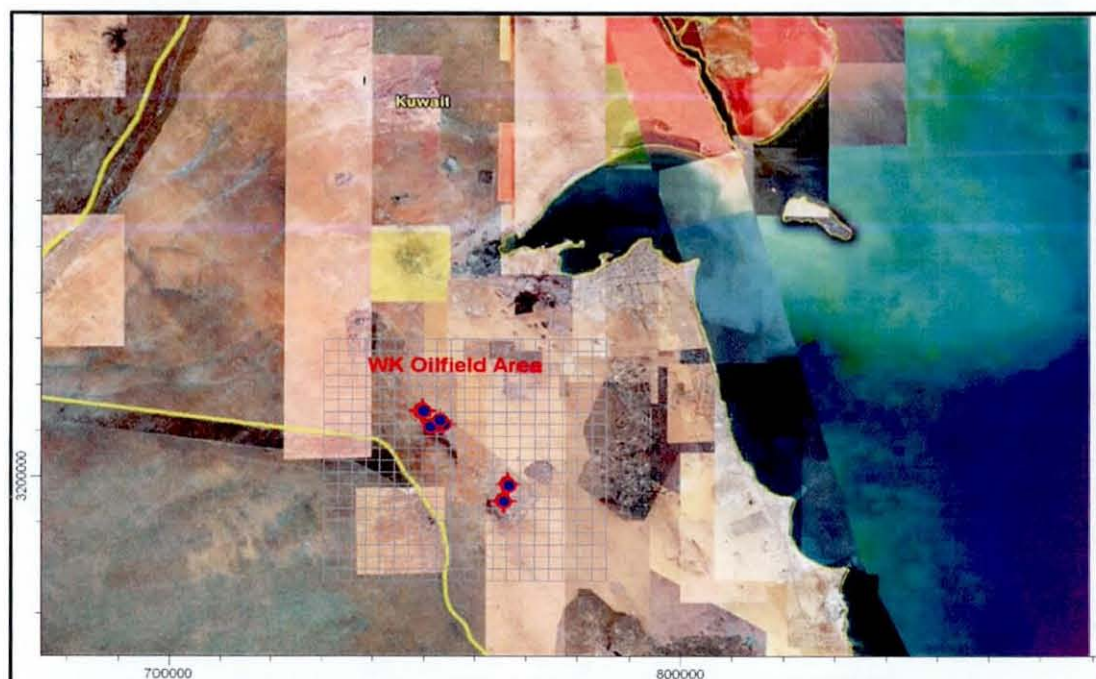
Figure 9.4: The third grid area (WK Oilfields Area) under study

Indeed, the uniform grid receptors are not needed for the model evaluation, neither for investigation of the efficiency of the monitoring sites, but it is a way to have a general view of the pollutants dispersion over the study area.

III. Meteorological Information

The meteorological data required for the ISCST3 model as discussed in chapter 7 are anemometer height (m) wind speed (m/s), wind direction (degree) clockwise from the north, air temperature, total and opaque cloud cover (%), stability class at the hour of measurement (dimensionless) and mixing height (m). The anemometer height about 10 m, wind speed, wind direction, air temperature and cloud cover have been obtained from direct measurements from KIA. One year hourly record of the surface and upper air meteorological data for year 2006 obtained from KIA weather station and is used in the present study for simulation of the dispersion of methane and non-methane hydrocarbons emitted from flaring in all Kuwait Oilfields areas (NK, SEK, WK) during the oil production and the dispersion SO_2 emitted from flaring in WK Oilfields. An example of the meteorological data inserted into the model is presented in Appendix B.

The hourly stability class mixing height is estimated using PCRAMMET that is a meteorological pre-processor for preparing National Weather Service (NWS) data for use in the ISCST3 US-EPA. The routine measurements of the surface and upper air meteorological data obtained from KIA for the year 2006 is used to run the PCRAMMET to generate an hourly ASCII input meteorological file containing the meteorological information parameters needed for the running of the ISCST3 model.

The stability class was defined on the basis of Pasquill categories, which are mainly a function of the hour of measurement, wind speed and sky cover (i.e., the amount of clouds). Based on temperature profile measurements, the mixing height was estimated by the model.

9.4   ISCST3 Model Output

The basic types of printed outputs available with the ISCST3 model are as follows
(See Appendix C):

- Concentration of various pollutants at a discrete receptor (Comparison between measured and model value).
- Full Cartesian grid contour map for each pollutant at each meteorological condition.
- Maximum concentration of pollutants along with locations and time of occurrence in the selected meteorological scenario.
- Effect of nearby terrain
- Average concentration calculated at a specified period of time (hourly, daily, monthly,....)
- Summaries of high values (highest, second highest, etc...) by receptor for each averaging period and source group combination.
- Summaries of overall maximum values (e.g. the maximum) for each averaging period and source group combination.
- Tables of concurrent values summarized by receptor for each averaging period and source group combination for each day of data processed.

9.5   Description of Study Area

The study area covers all of the Kuwait's oil producing zones which are located in three selections in the state of Kuwait (Figure 2.1).

Indeed the effect of topography is an important factor in identifying the location at which the pollutants can be occurred at the ground level from a source point. As discussed earlier in chapter 7, the total area of Kuwait around 1.8×10^4 km^2 is divided into three independent sectors to calculate the ground level concentrations of SO$_2$, methane and non-methane hydrocarbons. The modelling exercises are:

1. South East Kuwait (SEK) Area: Consisting of Greater Burgan area having 14 gathering centers and two BS's.

2. West Kuwait (WK) Area: Consisting of Minagish and Umm Gudair fields having 4 GCs and one BS.

3. North Kuwait (NK) Area: Consisting of Ratqa, Raudatin and Sabiriyah having 3 GCs and one BS.

9.6   Results and Discussion

ISCST3 model was used to simulate the ground level concentrations of SO$_2$, methane and non-methane hydrocarbons emitted from Kuwait Oilfields compute flaring activities in Kuwait Oilfields at all points covered by the receptors information. ISCST3 model was then executed by summing the steady state concentration contributions from each source at each receptor point in the study area. The calculations were done based on the model input parameters as described in the previous sections. The simulated results of the emission scenarios using the ISCST3 are on an hourly mean predicted ground level concentrations of methane, non-methane hydrocarbons and SO$_2$.

The hourly, daily and annual average maximum ground level concentrations of methane, non-methane hydrocarbons and SO$_2$ were predicted and output results were compared

with KAAQS at all of the grid point receptors under the study area (443 receptors). Allowable levels of pollutants specified by KAAQS are shown in Table 8.1.

9.6.1   Effect of Meteorological Conditions

In general, clear sky, high temperature and airborne dust is the feature of the summer season whereas mid to relatively cold with light rain is feature of the winter season. These two contrasting weather conditions would have opposite effects on the dispersion of the pollutants and the concentrations levels through the processes of transport and reaction in the atmosphere.   In winter season, the presence of the cloud cover results in the reduction of the solar energy, ambient temperature and wind speed, these conditions decrease the photochemical reactions for the formation of ozone and increase the incidence of the surface based inversion that results in lower mixing height. Thus, these meteorological conditions during winter season would tend to increase the concentrations of the primary pollutants.

The modelling results for the first five highest hourly ground level concentrations of methane at NK Oilfields area are resulted in winter. The top high hourly ground level concentration of methane is 7.95 ppm at 19:00 Hr on 16[th]Janurary 2006. The second high hourly ground level concentration of methane is 7.13 ppm at 23:00 Hr on 27th December 2006. Third high hourly ground level concentration of methane is 6.81 ppm at 19:00 Hr on 4th January 2006. The fourth high hourly ground level concentrations of methane is 6.79 ppm at 22:00 Hr on 16th December 2006 and the fifth high hourly ground level concentrations of methane is 5.78 ppm at 09:00 Hr on 10th January 2006.   From the above results, it is clear that all the five highest ground level concentrations of methane occur in winter where inversion layer, temperature and wind speed are low adversely effects the dispersion.

9.6.2 Model Performance and Validation

The performance of the model is evaluated based on the comparison of 50 highest daily measured and predicted concentrations of methane hydrocarbons from NK flaring activities at each monitoring station. It is clear that the model predictions are in good agreement with the observed data with scathe ± 50 at Al-Jahra monitoring stations used by Kuwait EPA (Figure 9.5).
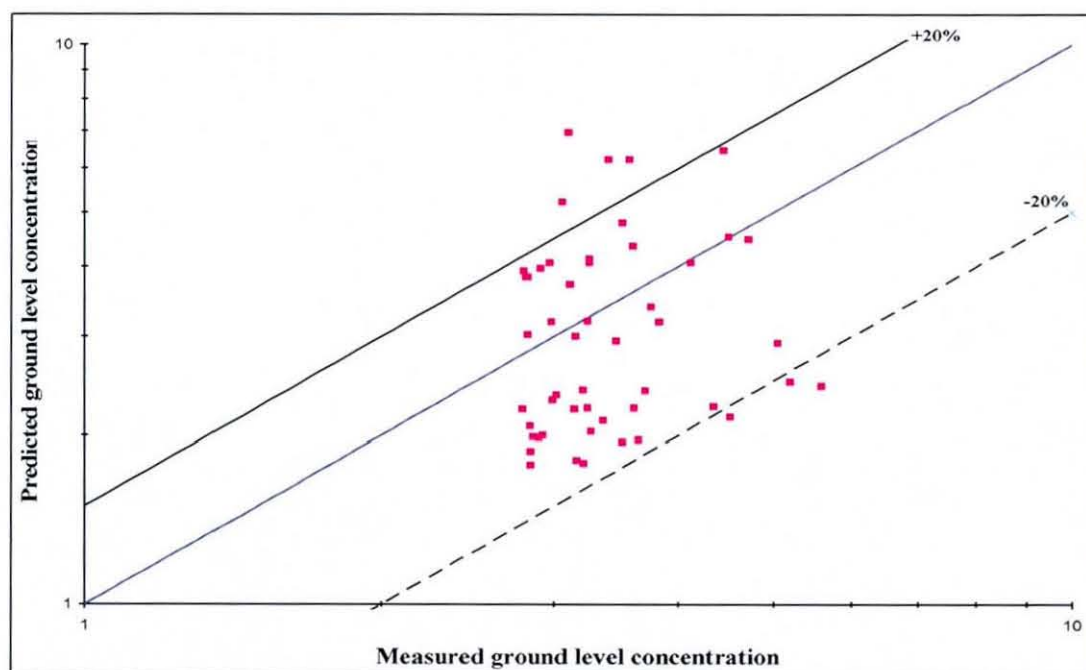
Figure 9.5: Comparison of the 50 highest daily measured recorded and predicted ground level concentrations of methane in NK Oilfields.

9.6.3 North Kuwait Oilfield Area Results

I. Non-methane hydrocarbon Concentrations

Figures 9.6a-9.6c show the modelling results as the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of non-methane hydrocarbons. The calculated values from the uniform grid receptors are discussed in

proceeding section and GC-15 (Source coordinate of X= 7.6×10^5, Y= 3.3×10^6) is considered as a reference point to interpret the location of not pots. Isopleths plots (contours) were generated, as shown in Figures 9.7a-9.7c. The predicted values are in terms of $\mu g/m^3$ and converted to ppm and ppb by using an average Molecular weight (46.9 g/gmole) for non-methane hydrocarbons.
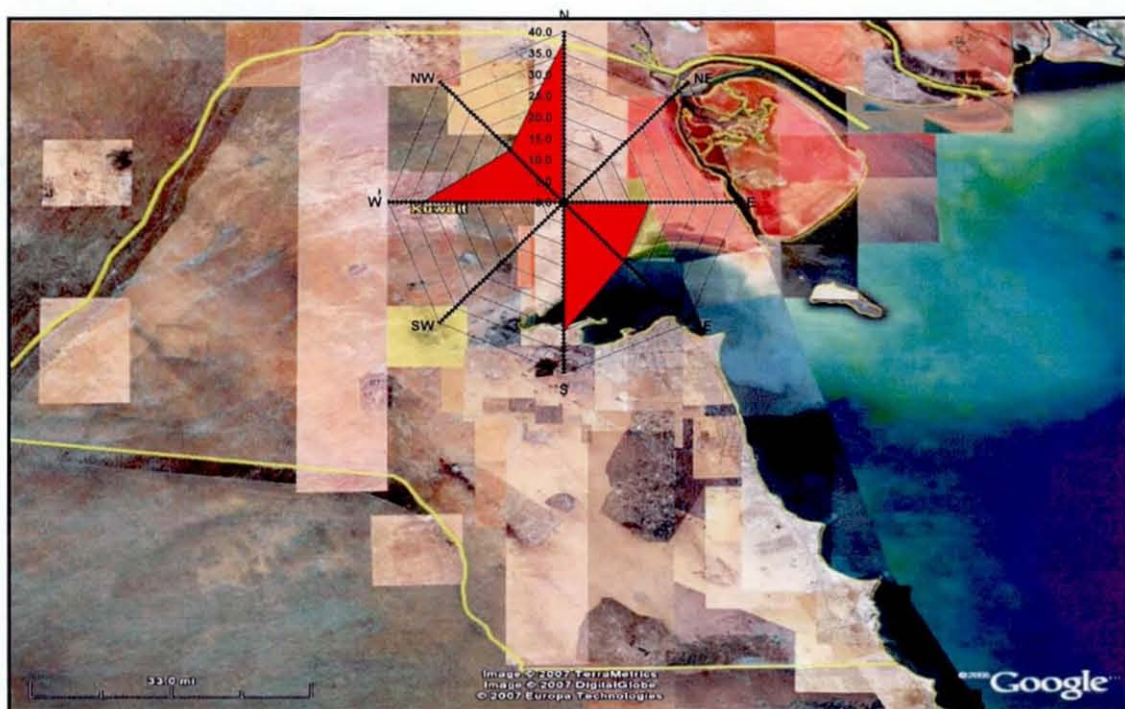
Figure 9.6a: ISCST3 output data modelling results for the 50 highest hourly average concentrations of non-methane hydrocarbons

Figure 9.6b: ISCST3 output data modelling results for the 50 highest daily average concentrations of non-methane hydrocarbons
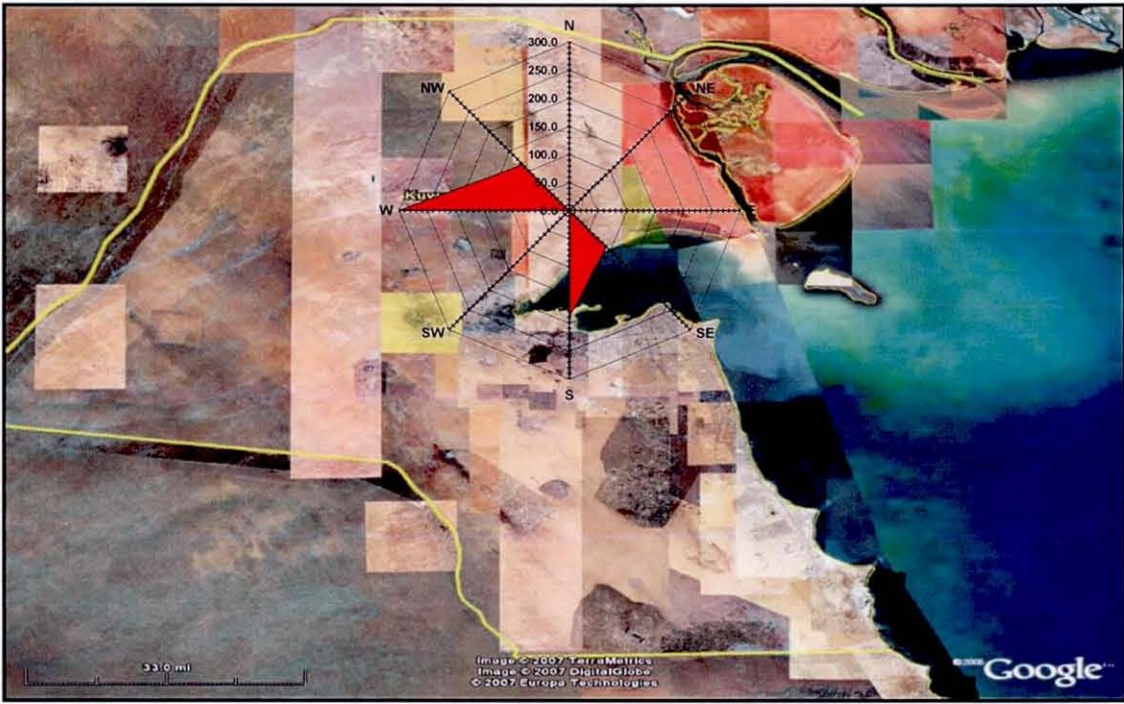
Figure 9.6c: ISCST3 output data modelling results for the 10th highest annual average concentrations of non-methane hydrocarbons
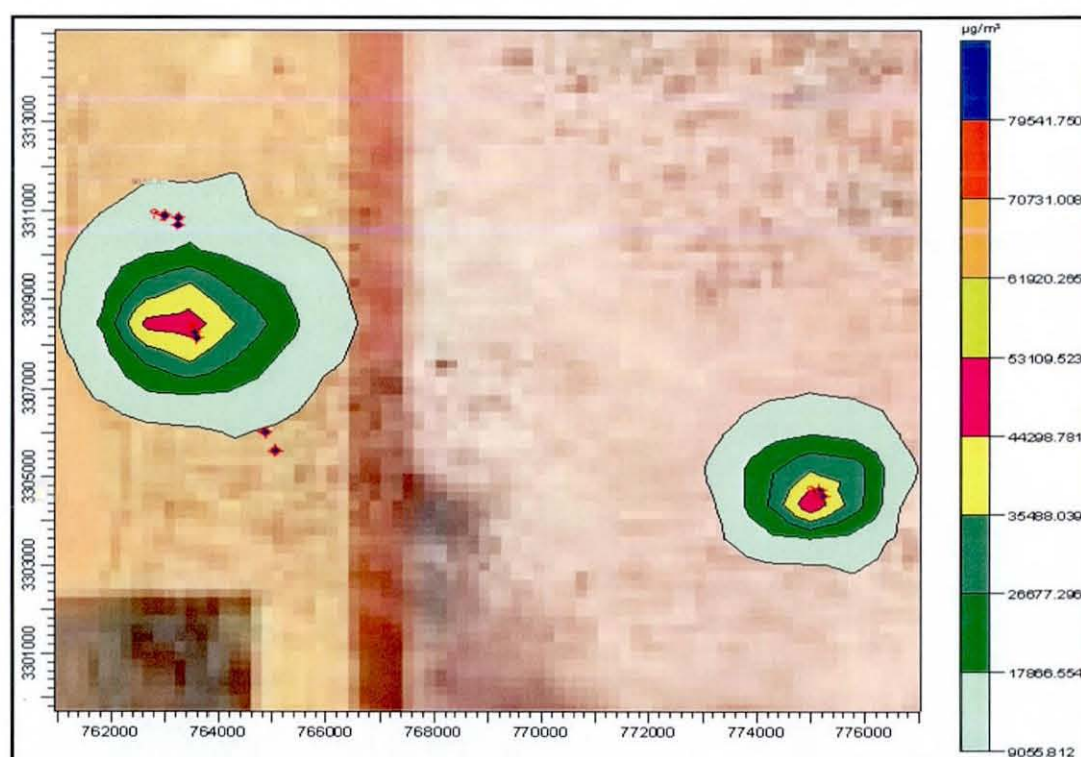
Figure 9.7a: Isopleths plot for the maximum hourly average ground level concentrations of non-methane hydrocarbons in μg/m³
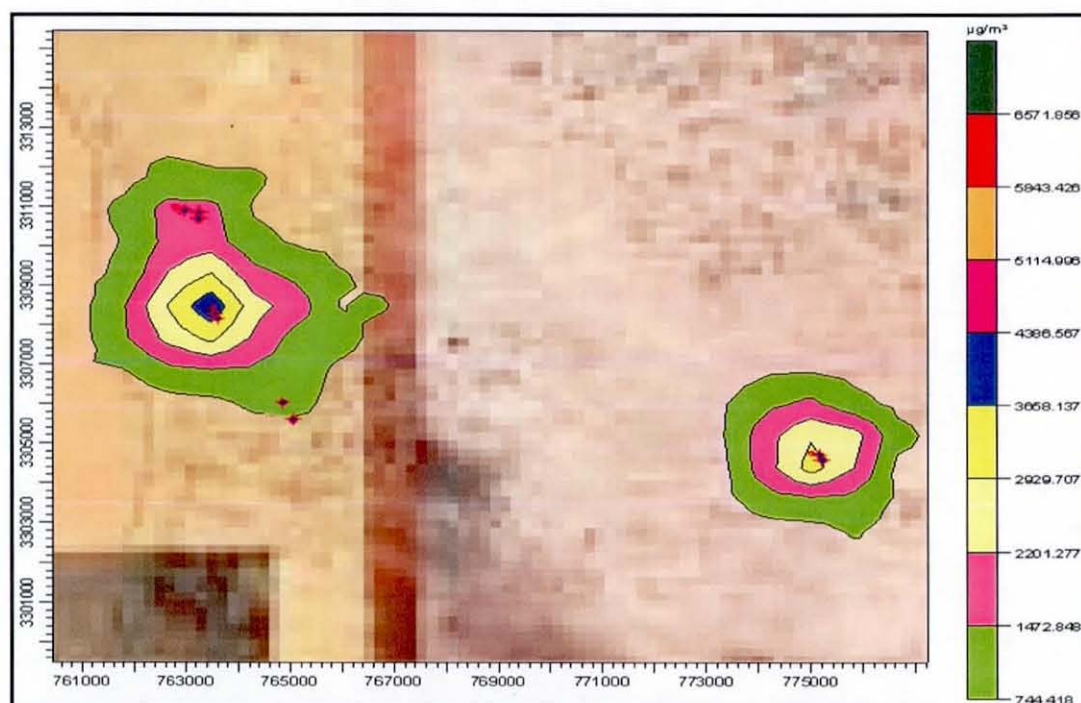
Figure 9.7b: Isopleths plot for the maximum daily average ground level concentrations of non-methane hydrocarbons in μg/m³
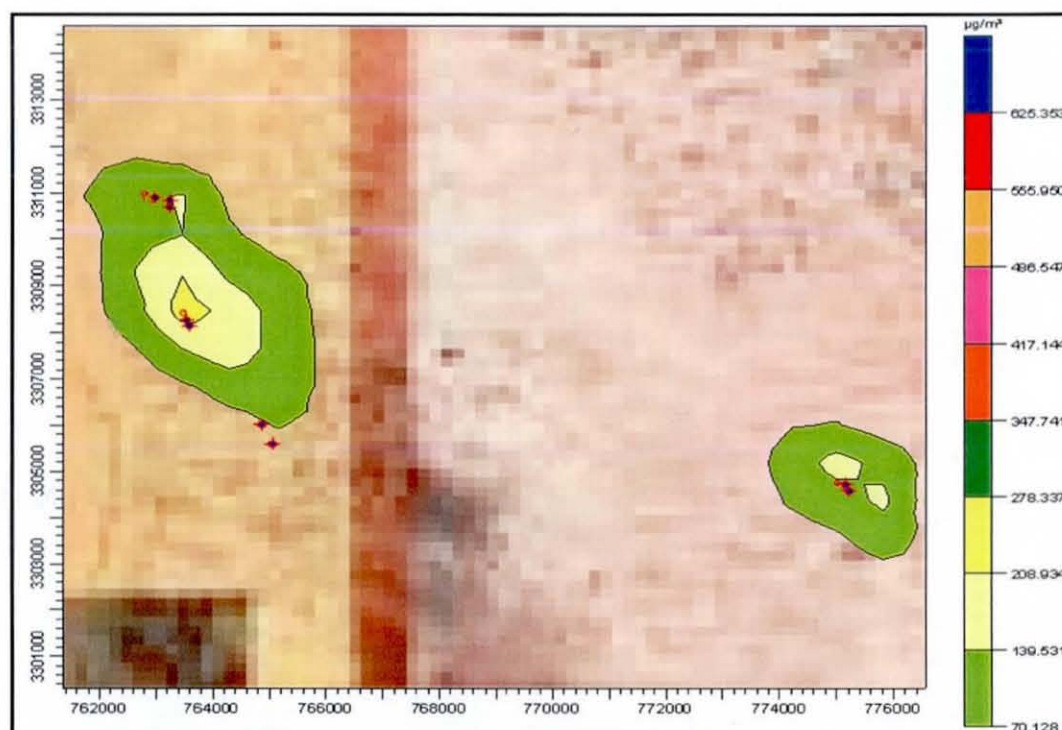
Figure 9.7c: Isopleths plot for the maximum annual average ground level concentrations of non-methane hydrocarbons in $\mu g/m^3$

The predicted maximum hourly average ground level concentration of non-methane hydrocarbons in the study area is 38 ppm on 16th January 2006 at 19:00 Hr at the receptor located nearly 11 km 104° bearing N from GC-15 as shown in Figure 9.6a and Figure 9.7a.

The predicted maximum daily average ground level concentration of non-methane hydrocarbons in the study area are shown in Figure 9.6b and Figure 9.7b is 3.14 ppm on 4th January 2006 at the receptor located nearly 11.8 km 105 ° bearing N from GC-15. This value is 11 times less than the maximum hourly average ground level concentration value. For the same location, Figure 9.6c and Figure 9.7c show that the highest annual maximum concentration of non-methane hydrocarbons is equal to 298.7 ppb, which is 11 times less than the maximum daily average ground level concentration value.

Kuwait-EPA has specified the concentration of non-methane hydrocarbons for early morning 3 Hours 6:00 -9:00 AM not exceeding 0.24 ppm. The computed 3 hours

average data reveal that the predicted ground level concentration of non-methane hydrocarbons for the specified time 6:00 -9:00 AM has exceeded 190 times of the KAAQS ambient air quality standard.

II. Methane Concentrations

Figures 9.8a-9.8c show the modelling results for the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of methane. The calculated values from the uniform grid receptors are described in proceeding section and GC-15 (Source coordinate of X= 7.6×10^5, Y= 3.3×10^6) is considered as a reference point to interpret the location of high concentration. Figures 9.9a-9.9c depicts the concentration variations in different zones. These present the maximum hourly, daily and annual ground level concentration of methane in ppm calculated at the specified uniform grid receptors. The background concentration of methane in the ambient air prior to computation input data were considered negligible (Zero).
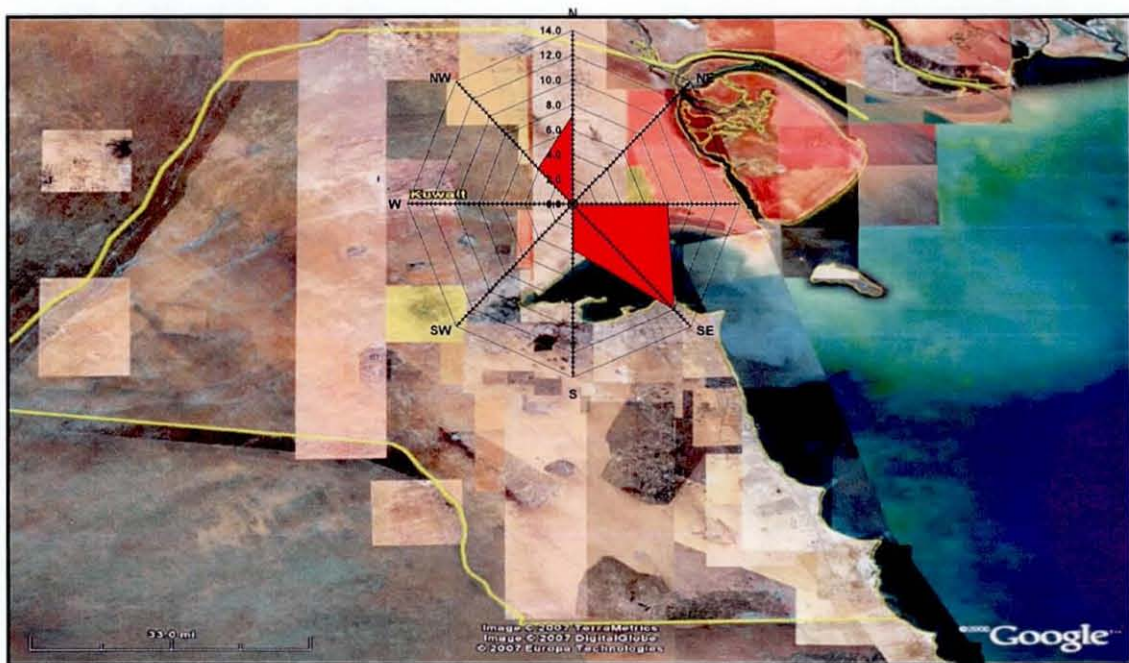
Figure 9.8a: ISCST3 output data modelling results for the 50 highest hourly average concentrations of methane

Figure 9.8b: ISCST3 output data modelling results for the 50 highest daily average concentrations of methane.
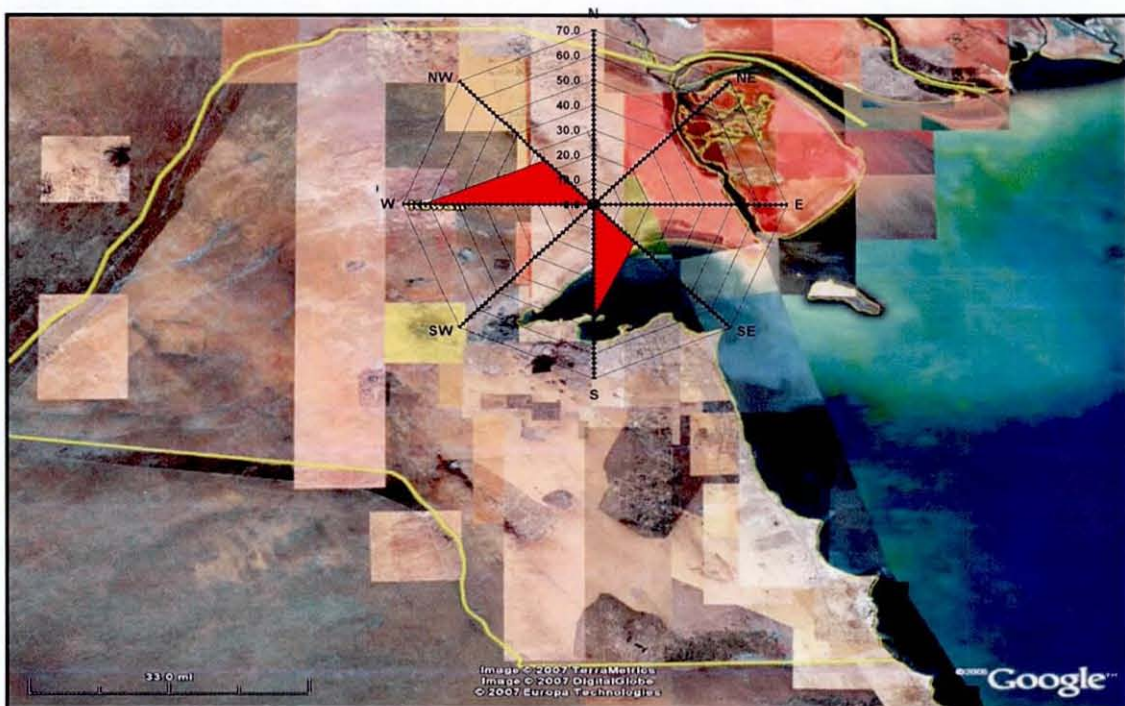
Figure 9.8c: ISCST3 output data modelling results for the 10th highest annual average concentrations of methane
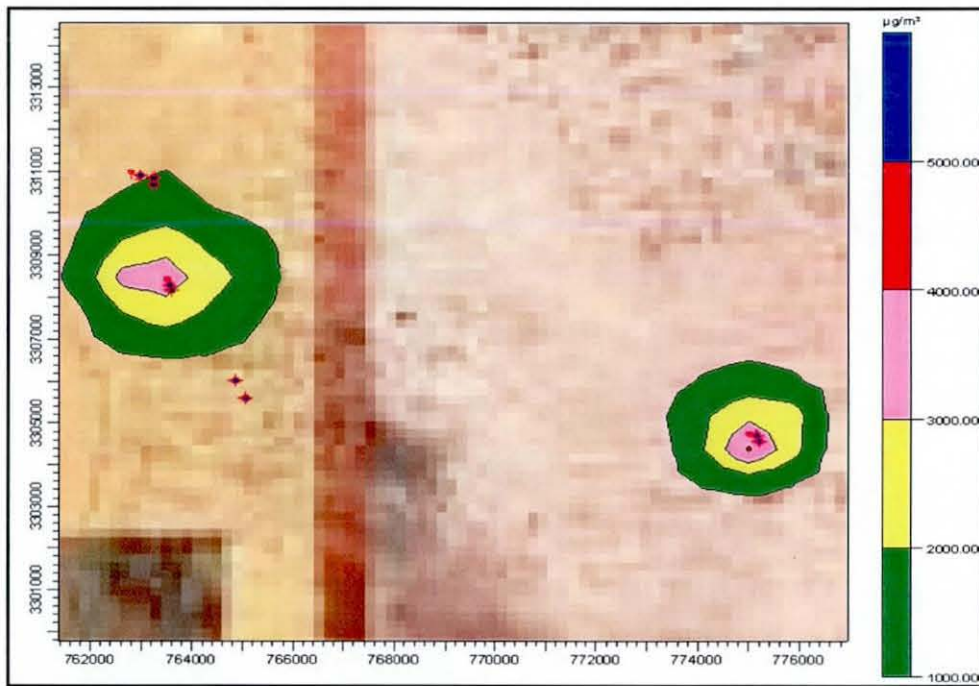
Figure 9.9a: Isopleths plot for the maximum hourly average ground level concentrations of methane in μg/m³
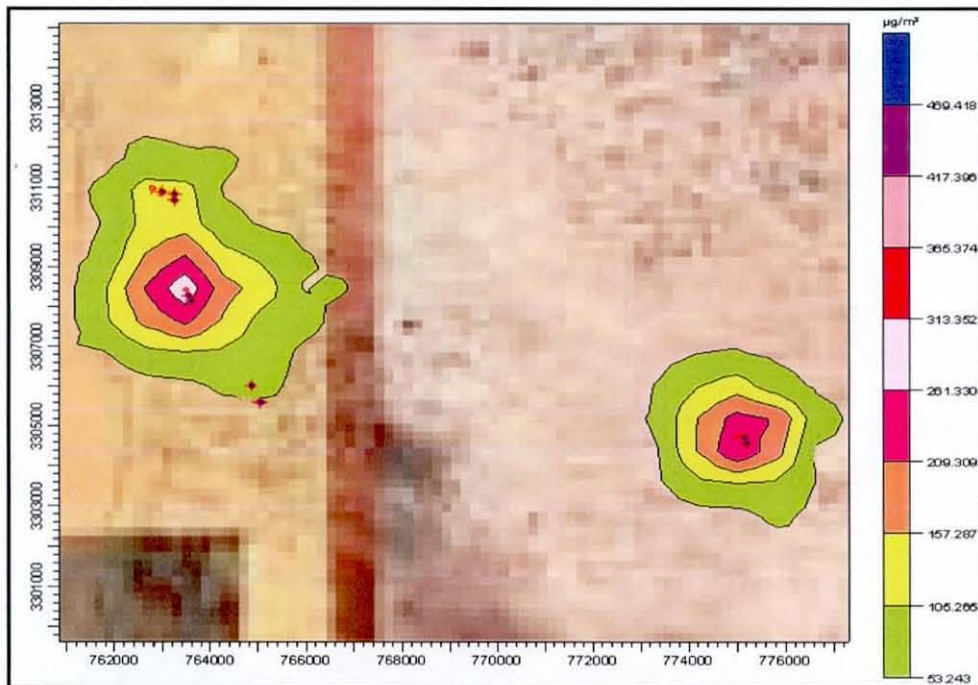
Figure 9.9b: Isopleths plot for the maximum daily average ground level concentrations of methane in μg/m³
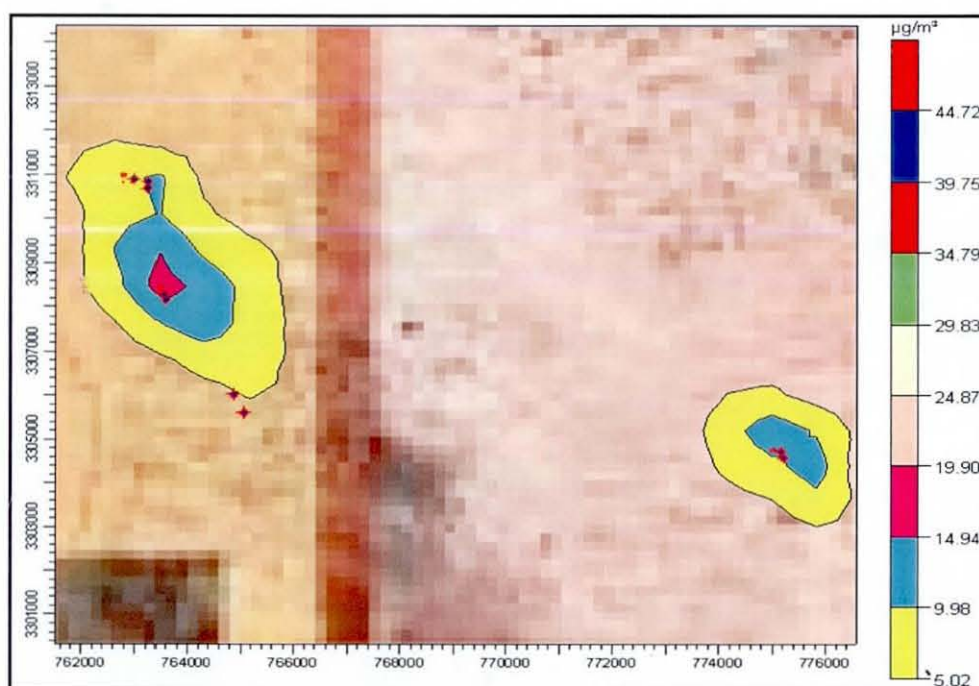
Figure 9.9c: Isopleths plot for the maximum annual average ground level concentrations of methane in μg/m^3

The results presented in Figures 9.8a-9.8c and Figures 9.9a-9.9c show the predicted ground level concentrations of methane. As shown in Figures 9.8a the predicted maximum hourly average ground level concentration of methane in the study areas is 7.95 ppm at 19:00 Hr on 16th January 2006 at the receptor located nearly 11 km bearing 104° N from GC-15, confirming the strong influence of prevailing north west wind in cold January hours evening. Most of the highest values predicted were in winter and early morning hours.

The predicted maximum daily average ground level concentration of methane in the study areas (Figures 9.8b) is 0.66 ppm on 4th January 2006. This value is 12 times less than the maximum hourly average ground level concentration value. Inspection of figure 9b, this receptor is located nearly 11.8 km 105° bearing N from GC-15. It is not surprising that the highest annual maximum concentration of methane also at the same spot as the maximum hourly and daily. The highest annual maximum concentration of

methane is 62.6 ppb which is 11 times less than the maximum daily average ground level concentration value.

The results reflect the increase in flaring in January year 2006, due to regular shut down of Condensate Recovery Unit (CRU's) in NK Oilfields and the strong influence of NW prevailing wind direction in Northern field Kuwait. It is concluded that the weather pattern in Kuwait in January 2006, especially the mean prevailing wind direction, significantly contributed to high concentrations of methane and non-methane hydrocarbons at ground level in residential areas located nearly 11 km 104° bearing N from GC-15 from the reference location.

9.6.4   South and East Kuwait Oilfield Area Results

I. Non-methane hydrocarbons Concentrations

Figures 9.10a-9.10c show the modelling results as the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of non-methane hydrocarbons. The calculated values from the uniform grid receptors are discussed in the proceeding section and GC-2 (Source coordinate of X= 7.8×10^5, Y= 3.2×10^6) is considered as a reference point to interpret all the location of high concentration. Isopleths plots (contours) were generated, as shown in Figures9.11a-9.11c. The predicted values are in terms of $\mu g/m^3$ and converted to ppm and ppb by using an average Molecular weight (46.9 g/gmole) for non-methane hydrocarbons.

Figure 9.10a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of non-methane hydrocarbons

Figure 9.10b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of non-methane hydrocarbons

Figure 9.10c: ISCST3 output data modelling results for the maximum predicted annual average concentrations of non-methane hydrocarbons
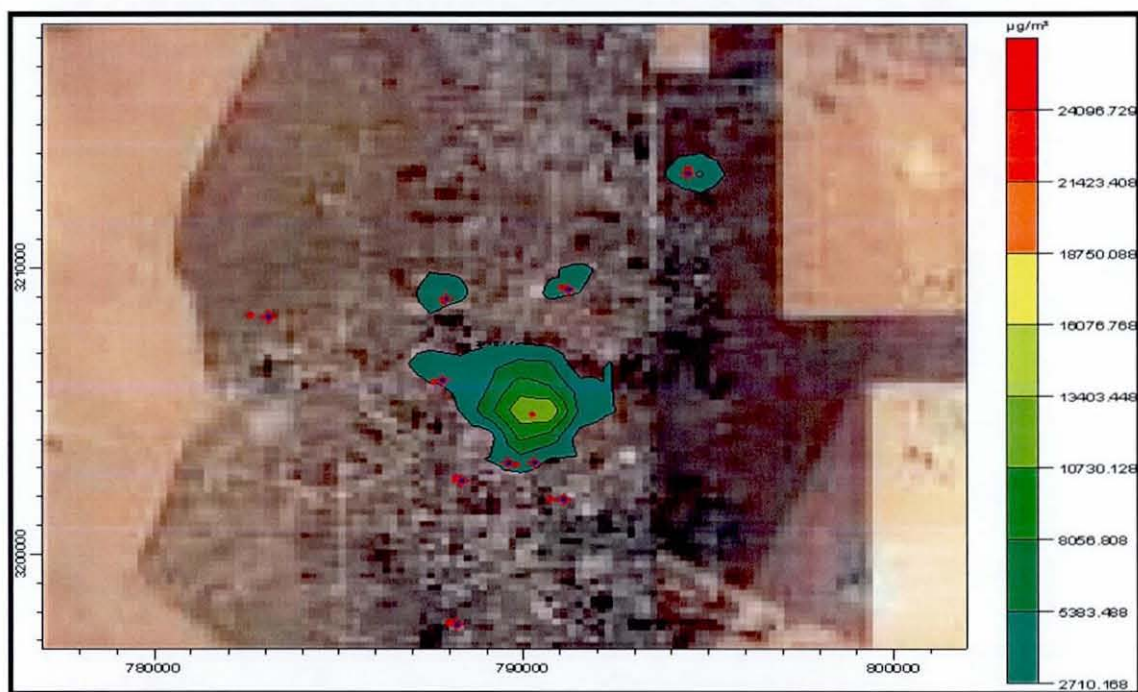
Figure 9.11a: Isopleths plot for the maximum hourly average ground level concentrations of non-methane hydrocarbons in $\mu g/m^3$
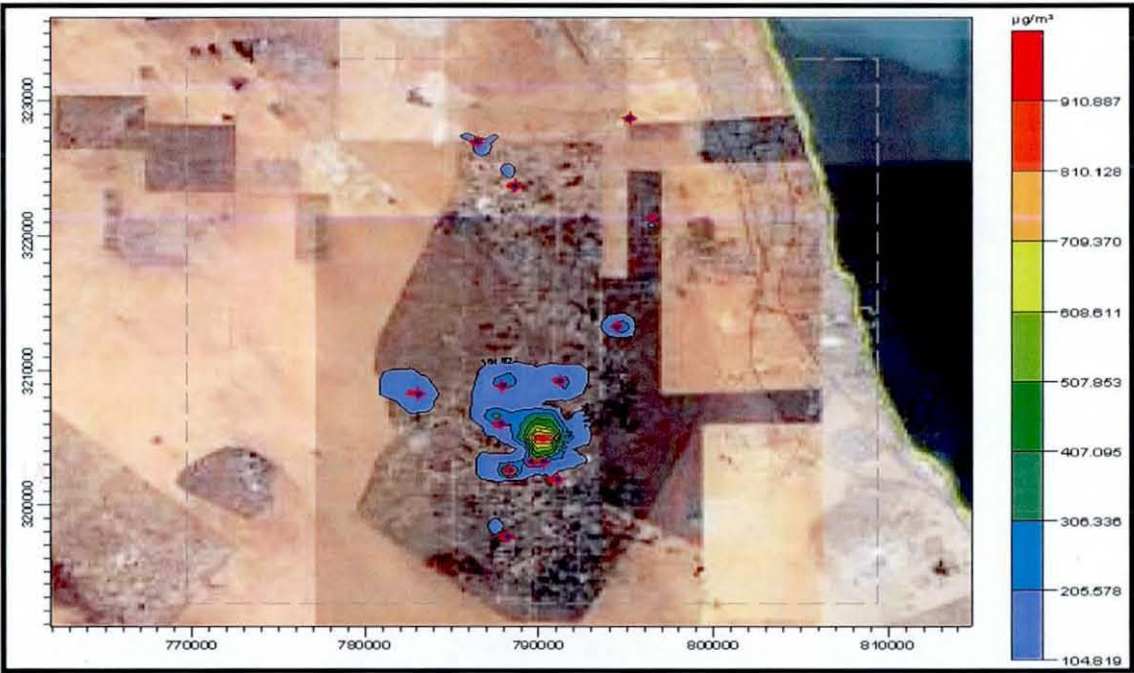
Figure 9.11b: Isopleths plot for the maximum daily average ground level concentrations of non-methane hydrocarbons in µg/m³
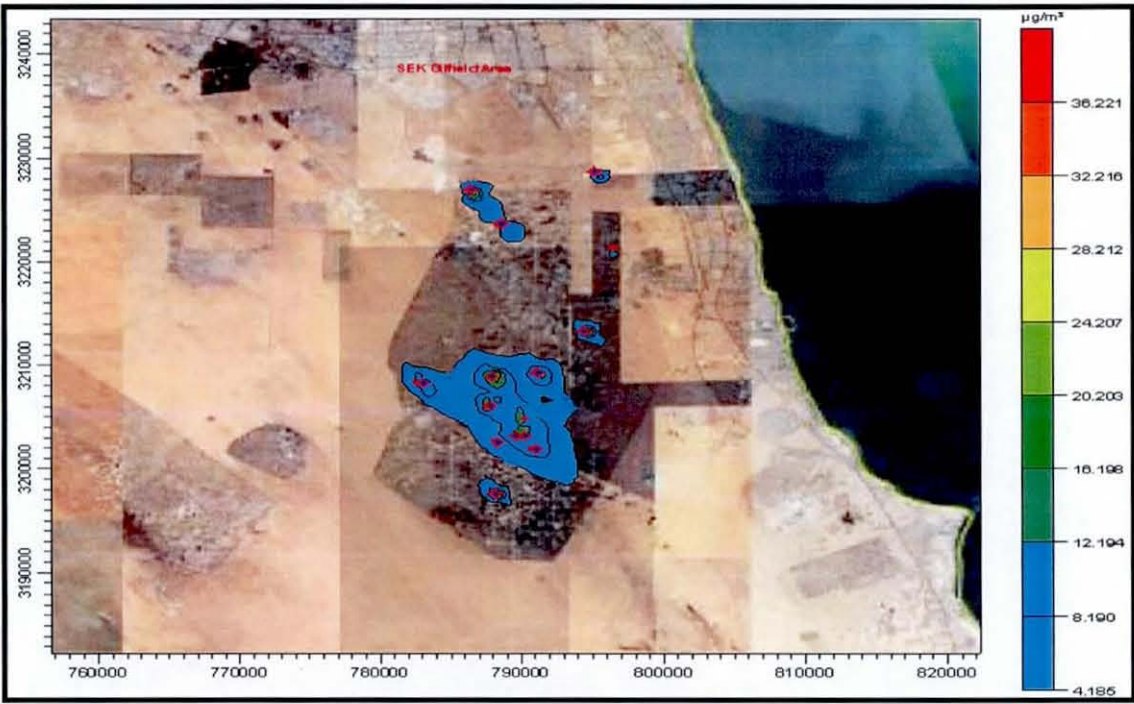
Figure 9.11c: Isopleths plot for the maximum annual average ground level concentrations of non-methane hydrocarbons in µg/m³

The predicted maximum hourly average ground level concentration of non-methane hydrocarbons in the study area is 11.5 ppm on 14th May 2006 at 04:00 Hr at the receptor located nearly 8.3 km 114° bearing N from GC-2 as shown in Figure 9.10a and Figure 9.11a.

The predicted maximum daily average ground level concentration of non-methane hydrocarbons in the study area are shown in Figure 9.10b and Figure 9.11b is 1.06 ppm on 27th May 2006 at the receptor located nearly 8.1 km 116 ° bearing N from GC-2. This value is 11 times less than the maximum hourly average ground level concentration value. For the same location, Figure 9.10c and Figure 9.11c show that the highest annual maximum concentration of non-methane hydrocarbons is equal to 60.4 ppb, which is 17 times less than the maximum daily average ground level concentration value.

Kuwait-EPA has specified the concentration of non-methane hydrocarbons for early morning 3 Hours 6:00 -9:00 AM not exceeding 0.24 ppm. The computed 3 hours average data reveal that the predicted ground level concentration of non-methane hydrocarbons for the specified time 6:00 -9:00 AM has exceeded 120 times almost 48% of the total study period of the KAAQS ambient air quality standard.
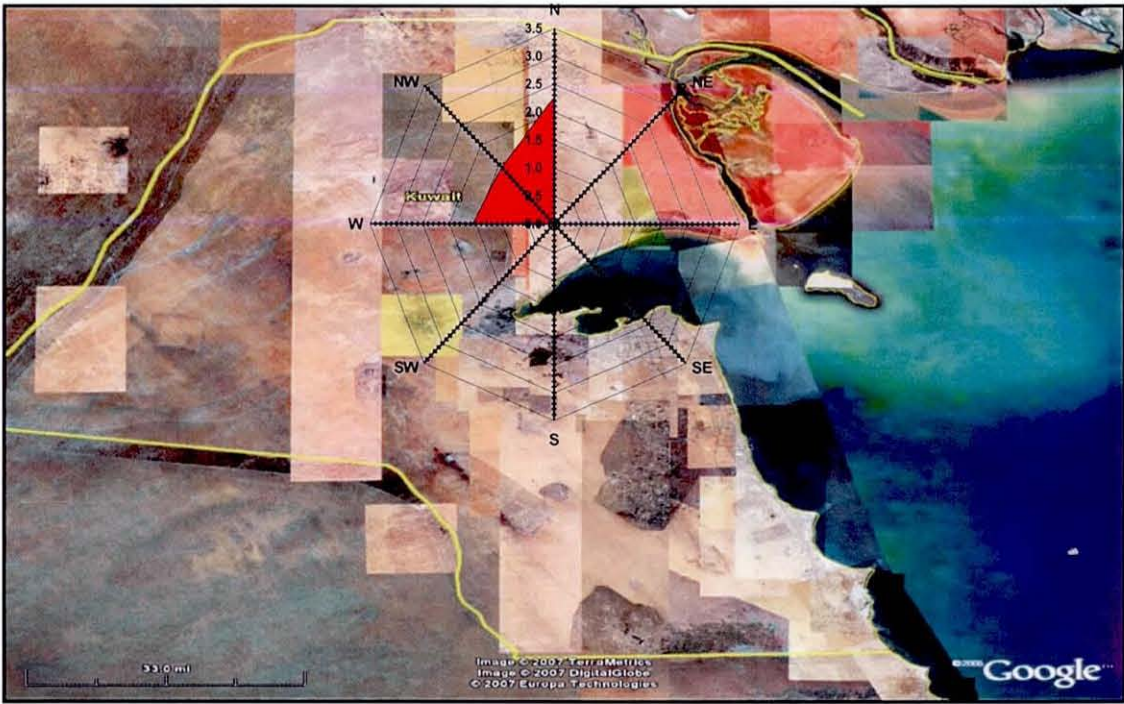
II. Methane Concentrations

Figures 9.12a-9.12c show the modelling results for the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of methane resulting from 12 stacks with total emission rate equal to 218.32 g/s. The calculated values from the uniform grid receptors are discussed in the proceeding section and GC-2 (Source coordinate of $X= 7.8 \times 10^5$, $Y= 3.2 \times 10^6$) is considered as a reference point to interpret the location of high concentration. Figures 9.13a-9.13c depicts the concentration variations in different zones. These present the maximum hourly, daily and annual ground level concentration of methane in ppm and ppb calculated at the specified uniform grid receptors are tabulated.

Figure 9.12a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of methane with respect to GC-2 Source

Figure 9.12b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of methane with respect to GC-2 Source

Figure 9.12c: : ISCST3 output data modelling results for the maximum predicted annual average concentrations of methane with respect to GC-2 Source

Figure 9.13a: Isopleths plot for the maximum hourly average ground level concentrations of methane in μg/m³

Figure 9.12a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of methane with respect to GC-2 Source

Figure 9.12b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of methane with respect to GC-2 Source

Figure 9.12c: : ISCST3 output data modelling results for the maximum predicted annual average concentrations of methane with respect to GC-2 Source

Figure 9.13a: Isopleths plot for the maximum hourly average ground level concentrations of methane in μg/m³

Figure 9.13b: Isopleths plot for the maximum daily average ground level concentrations of methane in μg/m³

Figure 9.13c: Isopleths plot for the maximum annual average ground level concentrations of methane in μg/m³

The results presented in Figures 9.12a-9.12c and Figures 9.13a-9.13c show the predicted ground level concentrations of methane. The predicted maximum hourly average ground level concentration of methane in the study areas is 2.53 ppm at 04:00 Hr on 14th May 2006 at the receptor located nearly 8.3 km 114° bearing N from GC-2 .

The predicted maximum daily average ground level concentration of methane in the study areas (Figure 9.12b) is 0.233 ppm on 27th May 2006. This value is 11 times less than the maximum hourly average ground level concentration value at location nearly 8.1 km 116° N bearing N from GC-2. It is not surprising that the highest annual maximum concentration of methane also at the same spot as the maximum hourly and daily. The highest annual maximum concentration of methane is 17.8 ppb which is 13 times less than the maximum daily average ground level concentration value.

The above results reflect the increase in flaring in May 2006, due to regular shut down of Condensate Recovery Unit (CRU's) in SEK Oilfields and the prevailing wind direction in Kuwait. Considering Figures 9.10a-9.10c and Figures 9.11a-9.11c and Figures 9.12a-9.12c and Figures 9.13a-9.13c together, it can be concluded the weather pattern in Kuwait in May 2006, especially the mean prevailing wind direction, significantly contributed to high concentrations of methane and non-methane hydrocarbons at ground level in residential areas located nearly 8.3 km 114° bearing N from GC-2 .

9.6.5   West Kuwait Oilfield Area Results

I. Non-methane hydrocarbons Concentrations

Figures 9.14a-9.14c show the modelling results as the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of non-methane hydrocarbons. The calculated values from the uniform grid receptors are described in proceeding section and GC-28 (Source coordinate of X= 7.5×10^5, Y=3.2×10^6) is considered as a reference point to interpret the location of high concentration. Isopleths plots (contours) were generated, as shown in Figures 9.15a-9.15c. The predicted values

are in terms of $\mu g/m^3$ and converted to ppm and ppb by using an average Molecular weight (46.9 g/gmole) for non-methane hydrocarbons.
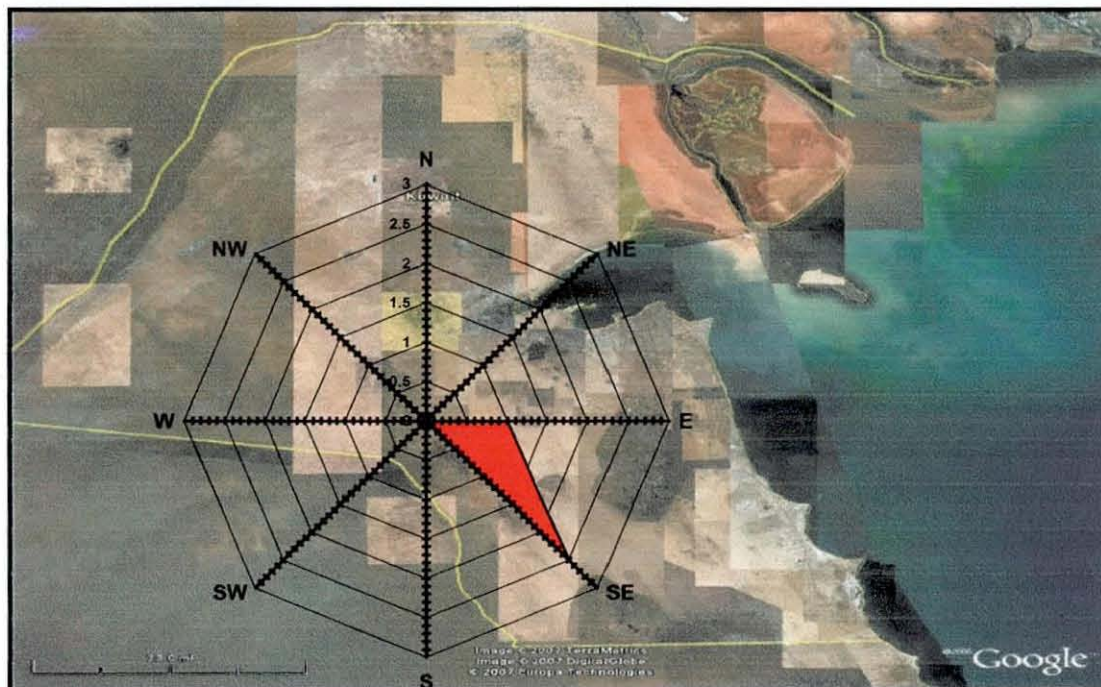
Figure 9.14a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of methane with respect to GC-28 Source
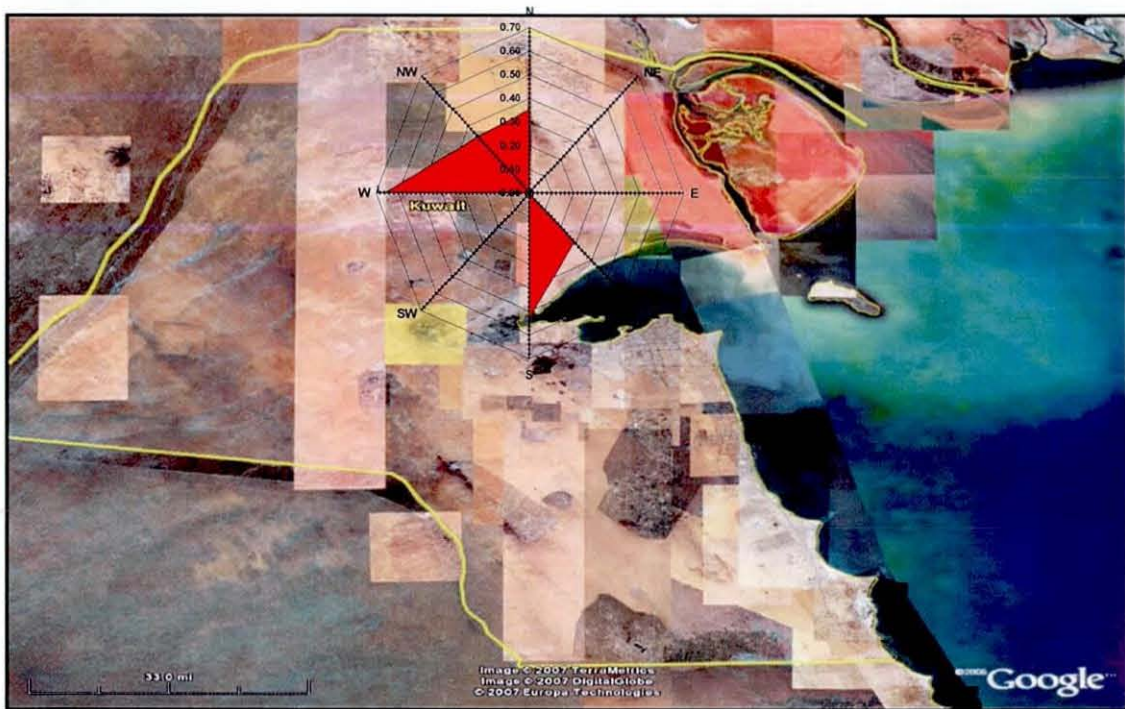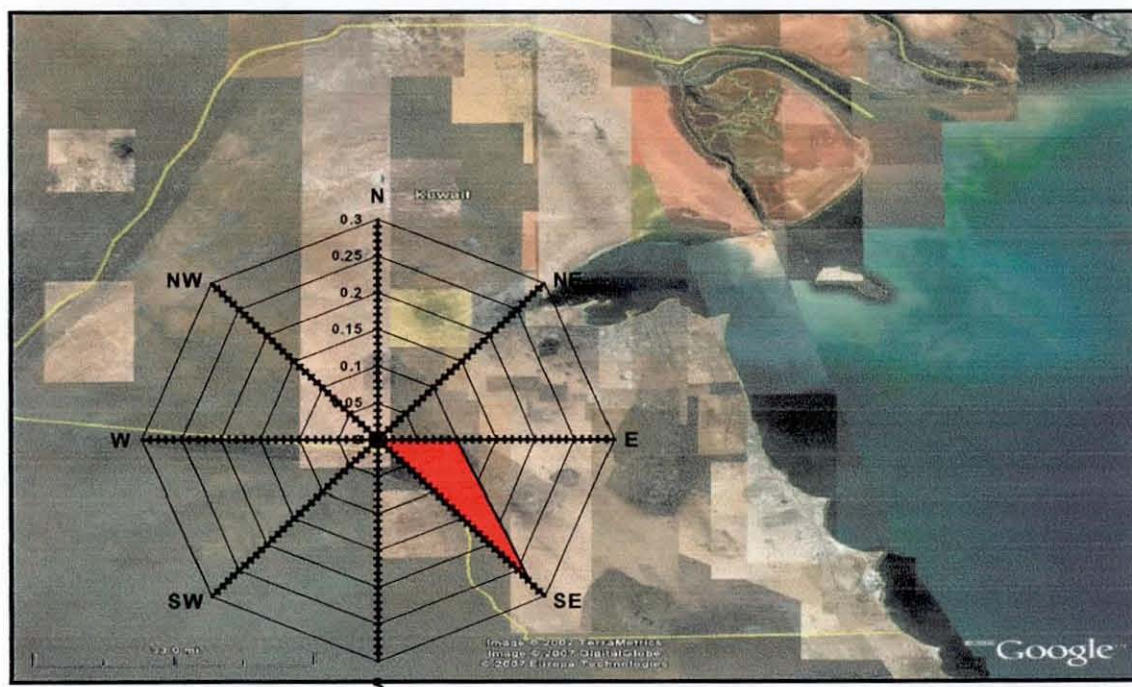

**Figure 9.14b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of methane with respect to GC-28 Source**
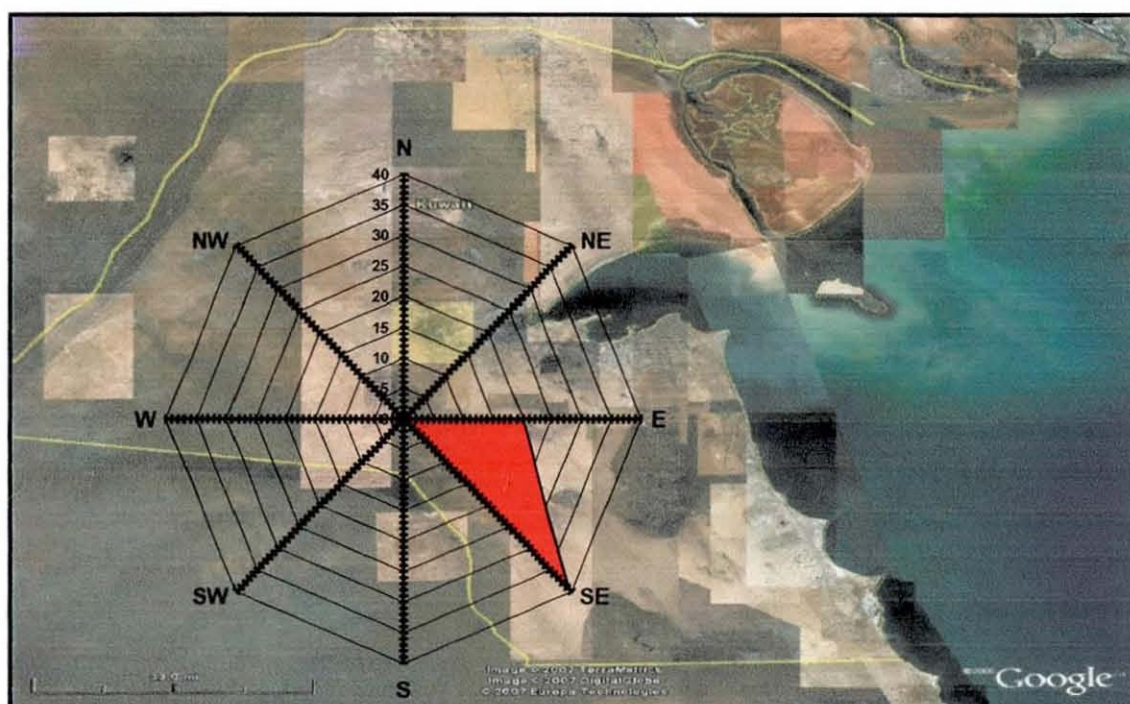
Figure 9.14c: : ISCST3 output data modelling results for the maximum predicted annual average concentrations of methane with respect to GC-28 Source
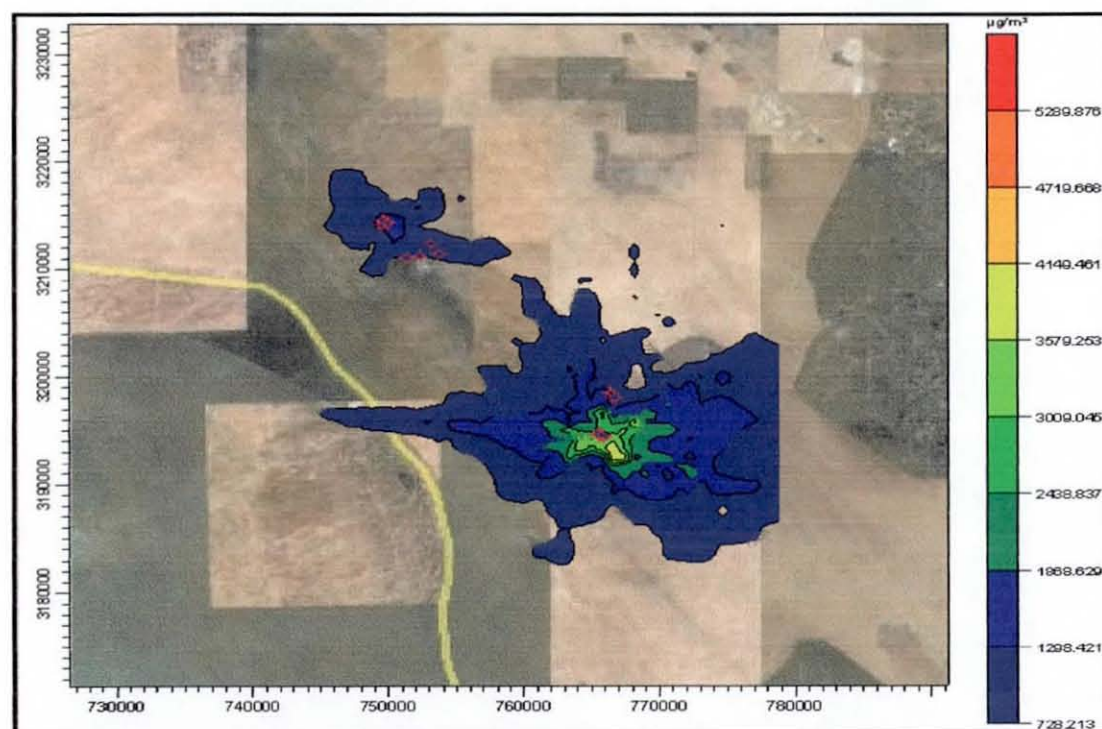
Figure 9.15a: Isopleths plot for the maximum hourly average ground level concentrations of non-methane hydrocarbons in $\mu g/m^3$
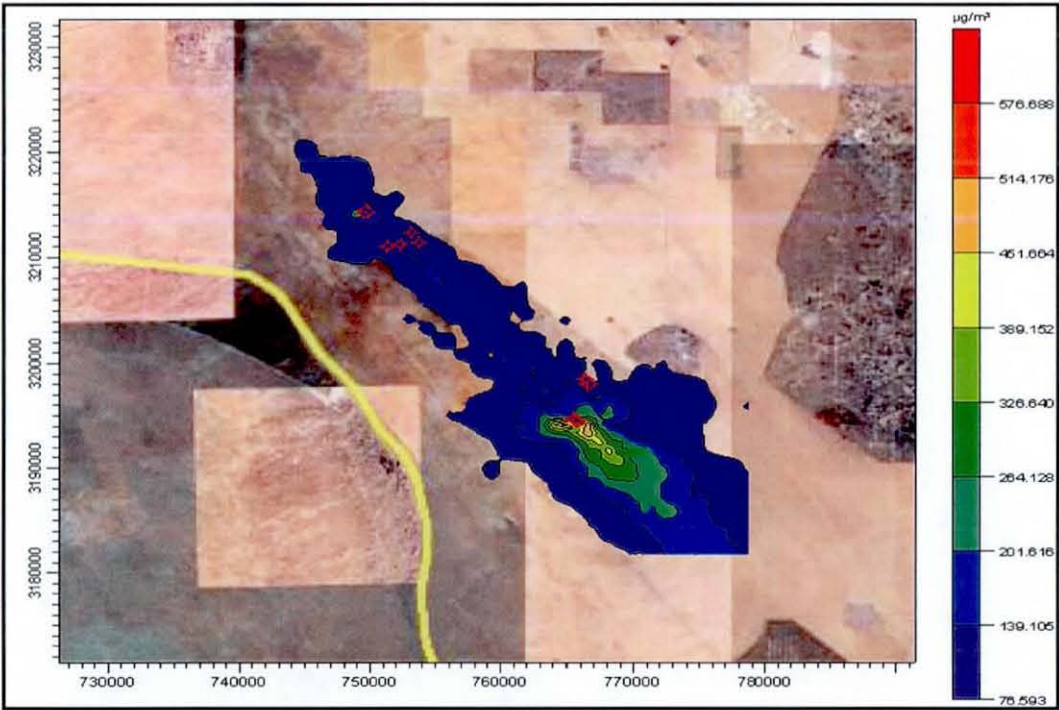
Figure 9.15b: Isopleths plot for the maximum daily average ground level concentrations of non-methane hydrocarbons in μg/m³
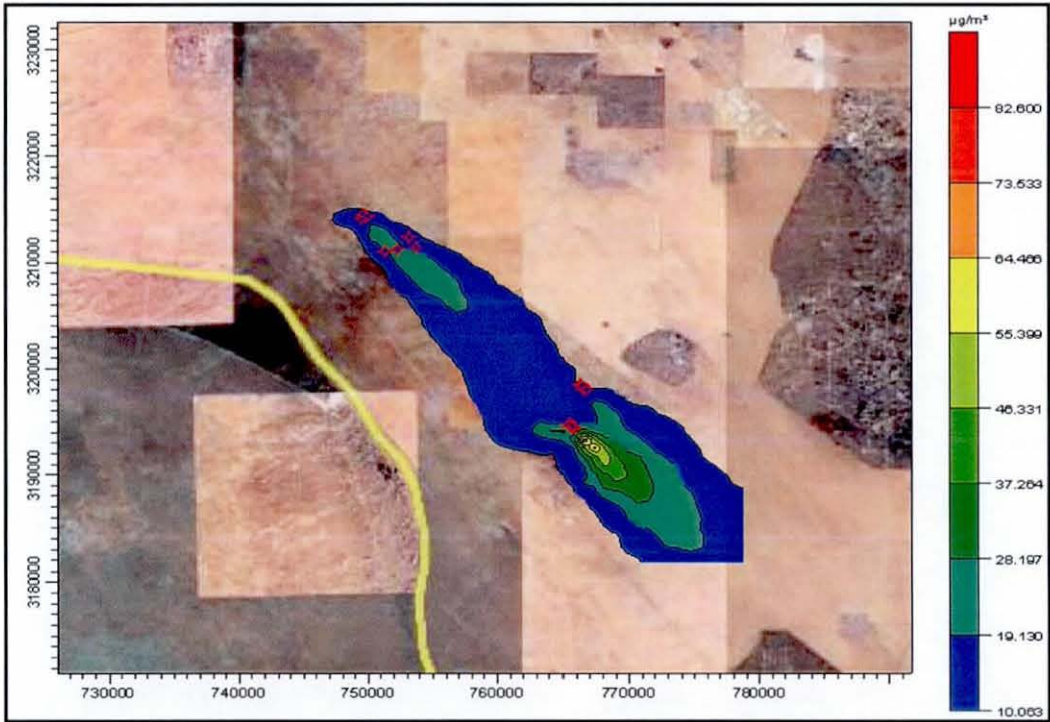
Figure 9.15c: Isopleths plot for the maximum annual average ground level concentrations of non-methane hydrocarbons in μg/m³

The predicted maximum hourly average ground level concentration of non-methane hydrocarbons in the study area is 2.53 ppm on 28th August 2006 at 09:00 Hr at the receptor located nearly 23.8 km 139° bearing N from GC-28, confirming source strength with Poe valued meteorological conditions. (Figure 9.14a and Figure 9.15a)

The predicted maximum daily average ground level concentration of non-methane hydrocarbons in the study area given in Figure 9.14b is 0.275 ppm on 25th August 2006 at the receptor located nearly 22.7 km bearing 140° bearing N from GC-28. This value is 10 times less than the maximum hourly average ground level concentration value. Figure 9.14c and Figure 9.15c show that the highest annual maximum concentration of non-methane hydrocarbons is equal to 39.5 ppb, which is 7 times less than the maximum daily average ground level concentration value.
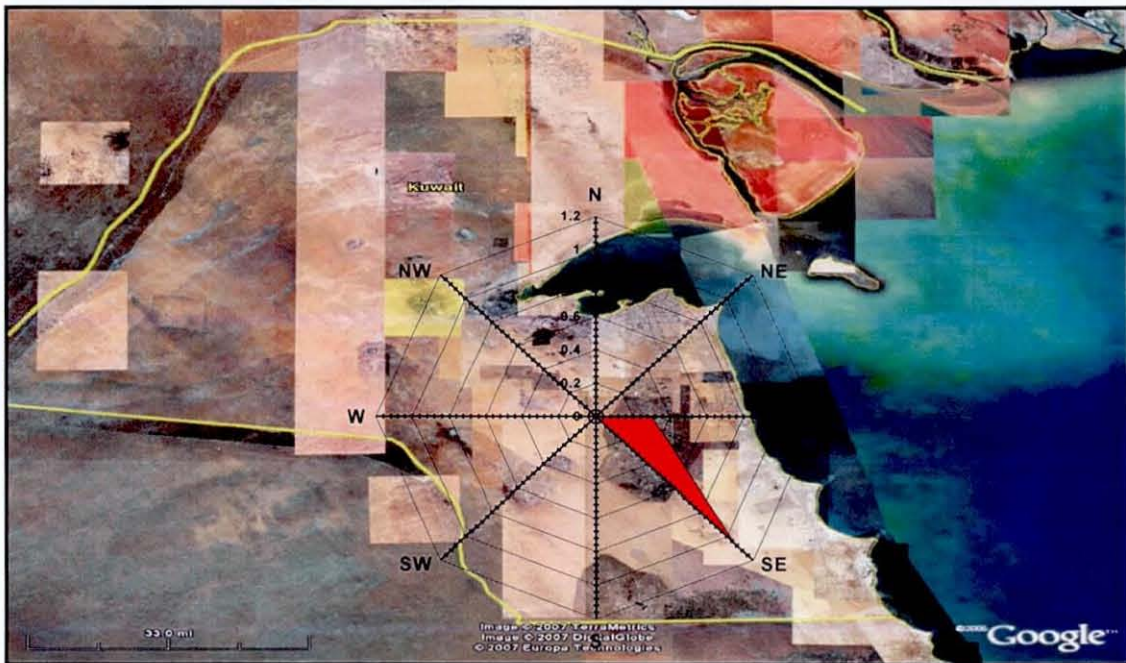
II. Methane Concentrations

Figure 9.16a-9.16c show the modelling results for the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of methane. The calculated values from the uniform grid receptors are discussed in the proceed section and GC-28 (Source coordinate of $X = 7.5 \times 10^5$, $Y = 3.2 \times 10^6$) is considered as a reference point to interpret the location of high concentration. Figures 9.17a-9.17c depicts the concentration variations in different zones that present the maximum hourly, daily and annual ground level concentration of methane in ppm and ppb are calculated at the specified uniform grid receptors and are tabulated
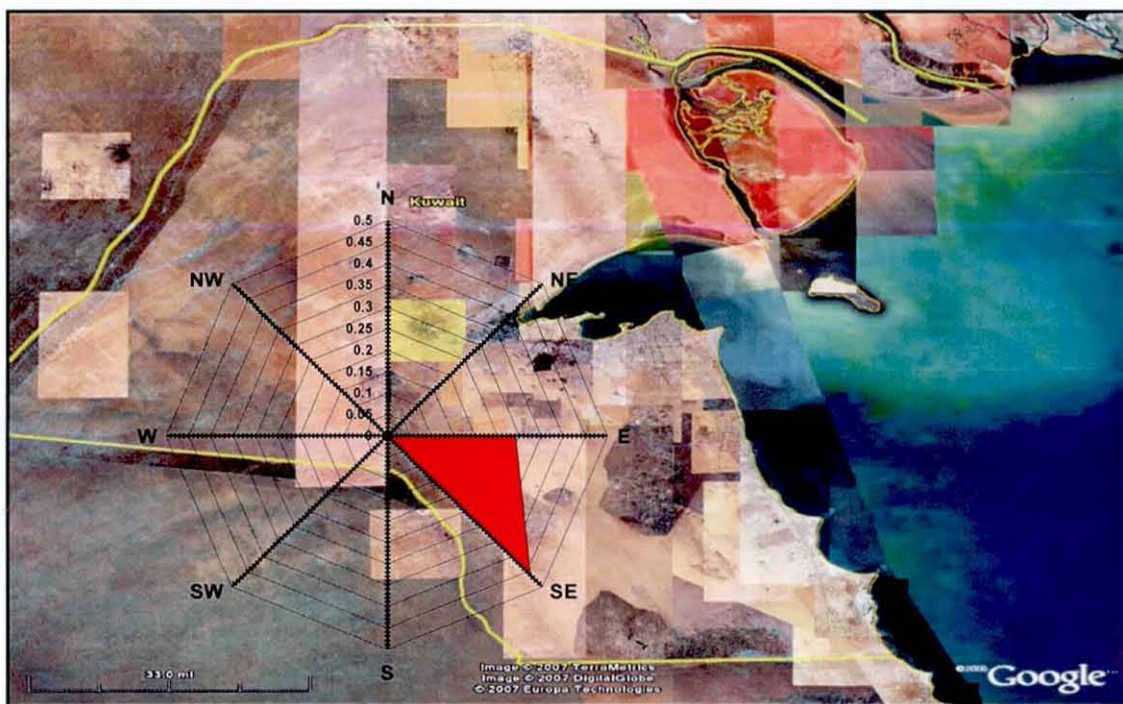
Figure 9.16a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of methane with respect to GC-28 Source
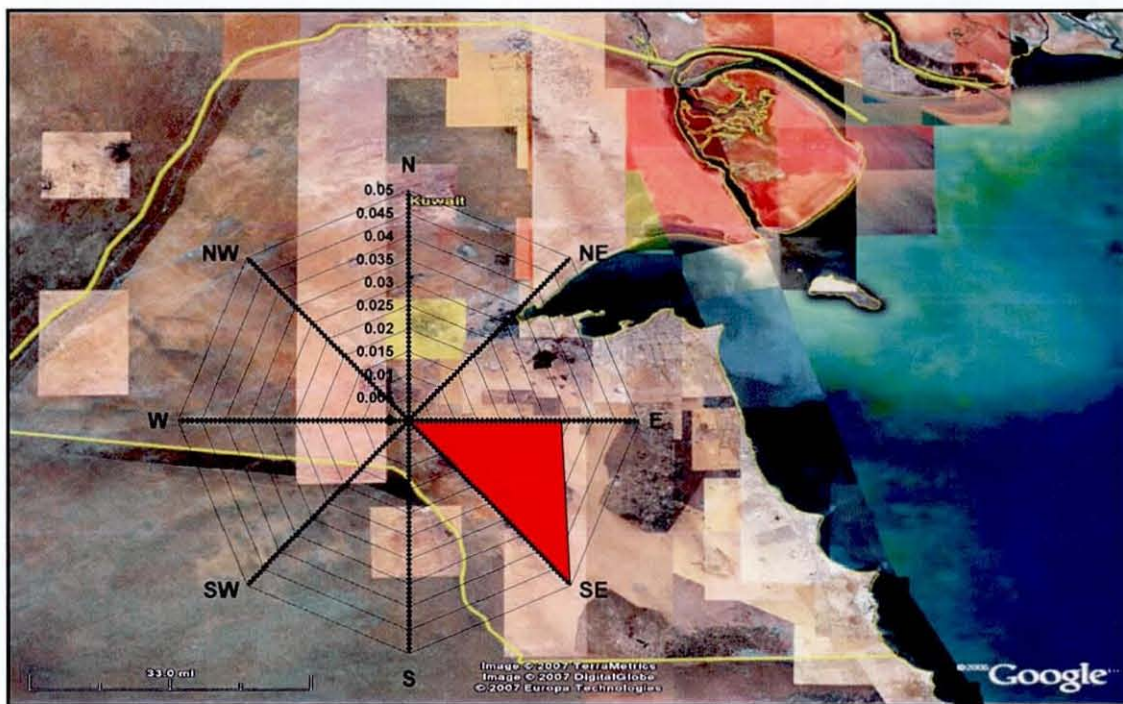
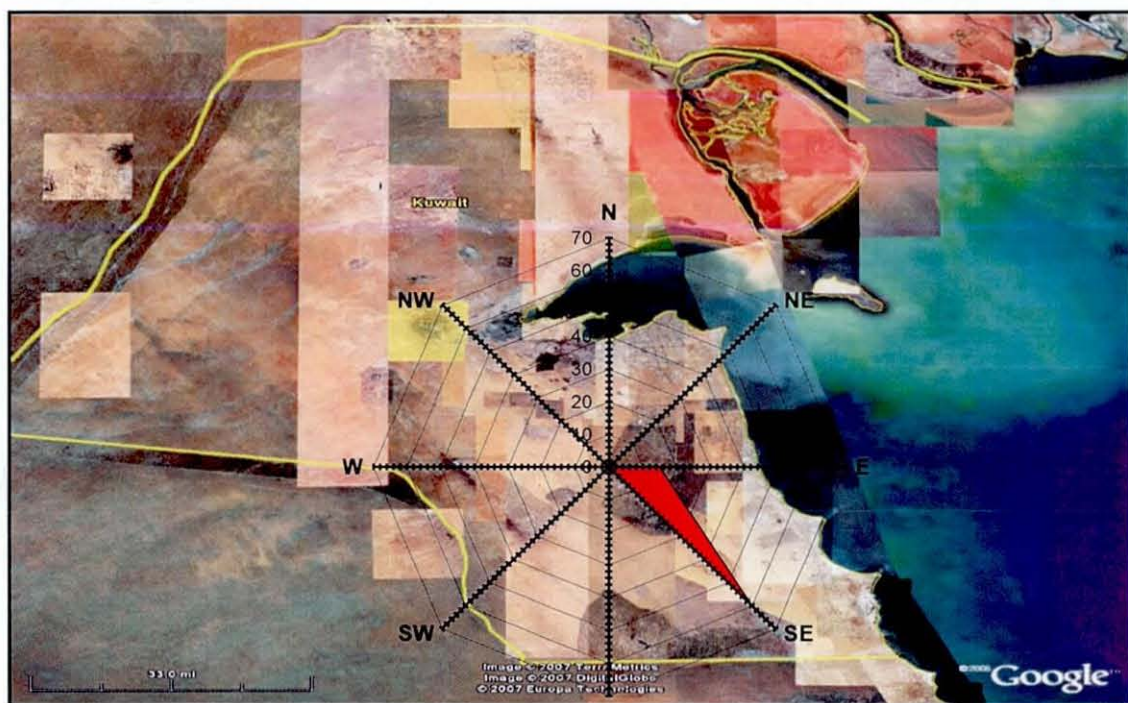**Figure 9.16b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of methane with respect to GC-2 Source**
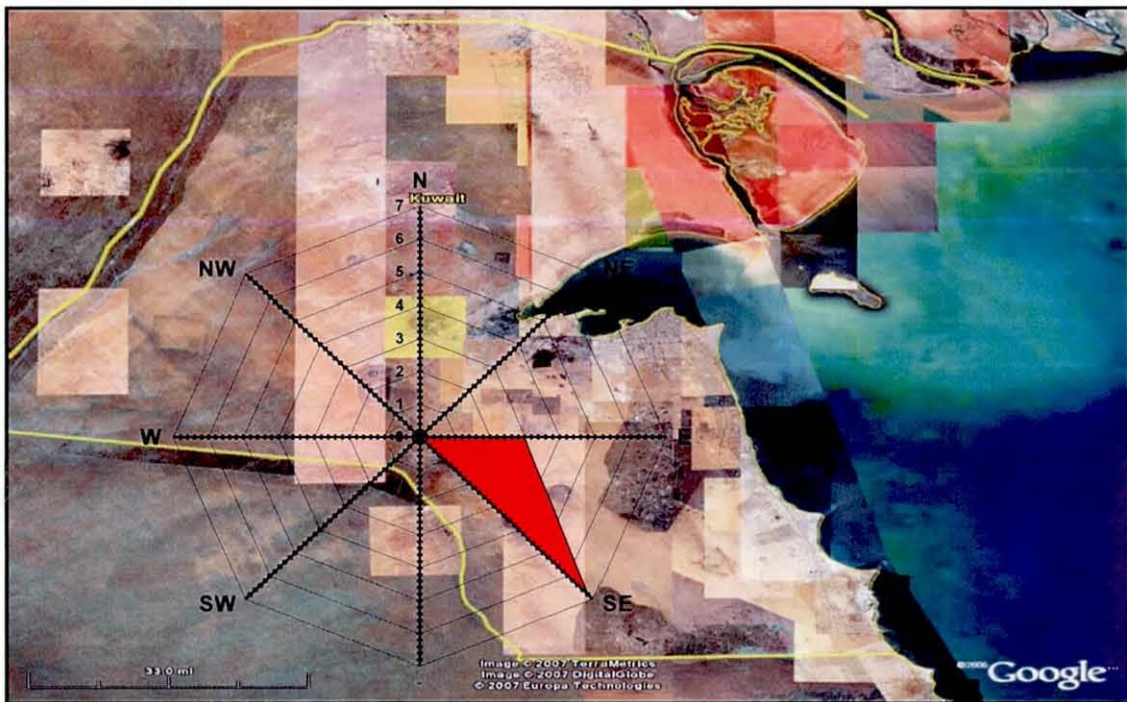
Figure 9.16c: : ISCST3 output data modelling results for the maximum predicted annual average concentrations of methane with respect to GC-28 Source
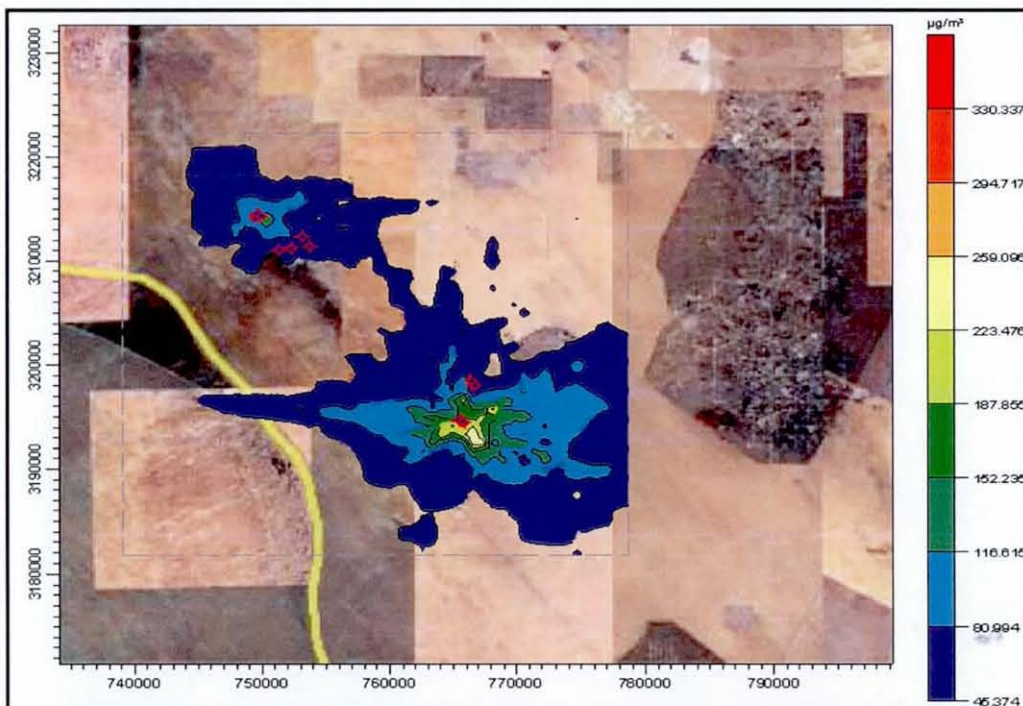
Figure 9.17a: Isopleths plot for the maximum hourly average ground level concentrations of methane in μg/m³
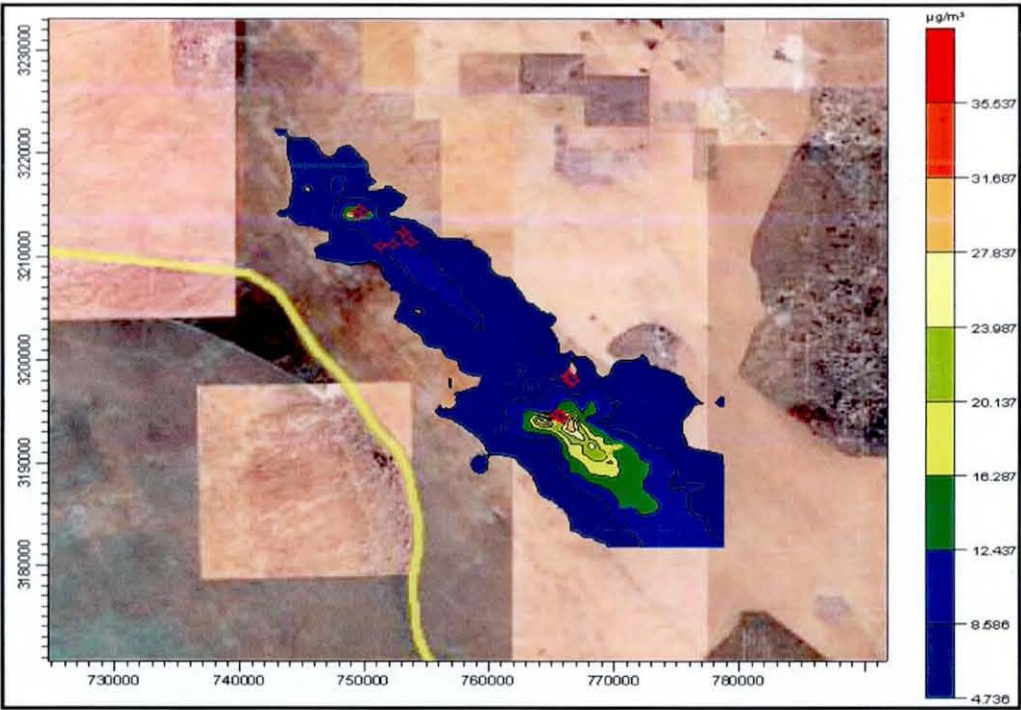
Figure 9.17b: Isopleths plot for the maximum daily average ground level concentrations of methane in μg/m³
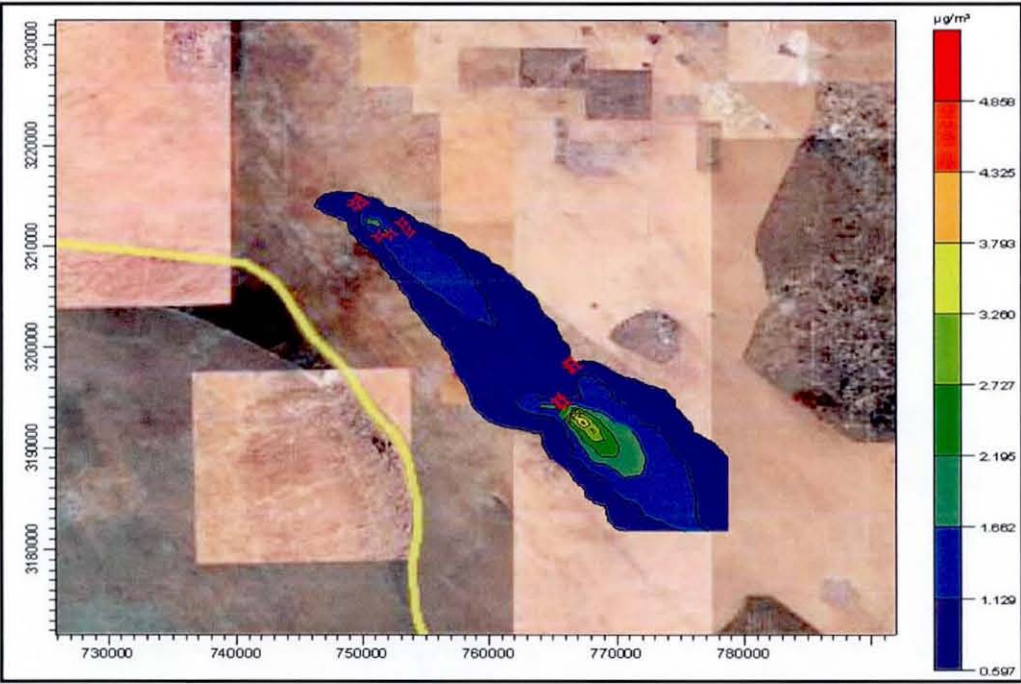
Figure 9.17c: Isopleths plot for the maximum annual average ground level concentrations of methane in μg/m³

The results presented in Figures 9.16a-9.16c and Figures 9.17a-9.17c revealed that predicted ground level concentrations of methane. The predicted maximum hourly average ground level concentration of methane in the study areas is 0.462 ppm on 28th August 2006 at 09:00 Hr at the receptor located nearly 23.8 km bearing 141° bearing N from GC-28.

The predicted maximum daily average ground level concentration of methane in the WK Oilfields is 50 ppb on 25th August 2006 given in Figure 9.16b. This value is 9 times less than the maximum hourly average ground level concentration value. This receptor is located nearly 22.7 km bearing 140° bearing N from GC-28. It is not surprising that the highest annual maximum concentration of methane also at the same spot as the maximum hourly and daily. The highest annual maximum concentration of methane is 6.8 ppb which is 7 times less than the maximum daily average ground level concentration value.

Due to Shutdown in KNPC (Acid Gas Removal Plant, AGRP), the percentage of flaring on WK Oilfields was high for months July and August (87% and 95%). There is strong influence of prevailing North West wind in summer, August hour's morning. Most of the highest values predicted were in summer and early morning hours due to low temperature and low in version layer.

The total gas production is from mainly three major oilfields and associated gas are respectively 55%,12 % and 33% from SEK, WK and NK.

The flaring due to complication in gas handling facilities are respectively 3.8 %, 66.8% and 29.4% from SEK, WK and NK.

I. The Impact of SO_2 emissions from flaring activities at WK Oilfield

The gas produced at WK Oilfields is mostly sour (20,000 to 30,000 ppm H_2S), hence after its compression and dehydration at local stations is first transported to the existing KNPC's Acid Gas Removal Plant (AGRP) for sweetening before being forwarded to LPG Plant.   In the present work an air quality screening study performed to assess the impacts of SO_2 emissions emitted by flaring in WK Oilfields. ISCST3 model was used to observe

the transport and dispersion patterns of SO_2, which is the main pollutant emitted from flaring in WK oilfields.

Results of SO_2 emissions from flaring activities at WK Oilfield
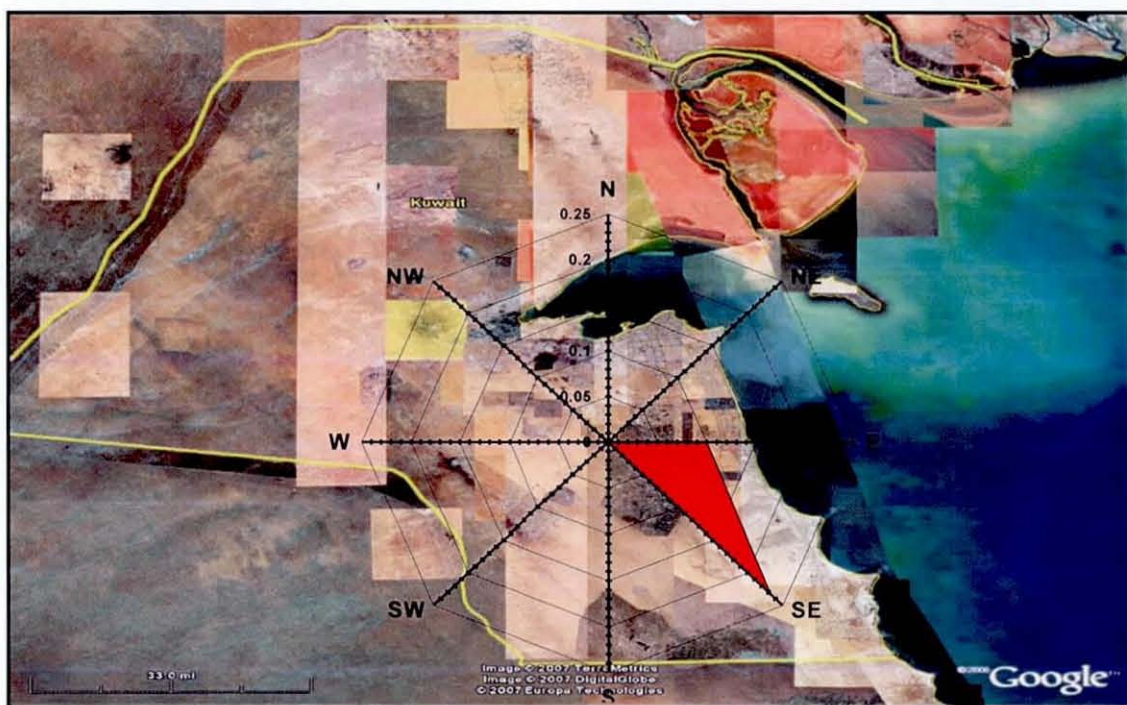
Figures 9.18a-9.18c show the modelling results for the 50 highest hourly, 50 highest daily and the 10 highest annual maximum ground level concentrations of SO_2 resulting from 18 stacks with total emission rate equal to 41460.1 g/s. The calculated values from the uniform grid receptors are described in proceeding section and GC-28 (Source receptor coordinate of X= 7.5 $\times 10^5$, Y= 3.2 $\times 10^6$) is considered as a reference point to interpret the location of high concentration. Figures 9.19a-9.19c depicts the concentration variations in different zones. These present the maximum hourly, daily and annual ground level concentration of SO_2 in ppb calculated at the specified uniform grid receptors.

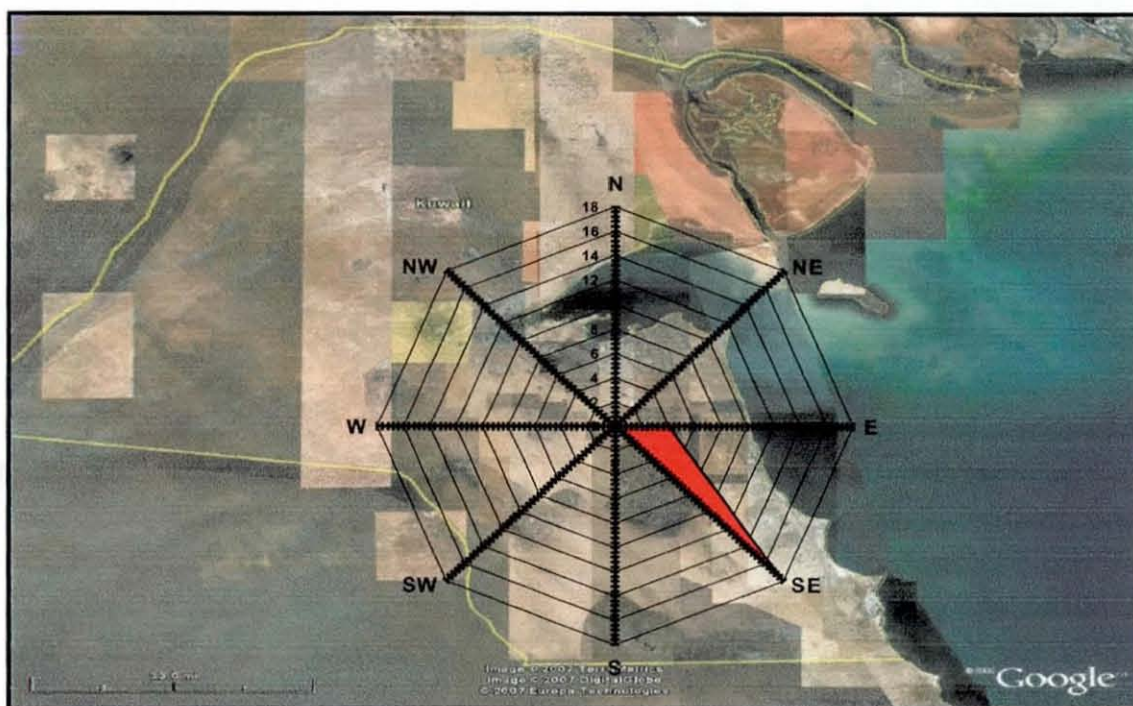**Figure 9.18a: ISCST3 output data modelling results for the Maximum predicted hourly average concentrations of SO_2**
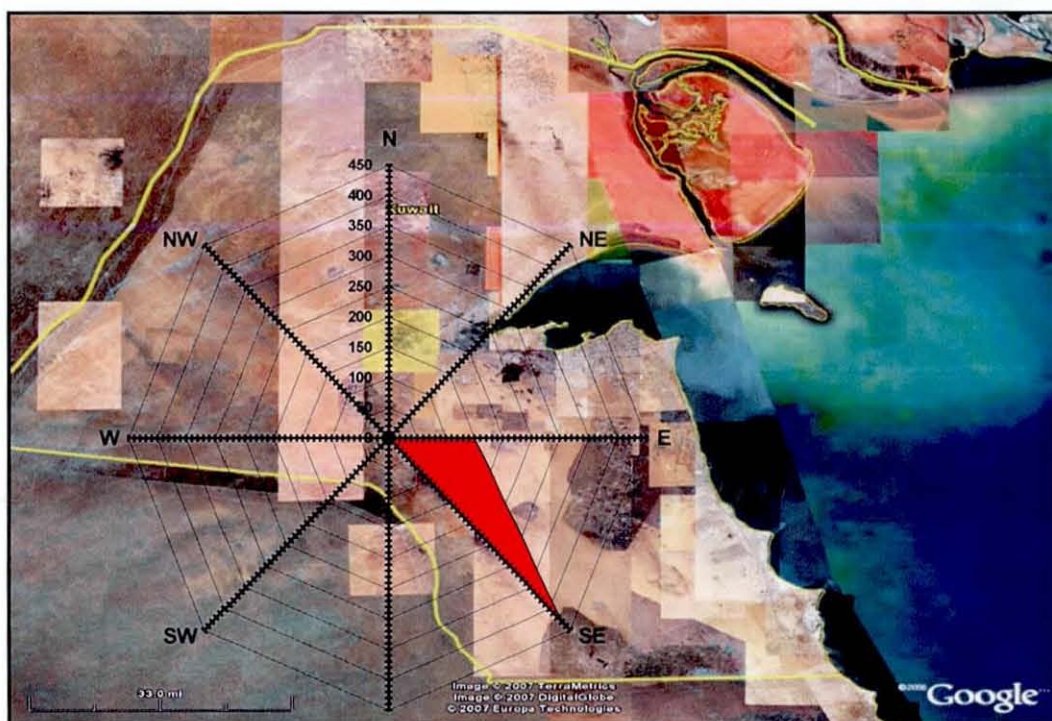
Figure 9.18b: ISCST3 output data modelling results for the maximum predicted daily average concentrations of SO$_2$
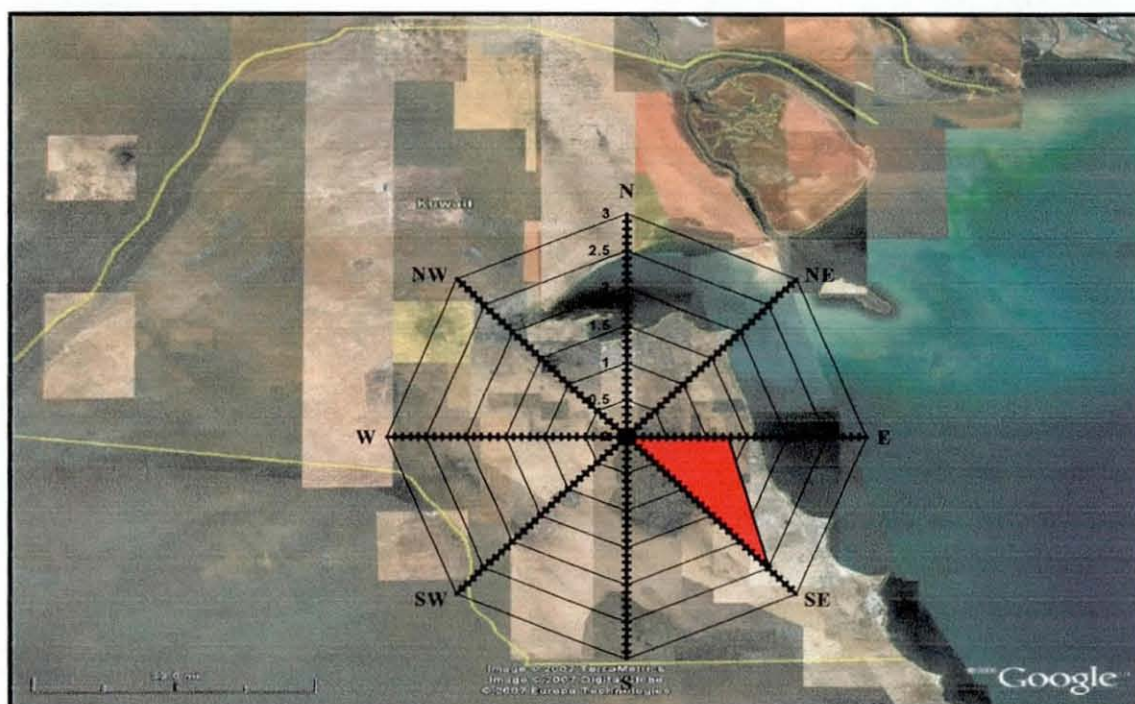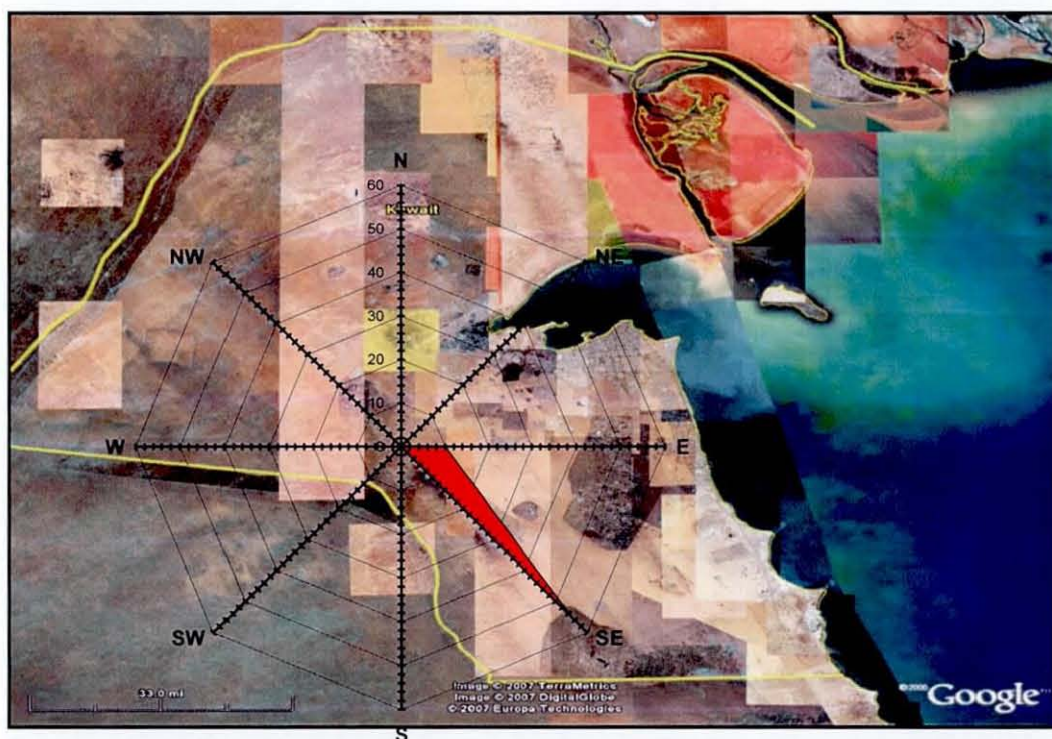

Figure 9.18c: ISCST3 output data modelling results for the maximum predicted annual average concentrations of SO$_2$
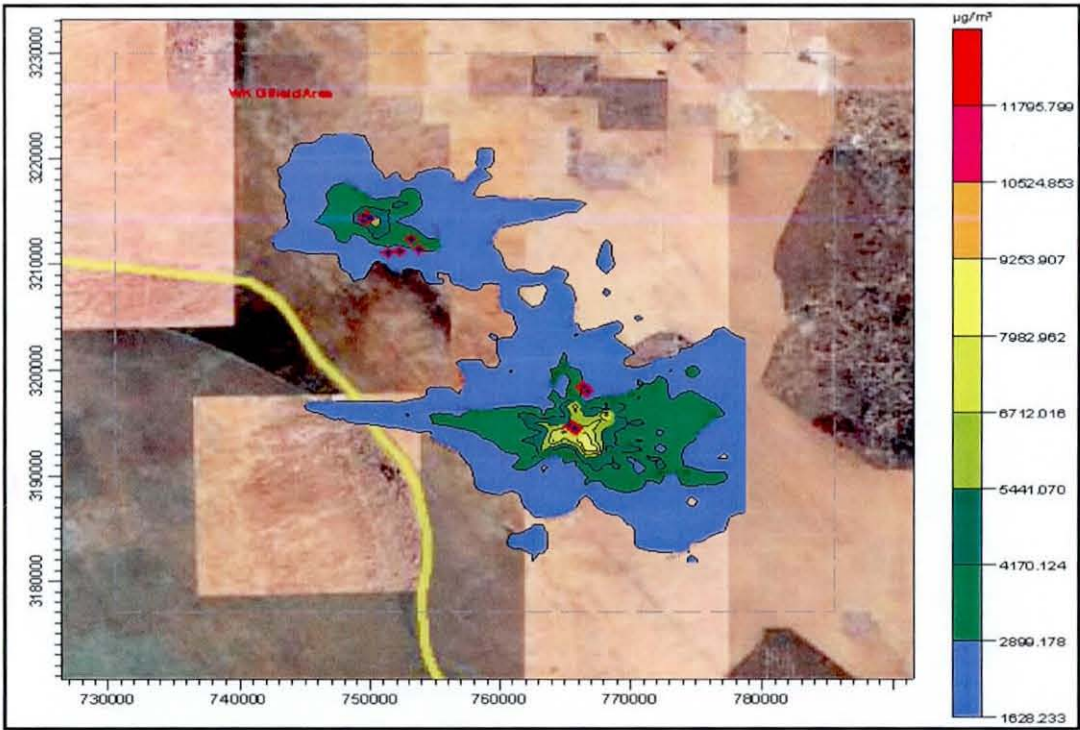
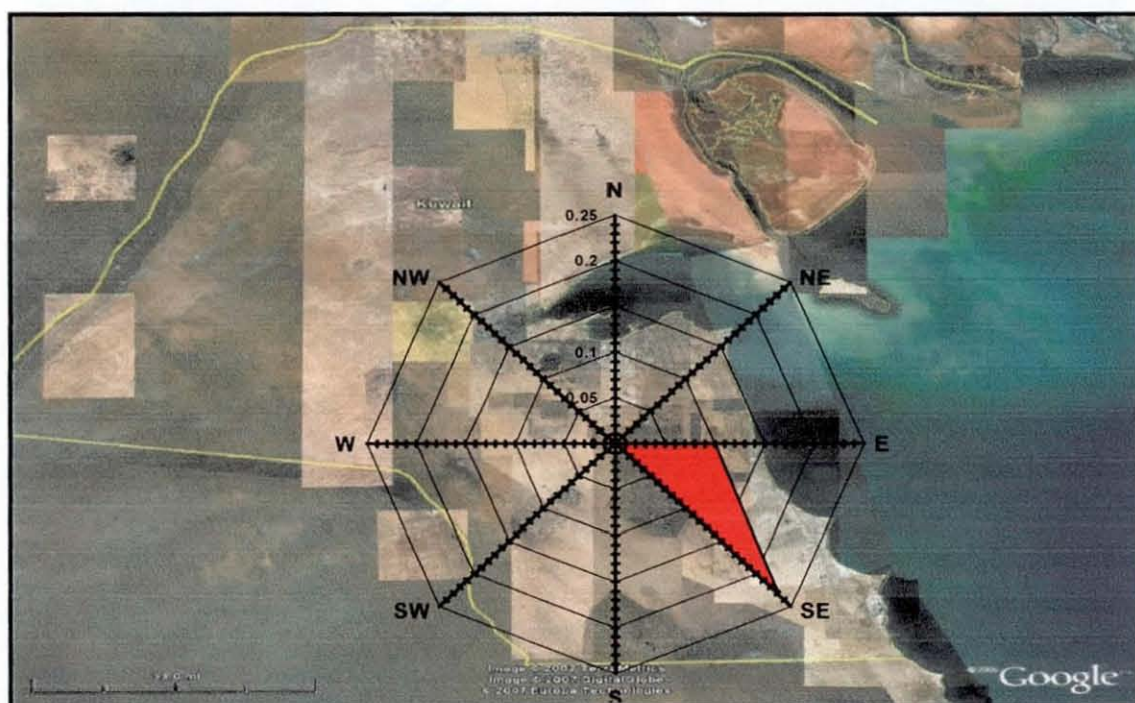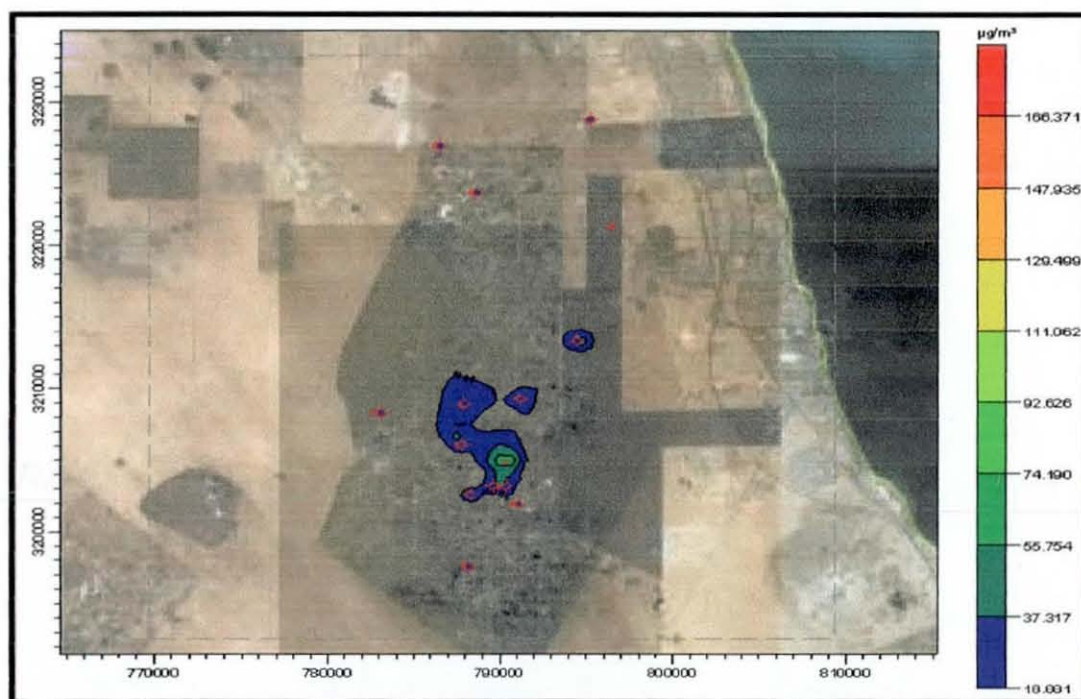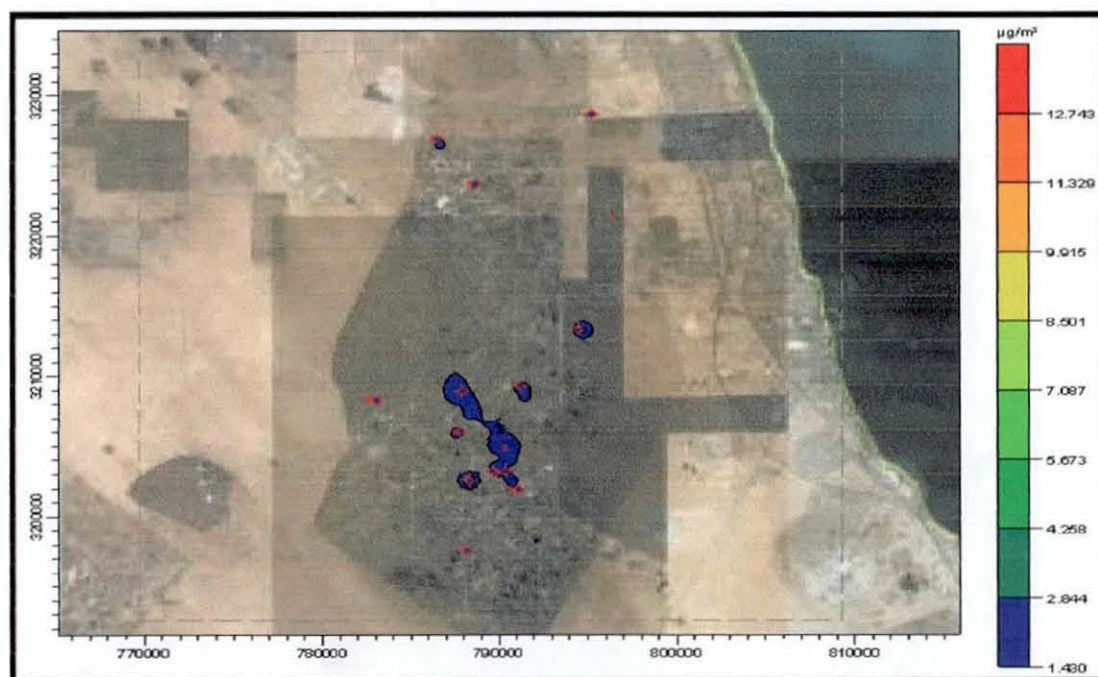**Figures 9.19a: Isopleths plot for the maximum hourly average ground level concentrations of SO$_2$ in μg/m^3**
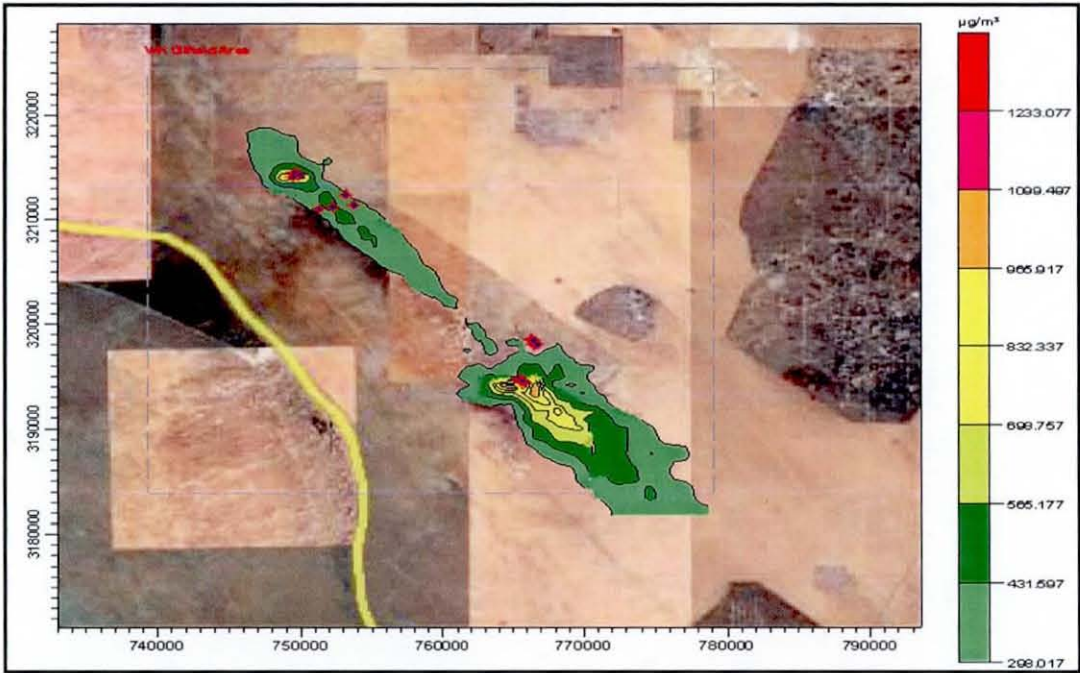
Figures 9.19b: Isopleths plot for the maximum daily average ground level concentrations of SO$_2$ in μg/m^3
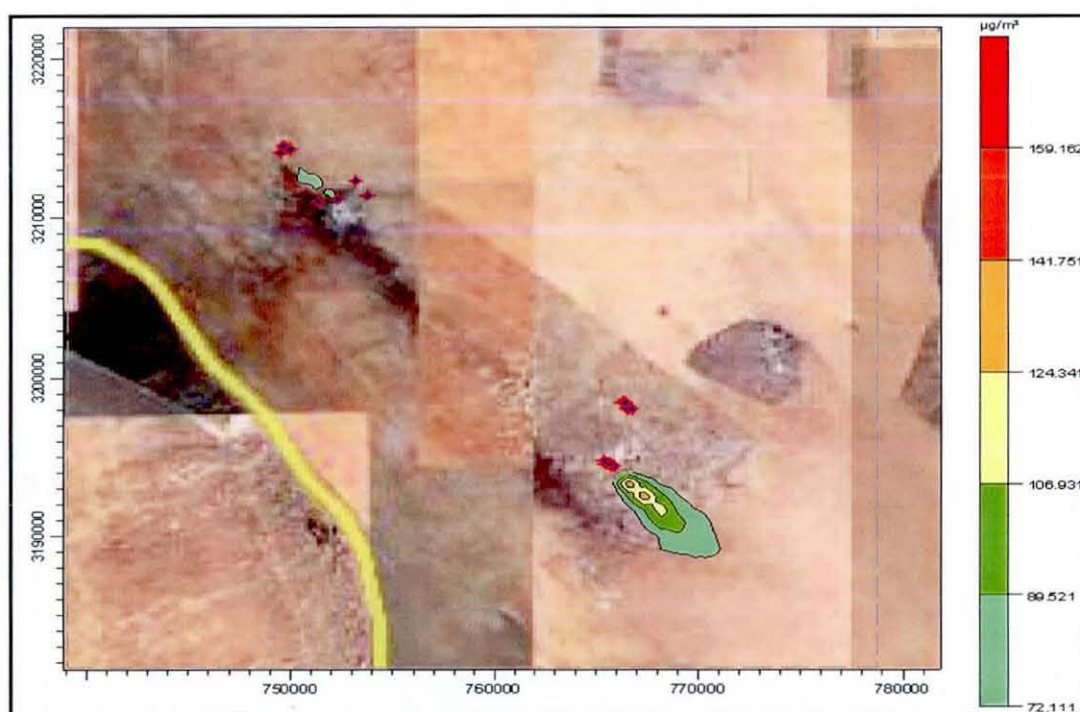
Figures 9.19c: Isopleths plot for the maximum annual average ground level concentrations of SO$_2$ in μg/m^3

The results presented in Figures 9.18a-9.18c and Figures 9.19a-9.19c reveals that predicted ground level concentrations of SO$_2$ for the specified time exceeds the KAAQS ambient air quality standard over the study area.

As shown in Figure 9.18a, the predicted maximum hourly average ground level concentration of SO$_2$ in the study areas is 4124 ppb at 10:00 Hr on 8th August 2006 at the receptor located nearly 23.2 km 141 ° bearing N from GC-28. Moreover, close inspection of Figure 9.19a, indicates that the predicted hourly concentration of SO$_2$ exceeded the allowable limit by more than 24%, which means that the KAAQA was exceeded more than once a year in the same location.

The predicted maximum daily average ground level concentration of SO$_2$ in the study areas in Figure 9.18b is 431 ppb on 25th August 2006. This value is 11 times less than the maximum hourly average ground level concentration value. Inspection of Figure 9.19b, this receptor located nearly 22.7 km 140 ° bearing N from GC-28, Moreover; the predicted daily concentration of SO$_2$ exceeded the allowable limit by more than 7%. It is

not surprising that the highest annual maximum concentration of SO_2 also at the same spot as the maximum hourly and daily. The highest annual maximum concentration of SO_2 is 55.6 ppb which is 13 times less than the maximum daily average ground level concentration value.

Due to Shutdown in KNPC (AGRP), the percentage of flaring on WK Oilfields was very high for months July and August (87%and 95%). Thus, the strong influence of prevailing NK wind in Summer, August morning hours. Most of the highest values predicted were in summer and early morning hours.

Chapter 10
Conclusions and Future Work

10.1   Conclusions

The flaring of excess gas is one of the largest single sources of atmospheric emissions arising from Kuwait Oilfields. However, flaring produces carbon dioxide, oxides of sulphur and nitrogen (NO_x) and other chemical species that are produced due to incomplete combustion, such as carbon monoxide, aldehydes, ketones and other organic compounds known as Volatile Organic Compounds (VOCs).

Al-Hamad and Khan [2007] have presented a detailed emission inventories for oil production facilities from flaring activities for a decade starting year 1997 in Kuwait Oilfields. The Environmental Pollution Inventory data for 1997- 2006 years were collected for flaring events from all oil production facilities in Kuwait. This inventory focused primarily on air emissions only. The inventory estimated the amount of each of the flaring pollutants generated by Kuwait Oilfields operations on a monthly basis and the analysis was repeated for the next year and results were compared and validated with preceding years known emissions.

It is observed from the first three years results that flaring emissions are reduced by 10% against 1997 baseline levels, although there has been sudden increase in 1998 due to certain malfunctions of the gas handling equipments. Total oil production decrease in 1998 but still atmospheric emissions from flaring showed a significant increased.

Emissions from flared gas have reduced in years 2000 to the minimum and continued further lowering than 1999 levels. But the quantity of gas flared has increased slightly in 2002 due to the frequent shutdowns of Condensate Recovery Unit (CRU's) and lack of gas compression facilities and the subsequent increased volume of flared gas in North Kuwait.

From the monitoring results that were carried out in year 2003 and 2004, it was shown that the emissions from flared gas have reduced to below year 2002 levels. The quantity of gas being flared in Kuwait Oilfields has been reduced from 14% of total production in 2002 to 10% in 2003, despite an increase in the total amount of gas being produced. There were unexpected problems in North Kuwait oilfields in year 2005, the amount of gas flared, as a percentage of production, was about double that of the previous year.

The total gas production for year 2006 is from mainly three major oilfields and associated gas are 33%, 55% and12% from North Kuwait (NK), South East Kuwait (SEK) and West Kuwait (WK) respectively. The flaring due to complication in gas handling facilities are 29.4% ,3.8 % and 66.8% and from NK, SEK and WK respectively.

In this research work, the widely used air pollution mathematical model namely, the Industrial Sources Complex for Short Terms prediction (ISCST3) was successfully applied under the real meteorological conditions to analyse the dispersion of methane, non-methane hydrocarbons emitted from flaring activities at oil production facilities in all over Kuwait Oilfields and SO_2 emitted from flaring activities in WK Oilfields. One year hourly meteorological records for the year 2006 together with the emissions inventory data and the topographical data were used to carryout the dispersion model calculations for the hourly, daily and the annual maximum average ground level concentrations of methane, non-methane hydrocarbons and SO_2 independently.

The problem of the other gaseous pollutants (such as Nitrogen Oxides....etc.) in the ambient air is less importance since their concentrations are only localized around their main emitting source.

In general, only three pollutants groups are always above the ambient standards set by Kuwait EPA. These pollutants are the methane, non-methane hydrocarbons and SO_2.

The results of the study have shown a temporal and spatial variation in the concentrations of the targeted pollutants. The temporal variation was mainly noticed as an increase in the pollution after the day working hours. This remarkable increase in the pollutants

concentrations during night shift can be explained by the change in the meteorological parameters such as lower temperature, lower wind speed, higher relative humidity and hence lower mixing depth resulting in to lower dispersion.

Al-Hamad, et al [2008], have discussed methane and non-methane hydrocarbons gases emissions from flaring activities in all over Kuwait Oilfields and resulting ground level concentration using ISCST3 model. Methane and non-methane hydrocarbons are not the only green house gasses (GHG) which resulted from flaring activities. The flaring of excess gas is the largest single source of atmospheric emissions arising from Kuwait Oilfields operations. The performance of the model is evaluated based on the comparison of 50 highest daily measured and predicted concentrations of methane and non-methane hydrocarbons from NK flaring activities at Al-Jahra monitoring station used by Kuwait EPA. It is clear that the model predictions are in good agreement with the observed data with an error bond of ± 50 %.

In *NK area*, the predicted maximum hourly average ground level concentration of non-methane hydrocarbons in the study area is 38 ppm on 16th January 2006 at 19:00 Hr at the receptor located nearly 11 km 104° bearing N from GC-15 with prevalent temperature equal to 12.8 °C and wind speed equal to 2 m/s. The predicted maximum daily average ground level concentration of non-methane hydrocarbons is 3.14 ppm on 4th January 2006 at the receptor located nearly 11.8 km 105° bearing N from GC-15 with prevalent temperature equal to 7.1°C and wind speed equal to 2 m/s. This value is 11 times less than the maximum hourly average ground level concentration value due to damping effect of 24 hourly values. For the same location the highest annual maximum concentration of non-methane hydrocarbons is equal to 298.7 ppb, which is 11 times less than the maximum daily average ground level concentration value that again is an average value of 365 daily values.

The predicted maximum hourly average ground level concentration of methane in NK area is 7.95 ppm at 19:00 Hr on 16th January 2006 at the receptor located nearly 11 km 104° bearing N from GC-15 with prevalent temperature equal to 12.8 °C and wind speed

equal to 2 m/s and the predicted maximum daily average ground level concentration of methane is 0.66 ppm on 4th January 2006 at the receptor located nearly 11.8 km 105° bearing N from GC-15 with prevalent temperature equal to 7.1°C and wind speed equal to 2 m/s. This value is 12 times less than the maximum hourly average ground level concentration value. It is not surprising that the highest annual maximum concentration of methane is also at the same spot as the maximum hourly and daily. The highest annual maximum concentration of methane is 62.6 ppb which is 11 times less than the maximum daily average ground level concentration value. This results confirming that the strong influence of prevailing North West (NW) wind in January month evening hours with strong cloud cover. Most of the highest values predicted were in winter and early morning hours

The above results reflect the increase in flaring in January year 2006, due to regular shutdown of CRU's in NK Oilfields and the strong influence of NW prevailing wind direction in NK Oilfields. It is concluded that the weather pattern in Kuwait in January 2006, especially the mean prevailing wind speed and direction, significantly contributed to high concentrations of methane and non-methane hydrocarbons at ground level in residential areas located nearly 11 km bearing 104° bearing N from GC-15 with prevalent temperature equal to 12.8 °C and wind speed equal to 2 m/s.

The simulated results from ISCST3 dispersion model in and around the NK Oilfields for the year 2006, by implementing only flare activities sources, from oil production facilities indicated the following;

- Predicted methane ground level concentrations have exceeded 2 ppm level over about 40% of the total study area (40kmx40km).

- The highest average ground level concentration of methane hourly, daily and annually were in the months of January and September due to high emission rates resulted due to malfunctioning of condensate recovery unit. The prevailing meteorological conditions in the month of January have facilitated low dispersion into the top

resulting in to the highest ground concentrations, low temperatures and low inversion layer and calm wind conditions were main causes for these elevated concentrations.

- The emission rate in September was the same as that of January but meteorological conditions influenced result into 11th among top 50 values hourly amount and 8th daily values at 11 km 104° bearing N from GC-15 with prevalent temperature equal to 12.8 °C and wind speed equal to 2 m/s.

- The predicted values for non-methane hydrocarbons are in terms of $\mu g/m^3$ and converted to ppm and ppb by using an average Molecular Weight (46.9 g/gmole) to compare with specified standards represented as ppm.

- The predicted non-methane hydrocarbons ground level concentrations have exceeded the Kuwait EPA standards over 190 occasions times in year 2006 while in general almost all the observed values at the air quality monitoring stations indicated high violation of this pollutant due to additional sources, oil storage, petroleum refining, petrochemical industries, oil transport and power generation, road traffic etc.

- Predicted non-methane hydrocarbons ground level concentrations have exceeded 0.24 ppm level over about 90% of the total study area (40kmx40km), in early morning 3 hours mean values, Kuwait EPA standard 6:00 AM to 9:00 AM.

In SEK area, the predicted maximum hourly average ground level concentration of non-methane hydrocarbons is 11.5 ppm on 14th May 2006 at 04:00 Hr at the receptor located nearly 8.3 km 114° bearing N from GC-2 with prevalent temperature equal to 26.1 °C and wind speed equal to 2 m/s. The predicted maximum daily average ground level concentration of non-methane hydrocarbons is 1.06 ppm on 27th May 2006 at the receptor located nearly 8.1 km 116° bearing N from GC-2 with prevalent temperature equal to 42.1 °C and wind speed equal to 7 m/s. This value is 11 times less than the maximum hourly average ground level concentration value. For the same location, the highest annual maximum concentration of non-methane hydrocarbons is equal to 60.4 ppb, which

is 17 times less than the maximum daily average ground level concentration value. The computed 3 hours average data reveal that the predicted ground level concentration of non-methane hydrocarbons for the specified time 6:00 -9:00 AM about 48% of the total study period of the Kuwait EPA standard.

The predicted maximum hourly average ground level concentration of methane in SEK area is 2.53 ppm at 04:00 Hr on 14th May 2006 at the receptor located nearly 8.3 km 114° bearing N from GC-2 with prevalent temperature equal to 26.1 °C and wind speed equal to 2 m/s. The predicted maximum daily average ground level concentration of methane is 0.233 ppm on 27th May 2006 with prevalent temperature equal to 42.1 °C and wind speed equal to 7 m/s. This value is 11 times less than the maximum hourly average ground level concentration value at location nearly 8.1 km 116° bearing N from GC-2. It is not surprising that the highest annual maximum concentration of methane also at the same location as the maximum hourly and daily. The highest annual maximum concentration of methane is 17.8 ppb which is 13 times lower than the maximum daily average ground level concentration value.

The above results reflect the increase in flaring activities in the month of May 2006, due to regular shutdown of CRU's in SEK Oilfields and north westerly prevailing wind in Kuwait. It is concluded that the weather pattern in Kuwait in May 2006, especially the mean prevailing wind speed and direction, significantly contributed to the high concentrations of methane and non-methane hydrocarbons at ground level in residential areas located nearly 8.3 km 114° bearing N from GC-2 with prevalent temperature equal to 26.1 °C and wind speed equal to 2 m/s.

In WK area, the predicted maximum hourly average ground level concentration of non-methane hydrocarbons is 2.53 ppm on 28th August 2006 at 09:00 Hr at the receptor located nearly 23.8 km 139° bearing N from GC-28 with prevalent temperature equal to 39.9 °C and wind speed equal to 2 m/s, confirming source strength with prevalent meteorological conditions. The predicted maximum daily average ground level concentration of non-methane hydrocarbons is 0.275 ppm on 25th August 2006 at the

receptor located nearly 22.7 km 140° bearing N from GC-28 with prevalent temperature equal to 48.6 °C and wind speed equal to 5 m/s. This value is 10 times less than the maximum hourly average ground level concentration value. In the same location the highest annual maximum concentration of non-methane hydrocarbons is equal to 39.5 ppb, which is 7 times less than the maximum daily average ground level concentration value.

The predicted maximum hourly average ground level concentration of methane in WK area is 0.462 ppm on 28th August 2006 at 09:00 Hr at the receptor located nearly 23.8 km 141° bearing N from GC-28 with prevalent temperature equal to 39.9 °C and wind speed equal to 2 m/s. The predicted maximum daily average ground level concentration of methane in the WK Oilfields is 50 ppb on 25th August 2006. This value is 9 times less than the maximum hourly average ground level concentration value. This receptor is located nearly 22.7 km 140° bearing N from GC-28 with prevalent temperature equal to 48.6 °C and wind speed equal to 5 m/s. It is not surprising that the highest annual maximum concentration of methane also at the same spot as the maximum hourly and daily, also at the same location the highest annual maximum concentration of methane is 6.8 ppb which is 7 times less than the maximum daily average ground level concentration value.

Due to Shutdown in KNPC (Acid Gas Removal Plant, AGRP), the percentage of flaring on WK Oilfields was high for the month of August (95%). There is strong influence of prevailing North West wind in summer in morning hours. Most of the highest predicted values were in summer and early morning hours due to low inversion layer.

The simulated results for emission scenarios from North, Southeast and West Kuwait Oilfields have been obtained independently and were compared;

- The emissions from flaring activities in different oilfields are used as an input for the ISCST3 model to investigate the impact on the air quality and methane and non-methane hydrocarbons levels. The statistical comparison between the 50 highest daily

measured and predicted concentrations emissions at SEK, WK and NK with existing air quality monitoring site showed a good agreement validating the model results.

- Based on methane and non-methane hydrocarbons emissions, NK, SEK and WK represented 73%, 22.1% and 4.9% from the total emissions respectively. The highest predicted concentration of methane and non-methane in NK Oilfields occurred in residential areas located nearly 11 km 104° bearing N from GC-15 with prevalent temperature equal to 12.8 °C and wind speed equal to 2 m/s.

- The maximum hourly average ground level concentration of non-methane hydrocarbons in NK Oilfields is 4 times higher than SEK Oilfields and 16 times higher than WK Oilfields. The maximum daily average ground level concentration of non-methane hydrocarbons in NK Oilfields is 4 times higher than SEK Oilfields and 13 times higher than WK Oilfields. The highest annual maximum concentration of non-methane hydrocarbons maximum in NK Oilfields is 6 times higher than SEK Oilfields and 9 times higher than WK Oilfields.

- The maximum hourly average ground level concentration of methane hydrocarbons in NK Oilfields is 4 times higher than SEK Oilfields and 18 times higher than WK Oilfields. The maximum daily average ground level concentration of methane hydrocarbons in NK Oilfields is 4 times higher than SEK Oilfields and 14 times higher than WK Oilfields. The highest annual maximum concentration of methane hydrocarbons maximum in NK Oilfields is 5 times higher than SEK Oilfields and 10 times higher than WK Oilfields.

In WK area the gas for nature has a significant amount of H_2S resulting in to sour gas, while in NK and SEK the associated gas is sweet. Therefore, ISCST3 was implemented to evaluate the impact of SO_2 released from flaring activities in WK Oilfields. The model applied to the real hourly meteorological conditions of the state of Kuwait for the year 2006 together with the emission data for year 2006. The predicted maximum hourly average ground level concentration of SO_2 in WK Oilfields area is 4124 ppb at 10:00 Hr

on 8th August 2006 at the receptor located nearly 23.2 km 141° bearing N from the GC-28 with prevalent temperature equal to 45.1 °C and wind speed equal to 3 m/s. The predicted hourly concentration of SO_2 exceeded the allowable limit by more than 24%, which means that the KAAQA was exceeded more than once a year in the same location.

The predicted maximum daily average ground level concentration of SO_2 is 431 ppb on 25th August 2006. This value is 11 times less than the maximum hourly average ground level concentration value, this receptor located nearly 22.7 km bearing 140° bearing N from the GC-28 with prevalent temperature equal to 48.6 °C and wind speed equal to 5 m/s, Moreover; the predicted daily concentration of SO_2 exceeded the allowable limit by more than 7%. It is not surprising that the highest annual maximum concentration of SO_2 also at the same location as the maximum hourly and daily. The highest annual maximum concentration of SO_2 is 55.6 ppb which is 13 times less than the maximum daily average ground level concentration value.

The simulated results from ISCST3 dispersion model to evaluate the impact of SO_2 released from flaring activities in WK Oilfields have been obtained and were compared;

- The emissions of SO_2, within flaring activities from WK oilfield exceeded the allowable daily ambient air quality standard by Kuwait EPA in by 10 fold. The weather pattern in Kuwait, especially the mean prevailing wind speed and direction, contributed to have the highest concentrations of SO_2, within flaring activities from WK oilfields at the ground level in residential areas located downwind of WK Oilfields.

- Predicted SO_2 ground level concentrations have exceeded the allowable hourly, daily and annually ambient air quality standard by Kuwait EPA level over about 90% of the total study area (40kmx40km).

- The highest average ground level concentration of SO_2 hourly, daily and annually were in the months of August and July. Due to Shutdown of AGRP, the percentage of flaring on WK Oilfields was the higher for the months of July and August (87% and

95%). There is strong influence of prevailing North West wind in morning hour's. Most of the highest predicted values were in summer and early morning hours due to low inversion layer.

It is concluded that three major weather factors play important role in the dispersion of the pollutants over inland areas of Kuwait. These are wind speed and direction, solar radiation and the formation of the temperature inversion.

Overall it seems that the levels of pollutants in winter period are higher than summer. This is because the winters in Kuwait portray low temperatures, low inversion layers, lesser wind movements, which relegated the dispersion of pollutants as compared to summer, that have high temperature, high inversion layers, and high wind movements strongly influencing the dispersion of pollutants.

10.2   Future Work

For accurate assessment, detailed inventories are needed. Therefore, an extensive source emission inventory with better data input for operation on regular basis is required.

A study to use different model having various pollutants and their interaction with photo chemistry, dry and wet dispersion reflecting the actual realistic atmosphere chemistry is recommended.

Currently there are some monitoring stations belong to Kuwait EPA distributed randomly at different locations within Kuwait urban areas. However, until today there are no monitoring stations installed within the oil production field areas. Therefore, the specific important conclusion of this study is that, there is a strong need to construction a new monitoring network close to all Kuwait Oilfields to measure the accurate impact of SO_2 concentrations and other pollutants concentrations emitted from flaring activities. In

additional, this work could be extended to include other pollutants such as NO_X, SO_2, CO, CO_2 and other organic components.

Since the Kuwait Oilfields emissions are not directly from a single source or one defined operation, investigation of pollution prevention opportunities other than 'end-of-pipe' treatment is highly recommended. Pollution prevention provides a wide range of options for reducing emissions to levels well below those provided by classical treatment methods. The highest priority of pollution prevention is given to source reduction, while 'end-of-pipe' treatment is usually kept as the last and unfavourable option.

It is necessity to reduce the amount of gas being flared in petroleum and oil related industries. New technologies are being developed to assist in the commercialization of associated gas reserves. Operation, maintenance and design of flare systems are improving. New ways of storing associated gas are being investigated. The selection among technologies, choosing between flaring, or maintaining a balance between climate change and other environmental concerns, regulatory frameworks need to allow for the best practicable choices to be made, rather than mandating a specific solution. Government regulatory policy needs to be sufficiently flexible to facilitate the choice of the management approach most appropriate for the project and the situation.

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Nomenclature and Abbreviations

Alpha-Numeric

ppb	parts per billion
ppm	parts per million
RH%	Relative Humidity in percentage
SPM	Suspended Particulates Matter
TSP	Total Suspended Particles
IA	Index of agreement
UTM	Universal Transverse Mercator
GOR	Gas Oil Ratio
NLR	Normal Lapse Rate of temperature
PBL	Planetary Boundary Layer
GMT	Greenwich Median Time
LST	Local Standard Time
MMWS	Mean Monthly Wind Speed
MMAT	Mean Monthly Ambient Temperature
E	Emissions
A	Activity rate
EF	Emission factor
ER	Overall emission reduction efficiency, %
MWt	Molecular Weight
T	Air temperature (°K)
Cp	Specific heat of dry air constant (J/(Kg °K)
Vs	Exit velocity (m/s)
rs	Stack inner radius (m)
Ts	Stack exit temperature (°K)
u	Wind Speed
ug/m3	micro gram per cubic meter
PE	Pollutant Emission in Tonnes
LA	Level of Activity

EF	Emission Factor
C	Concentration of emissions, in g/m^3, at any receptor located:
	x meters downwind from the emission source point
	y meters crosswind from the emission plume centreline
	z meters above ground level
H	Height of emission plume centerline above ground level, in m
L	Height from ground level to bottom of the inversion aloft, in m
P	Exponent depending upon atmospheric stability and the characteristics of the underlying surface (varies from about 0.1 to 0.3)
Q	Pollutant emission rate (mass per unit time)
U	Mean wind speed (m/s) at release height
H	Source height (m)
f	Crosswind dispersion parameter
Q	Source pollutant emission rate, in g/s
u	Horizontal wind velocity along the plume centerline, m/s
u_z	Wind speed at height
z	Above the ground in (m/s)
u_{10}	Wind speed at 10 m height
z_{10}	Measurement height specified by World Meteorological Organization for meteorological stations) in (m/s)
Hsl	Effective flare height (m)
Hs	Stack height above ground (m)
Hr	Net heat release rate (Joules per sec, J/s)
V	Volumetric flow rate to the flare (m^3/s)
fi	Volume fraction of each gas component
Hi	Net heating value of each component (J/g-mole)
Fr	Fraction of radiative heat loss
g	Acceleration due to gravity (m/s^2)

Greek Letters

B_v	Net heating value in Btu/scf
σ_z	Vertical standard deviation of the emission distribution, in m
σ_y	Horizontal standard deviation of the emission distribution, in m
σ_y	Standard deviation of lateral and vertical concentration distribution (m)
ρ	Density of air (kg/m^3)

Acronyms

KOC	Kuwait Oil Company
KPC	Kuwait Petroleum Corporation
KNPC	Kuwait National Petroleum Company
PIC	Petrochemical Industries Company
KEPA	Kuwait Environmental Public Authority
EPA	Environmental Protection Agency
KAAQS	Kuwait Ambient Air Quality Standards
AQMN	Air quality monitoring networks
KIA	Kuwait International Airport
ISC	Industrial Source Complex Model
ISCST3	Industrial Source Complex model for Short Term Model
NWS	National Weather Service
MPRM	Regulatory Models
OSHA	Occupational Safety and Health Organization
U.S. EPA	United States Environmental Protection Agency
ACGIH	Association of Occupational Health Practioners
WHO	World Health Organisation
CAA	American Clean Air Act
WSIA	Western Shuaiba Industrial Area
SEK	South East Kuwait
WK	West Kuwait
NK	North Kuwait

STD	Standard
STF	South Tank Farm
HP	High Pressure
LP	Low Pressure
AGRP	Acid Gas Removal Plant
GHG	Green House Gases
GC	Gathering Centers
BS	Booster Stations
CRU	Condensate Recovery Units
BS&W	Basic Sediment & Water
TV	Tank Vapours
TVC	Tank Vapour Compressor
AGRP	Acid Gas Removal Plant
MEPA	Metrology and Environmental Protection Agency
BTEX	Benzene, Toluene, Ethylbenzene and xylenes
PM	Particulate Matter
PM_{10}	Particulate matter smaller than 10 microns in diameter
CEMS	Continuous Emission Monitoring Systems
HAP	Hazardous Air Pollutants
SRU	Sulfur Recovery Unit
MAA	Mina Al-Ahmadi Refinery
API	American Petroleum Institute
GRI	Gas Research Institute
CMA	Chemical Manufacturers Association
CMB	Chemical Mass Balance
DALR	Dry Adiabatic Lapse Rate
NW	Northwest
SE	Southeast
DM	Decision Makers
PAH	Poly Cyclic Aromatic Hydrocarbon
NMHC	Non-methane hydrocarbons

CO_2 Carbon Dioxide

CO Carbon Monoxide

H_2S Hydrogen Sulfide

SO_2 Sulphur Dioxide

NO_2 & NO & N_2O Nitrogen Oxides

CH_4 Methane

VOCs   Volatile Organic Compounds

O3   Ozone

LPG   Liquefied Petroleum Gases

During this work the below papers has been published as mentioned below.

A.1 Journal Papers

1. Al-Hamad, K Kh. and A. R. Khan. **"Total Emissions from Flaring in Kuwait Oilfields"**, *American Journal of Environmental Sciences* 4(1), 2008, pp 31-38.
    http://www.scipub.org/fulltext/ajes/ajes4131-38.pdf

2. Al-Hamad, K Kh., Nassehi V. and A. R. Khan. **"Using a Simulation Tool to Model the Ground Level Concentrations of Green House Gases Emitted by Flaring in Petroleum Production in Kuwait Oilfields"**, *American Journal of Environmental Sciences* 4(5), 2008, pp 420-438.
    http://www.scipub.org/fulltext/ajes/ajes45420-438.pdf

3. Al-Hamad, K Kh., Nassehi V. and A. R. Khan. **"Impact of Green House Gases (GHG) Emissions from Oil Production Facilities at Northern Kuwait Oilfields: Simulated Results"**, *American Journal of Environmental Sciences* 4(5), 2008, pp 491-501.
    http://www.scipub.org/fulltext/ajes/ajes45491-501.pdf.

4. Al-Hamad, K Kh., Nassehi V. and A. R. Khan. **"Methane and Other Hydrocarbon Gas Emissions Resulting from Flaring in Kuwait Oilfields"**, *Proceedings Of World Academy Of Science, Engineering and Technology (PWASET) Journal,* Volume 34, October 2008, ISSN: 2070-3740.
    http://www.waset.org/pwaset/v34/v34-14.pdf

5. Khaireyah Kh. AL-Hamad, V. Nassehi and A. R. Khan . "**The Impact of SO_2 Emissions from Flaring Activities of Crude Oil Production Operation at West Kuwait Oilfields**". *Submit*

A.2 Conference Papers

1. Al-Hamad, K Kh., "**Total Emissions from Flaring in Kuwait Oilfields**" of abstract # **PDC-07- 82**, The 4th International Health, Safety, Environment and Loss Prevention Professional Development Conference and Exposition, "Business Excellence through HSE - 2007" conducted during 15th -17th April 2007, at Kuwait. *Certificate is attached*

2. Al-Hamad, K Kh, "**Wall Effects in Fixed and Fluidized Beds**", ECI conference "Computational Fluid Dynamics in Chemical Reaction Engineering IV." The conference was held from June 19 - 24, 2005 in Barga, Italy. *Certificate is attached.*

3. Al-Hamad, K Kh., "**Methane and Other Hydrocarbon Gas Emissions Resulting from Flaring in Kuwait Oilfields**", Conference of World Academy on Science, Engineering and Technology (WCSET 2008) on Computational Mathematics, OCTOBER 29-31, 2008, VENICE, ITALY, ISSN: 2070-3740, Volume 34, Article No. 14. *Certificate is attached*
   http://www.waset.org/pwaset/v34.html
   http://www.waset.org/lectures/Venice08.pdf.

A.3 Conference and Workshop Participation

1. 5th International Symposium on Naturally Occurring Radioactive Material (NORM IV), March 19th- 22nd, 2007 Seville, Spain. *Certificate is attached.*
   http://alojamientos.us.es/normv/

2. Workshop on "Environmental Impact Assessment", the conference was held from November 25 - 29, 2007 in Kuwait. ***Certificate is attached***
http://www.arabschool.org/
http://www.arabschool.org/Brochure_environmental_impact_assessment.pdf

3. The Ninth SPE International Conference on Health, Safety & Environment in Oil and Gas Exploration and Production, 15-17 April 2008, Nice, France.
http://www.spe.org/spe-site/spe/spe/meetings/HSE/2008/08HSE_Program.pdf

A.1: Abstract

Total Emissions from Flaring in Kuwait Oilfields

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Abstract: Kuwait is a major oil producing country and its economy directly depends on its export of crude and refined products. Kuwait Oil Company (KOC) is responsible for all exploration and production of crude oil in Kuwait. These activities result in the emission of gaseous pollutants to the atmosphere, particularly from the flaring of undesirable product and excess gases. For environmental and resource conservation reasons, KOC is required to minimize the amount of gas flared in order to control and reduce the emissions of major pollutants in the State of Kuwait and neighbors countries. In the present study the total emissions of primary pollutants associated from flaring activities from Kuwait oil field have been estimated. An inventory records the annual emissions of air pollutants: NO_x, SO_2, CO, CO_2, Methane and non-methane, Volatile Organic Compounds (VOC): resulting from oil production operations in the Kuwait Oil Fields. The emissions are generated from various point sources and aggregated to have total pollutants load of ambient air. Emissions of flaring pollutants are associated with all operations in Oil fields, Gathering Centers (GC), Boaster Stations (BS), Tank areas and other oil production related activities. The objective of this work was to obtain an accurate estimation of the total flare emission from oil production activities thereby aiding the effective planning of mitigation strategies to control and reduce the pollution from crude related operation.

Key words: Kuwait oilfields, accurate estimation, total flare emission, oil production activities

INTRODUCTION

Kuwait is major oil exporting country and its economy, growth and prosperity is heavily dependent on oil production. This activity is carried out by KOC, which produces oil from 14 fields, including the oldest giant Burgan oil field. Crude is processed through a network of 21 gathering centres, where gas and water are separated. The processed oil is exported or refined at Kuwait's large refining Industries. Separated gas that cannot be utilised economically is flared. This flaring produces a number of undesirable atmospheric emissions, including CO, CO_2, SO_2, H_2S, NOx and particulates ($PM_{2.5}$ and PM_{10}). These pollutants are also released from other activities associated with the production of crude oil, such as local power generation (Gas Turbines, Diesel Turbines, Gas Engines, Gas/Diesel Engines,) and heating operation (Gas Boilers, Gas Heater Furnaces).

In practice, these other sources of emissions are small compared with emissions from flaring. This is largely due to relatively low energy requirement of upstream oil processing in Kuwait, where oil is currently produced largely by natural depletion and energy demand is limited for production and export.

Flaring is usual method for the safe disposal of excess hydrocarbons. By burning these hydrocarbons, thereby converting them largely to carbon dioxide and water, their environmental impact is greatly reduced. For example, the global warming potential of methane is about 21 times than of CO_2.

To safe guard the environment, one should have a thorough knowledge of gaseous emissions resulting from the flaring of associated gaseous mixture of known composition on daily basis through combustion activities under several operating conditions. This helps in the control of gaseous emission from flares and thus in the protection of immediate and distant environment against environmental degradation due to air pollution.

A detailed literature search has been conducted to collect the most relevant publications relating average annual emissions of various air pollutants; NO_x, SO_2, CO_2, particulate matter and hydrocarbons; from oil production operations facilities in the world.

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Using a Simulation Tool to Model the Ground Level Concentrations of Green House Gases Emitted by Flaring in Petroleum Production in Kuwait Oilfields

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Abstract: Air pollution and its effects on the ecosystem has been a source of concern for many environmental pollution organizations in the world. In particular climatologists who are not directly involved in petroleum industry sometimes express concerns about the environmental impacts of gas emissions from flaring at well heads. For environmental and resource conservation reasons, flaring should always be minimized as much as practicable and consistent with safety considerations. However, any level of flaring has a local environmental impact, as well as producing emissions which have the potential to contribute to the global warming. In the present research the Industrial Source Complex (ISCST3) Dispersion Model is used to calculate the ground level concentrations of two selected primary pollutants (i.e. methane and non-methane hydrocarbons) emitted due to flaring in all of Kuwait Oilfields. In additional, the performance of the ISCST3 model is assessed, by comparing the model prediction with the observed concentration of methane and non-methane hydrocarbons obtained from the monitoring sites. The described model evaluation is based on the comparison of 50 highest daily measured and predicted concentrations of methane and non-methane hydrocarbons. The overall conclusion of this comparison is that the model predictions are in good agreement with the observed data (accuracy range of 60-95%) from the monitoring stations maintained by the Kuwait Environmental Public Authority (EPA). A specific important conclusion of this study is that, there is a need for a proper emission inventory strategy for Kuwait Oil Company (KOC) as means of monitoring and minimizing the impact of methane and non-methane hydrocarbons released because of flaring activities.

Key words: Kuwait oilfields, ISCST3 model, flare activities, Kuwait-EPA monitoring station

INTRODUCTION

Kuwait is a major oil exporting country and its economy, growth and prosperity is heavily dependent on oil production. KOC is at the heart of the petroleum production in Kuwait. The oilfields involve various types of industrial operations and activities, such as drilling, production of crude oil, fuel combustion and flaring of gases which all result in gas emission into atmosphere. In practice, all other sources of emissions are small compared with emissions from flaring. Consequently, a wide range of air pollutant emissions is generated on various sites. Such emissions include carbon dioxide, nitrogen and sulfur oxide gases, methane and non-methane hydrocarbons and suspended particulates.

A comprehensive impact assessment study has been previously published[1] which provides an account and estimates of all emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields. This inventory records the annual emissions of air pollutants: NO_x, SO_2, CO, CO_2, methane and non-methane hydrocarbons. The emissions are generated from various point sources and aggregated to obtain total pollutants load of ambient air. The emissions of pollutants from the flaring associated with all types of operations in the oilfields, Gathering Centers (GC), Booster Stations (BS), tank areas and other oil production related activities.

In the present research the previously published data are used as the necessary input for the ISCST3 model. Obviously methane and non-methane hydrocarbons are not the only green house gasses which result from flaring activities.

However these gases provide a typical sample which can be used as an input for the ISCST3 model to

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Methane and Other Hydrocarbon Gas Emissions Resulting from Flaring in Kuwait Oilfields

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Abstract—Air pollution is a major environmental health problem, affecting developed and developing countries around the world. Increasing amounts of potentially harmful gases and particulate matter are being emitted into the atmosphere on a global scale, resulting in damage to human health and the environment. Petroleum-related air pollutants can have a wide variety of adverse environmental impacts. In the crude oil production sectors, there is a strong need for a thorough knowledge of gaseous emissions resulting from the flaring of associated gas of known composition on daily basis through combustion activities under several operating conditions. This can help in the control of gaseous emission from flares and thus in the protection of their immediate and distant surrounding against environmental degradation.

The impacts of methane and non-methane hydrocarbons emissions from flaring activities at oil production facilities at Kuwait Oilfields have been assessed through a screening study using records of flaring operations taken at the gas and oil production sites, and by analyzing available meteorological and air quality data measured at stations located near anthropogenic sources. In the present study the Industrial Source Complex (ISCST3) Dispersion Model is used to calculate the ground level concentrations of methane and non-methane hydrocarbons emitted due to flaring in all over Kuwait Oilfields.

The simulation of real hourly air quality in and around oil production facilities in the State of Kuwait for the year 2006, inserting the respective source emission data into the ISCST3 software indicates that the levels of non-methane hydrocarbons from the flaring activities exceed the allowable ambient air standard set by Kuwait EPA. So, there is a strong need to address this acute problem to minimize the impact of methane and non-methane hydrocarbons released from flaring activities over the urban area of Kuwait.

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I. INTRODUCTION

KUWAIT is shaped roughly like a triangle, surrounded by land on its northern, western and southern sides and sea on its eastern side, with 195 kilometers of coastlines, has an area of about 1.8×10^4 square kilometers and its most distant points, are about 200 kilometers north to south and 170 kilometers east to west. The bulk of the Kuwaiti populations live in the coastal area of Kuwait. Smaller populations inhabit the nearby city of Al-Jahrah. Kuwait's land is mostly flat and arid with little or no ground water.

Crude oil is the only energy viable source and the major generating commodity in Kuwait. Kuwait Oil Company (KOC) is a state owned subsidiary of Kuwait Petroleum Corporation (KPC) that explores, produces and exports crude oil from the State of Kuwait. With a production of over two million barrels of oil a day it is one of the largest oil producing companies in the world. KOC is organized into four main producing areas: North Kuwait (NK), West Kuwait (WK) and South and East Kuwait (SEK). The second largest oil field in the world is Burgan Field which is managed and operated since 1938. Kuwait Oil Company manages the production and export of oil and gas with the associated facilities from more than twelve developed oil fields in the state of Kuwait. Crude is processed through a network of 21 gathering centres, where gas and water are separated. The processed oil is exported or refined at Kuwait's large refining Industries. Separated gas that cannot be utilized economically is flared. This flaring produces a number of undesirable atmospheric emissions, including CO, CO_2, SO_2, H_2S, NOx and particulates ($PM_{2.5}$ and PM_{10}). These pollutants are also released from other activities associated with the production of crude oil, such as local power generation (Gas Turbines, Diesel Turbines, Gas Engines, Gas Diesel Engines), and heating operation (Gas Boilers, Gas Heater Furnaces). Ambient air in Kuwait has the highest hydrocarbon concentrations by comparison to any developed country. The oilfields spread over the State and split off into four main parts of North Field, West Field, South and East Field that are locally administered at the site headquarters. Approximate distance from Ahmadi city: North Field is 70 miles (112 Km), West Field is 38 miles (60 Km) and South East Field is 12 miles (20 Km) (See Fig. 1).

Impact of Green House Gases (GHG) Emissions from Oil Production Facilities at Northern Kuwait Oilfields: Simulated Results

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Abstract: Air pollution and its effects on the ecosystem has been a source of concern for many environmental pollution organizations in the world. In particular climatologists who are not directly involved in petroleum industry sometimes express concerns about the environmental impacts of gaseous emissions from flaring at various despised points. For environmental and resource conservation reasons, flaring should always be minimized as much as practicable and be consistent with safety considerations. However, any level of flaring has a local environmental impact, as well as producing emissions which have the potential to contribute to the global warming. In this study the Industrial Source Complex (ISCST3) Dispersion Model is used to calculate the ground level concentrations of two selected primary pollutants (i.e. methane and non-methane hydrocarbons) emitted from flaring activities at oil production facilities at North Kuwait. Model validation is based on the comparison of the 50 highest daily measured values and their respective predicted concentrations of methane and non-methane hydrocarbons. At discrete receptors, it is noticed that the predicted values are in good agreement with the observed data (accuracy range of 60-90%) from the monitoring stations maintained by the Kuwait Environmental Public Authority (EPA). The predicted results are based on emission inventories. Therefore, accurate emission inventory strategy for Kuwait Oil Company (KOC) as means of monitoring and minimizing the impact of methane and non-methane hydrocarbons emissions is of prime importance.

Key words: Kuwait oilfields, iscst3 model, flaring, air pollution, green house gases

INTRODUCTION

Kuwait is a major oil exporting country and its economy, growth and prosperity is heavily dependent on oil production. KOC is at the heart of the petroleum production in Kuwait. The oilfields involve various types of industrial operations and activities, such as drilling, production of crude oil, fuel combustion, and flaring of gases which all result in gas emission into atmosphere. In practice, all other sources of emissions are small compared with emissions from flaring. Consequently, a wide range of air pollutant emissions is generated on various sites on oil fields. Such emissions include carbon dioxide, nitrogen and sulfur oxide gases, methane and non-methane hydrocarbons and Suspended Particulates Matter (SPM).

A comprehensive emission inventories from Kuwait Oilfields has been published[1], which provides a comprehensive account and estimates of all emissions of primary pollutants associated from flaring activities in the Kuwait Oilfields. This inventory records the annual emissions of air pollutants: NO_X, SO_2, CO, CO_2, methane and non-methane hydrocarbons. The emissions are generated from various point sources and aggregated to obtain total pollutants load of ambient air in and around oil fields. The emissions of pollutants from the flaring associated with all types of operations in the oilfields, Gathering Centers (GC), booster stations (BS), tank areas and other oil production related emission activities.

In this work the data are used as the necessary input for the ISCST3 model. Obviously methane and non-methane hydrocarbons are not the only pollutants gasses, which result from flaring activities, but their high concentrations in ambient air is a matter of grave concern. Methane and non-methane hydrocarbons are

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The Impact of SO$_2$ Emissions from Flaring Activities of Crude Oil Production Operation at West Kuwait Oilfields

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Abstract: An air quality screening study was performed to assess the impacts of SO$_2$ emissions emitted by flaring in West Kuwait (WK) oilfields. A preliminary air quality model simulation was performed to observe the transport and dispersion patterns of SO$_2$, which is the main pollutant emitted from flaring in WK oilfields. The meteorological wind and temperature fields were generated with the Industrial Source Complex model for Short Term Model (ISCST3), a diagnostic meteorological model that used surface observations and upper air soundings from one year hourly record data for year 2006 obtained from the Kuwait International Airport (KIA) weather station. Model results were compared with the 50 highest daily value of SO$_2$ measured taken from the nearest Kuwait-EPA air quality-monitoring network.

The significant conclusion of this study is that the existing locations of Kuwait-EPA monitoring stations are located far away from WK Oilfields area. Therefore, there is a need to construction a new monitoring station close to West Kuwait Oilfields to measure the accurate impact of SO$_2$ emissions emitted from flaring activities. Also, the specific important conclusion of this study is that, there is a need for a proper emission inventory strategy for KOC as means of monitoring and minimizing the impact of SO$_2$ released from Crude Oil Production Operation activities at WK oilfields.

1. Introduction

Air pollution is a major environmental health problem, affecting developed and developing countries around the world. Increasing amounts of potentially harmful gases and particles are being emitted into the atmosphere on a global scale, resulting in damage to human health and the environment. It is damaging the resources needed for the long-term sustainable development of the planet. The petroleum industry is committed to improving air quality, while continuing to meet the energy demands of our nation. Cleaning the air requires a sound scientific understanding of the sources and impacts of air contaminants. According to Hamzeh[1], the World Bank estimates that the transport sectors' contribution to global SO2 emissions is between 2-6%. With this in mind, the importance of capping the SO2 emissions from WK oilfields is indisputable. In order to plan the required fuel quality for the existing and planned flaring design, it is imperative to consider the variation of air pollutant concentrations due to different types of fuels as well as the behaviour of these pollutants in response to the prevailing meteorological conditions.

M.S. AL-Rashidi[2] et al. [2005] have presented the impact of SO$_2$ emissions from power stations in the state of Kuwait and the Industrial Source Complex model for Short Term(ISCST3) model is utilized to measured the sptial and temporal variations of SO$_2$ over residential area. The study indicates that the emissions of SO$_2$ from the existing power stations exceed the allaowable daily ambient air quality standard specified by Kuwait-EPA by as much as 600 μg/m^3 and the weather patteen in Kuwait, especially the mean prevailing wind direction, contributes to having high concentrations of SO$_2$ at the Doha power generation complex. A.A. Ramadan[3] et al., have presented the total SO$_2$ emissions from power stations and evaluation of their impact in Kuwait and the results obtained using the Industrial Sources Complex Short Term (ISCST3) model to calculate the SO$_2$ concentration resulting from existing power

American Society of Safety Engineers
Kuwait Chapter

Certificate Of Appreciation

This certificate of appreciation is awarded to

Khaireyah Kh. AL - Hamad

In Recognition of

his / her efforts in Presenting a Paper in

The 4th International Health, Safety, Environment and Loss Prevention Professional Development Conference and Exposition,

"Business Excellence Through HSE – 2007"
conducted during 15th – 17th April 2007, at Kuwait.

Ujwal Ritwik
President - Organizing committee

Fadhel Al-Ali
Chairman - Organizing committee

A2.2A: Poster of "Wall Effects in Fixed and Fluidized Beds", ECI conference "Computational Fluid Dynamics in Chemical Reaction Engineering IV."

Technical Paper in Process Engineering

By
Khairyah Al-Hamad

Poster Presentation: Computational Fluid Dynamics in Chemical Reaction Engineering IV,19-24 June 2005, Il Ciocco Hotel and Conference Center Barga, Italy.

SYNOPSIS

- Solid-Fluid system in oil operation (Mass, Heat and Fluid transport).
- Fixed and Fluidized beds application in transport phenomena.
- The influence of column diameter (wall effect) on characteristics of fixed and fluidized beds.

Introduction

Fluidization

Fluidization is defined as the process by which solid particles are transformed into a fluid like state through suspension in a gas or liquid.

- A simple example of particle fluidization is the vacuum cleaner in your home, where high airflow provided by the vacuum cleaner is used to suspend dust particles and carry them into another chamber where they are then disengaged from the gas.

Fluidization

Definition

- The upward flow of fluid through a bed of particles gives rise to a pressure drop and when this is equal to the weight of the bed per unit area of cross section particles are freely supported in the fluid and they become free to move relative to another.

- A fluidized bed is a packed bed through which fluid flows at such a high velocity that the bed is loosened and the particle-fluid mixture behaves as though it is a fluid, Thus, when a bed of particles is fluidized, the entire bed can be transported like a fluid, if desired. oth gas and liquid flows can be used to fluidize a bed of particles.

- The most common reason for fluidizing a bed is to obtain vigorous agitation of the solids in contact with the fluid, leading to excellent contact of the solid and the fluid. This means than early uniform temperatures can be maintained even in highly exothermic reaction situations where the particles are used to catalyze a reaction in the species contained in the fluid.
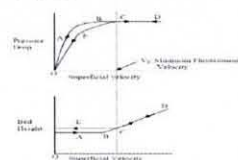
Application in Oil Production

- Drilling, removing cuts from oil bore by transporting mud.
- Dehydration, DEG or TEG.
- Sweetening, removing of free sulfur component from crude or gas. (H2S, CH3SCH3)

The Advantages of Fluidized Beds

- Liquid like behavior, easy to control and automate.
- Rapid mixing, uniform temperature and concentrations.
- Resists rapid temperature changes, hence responds slowly to changes in operating conditions and avoids temperature run-away with chemical reactions and mass and heat transfer processes (Absorption- Dehydration- Sweetening).

- Circulate solids between fluidized beds for heat exchange.
- Applicable for large or small scale operations.
- Heat and mass transfer rates are high, requiring smaller surfaces.

Fixed and Fluidized Bed

- Fixed beds
  DP less
  Low Mass, Heat Transfer
  Low Temp. and Concentration
- Fluidized beds
  DP High
  High Mass, Heat Transfer
  High Temp. and Concentration
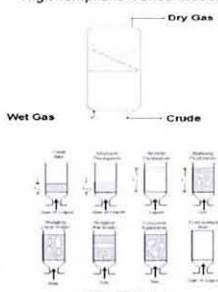
Applications of Fluidized Beds

Fluidization is extremely useful and very common in the process Industries. Examples of fluidization are given as follows;

- Reactors
- Adsorption/Absorption
- Cracking hydrocarbons
- Carbonization
- Calcinations
- Heat exchange
- Drying operations
- Coating(exp:metals with polymer)
- Solidification/Granulation
- Growth of particles
- Bio fluidization
- Others

Fluidized beds are also helpful for the removal of pollutants from the gas before its release into the atmosphere.

Wall Effect

The wall effects are also important in transportation of solid suspension, or solid slurries. Its application in oil industry in oil extraction, transportation to gathering center is very necessary for providing the right pumps.

There is a need for correlations for the wall effect on e for common suspension packing such as spheres. These should be in the form of equations suitable for use in computer simulations and design calculations.

The investigations of wall effect in fluidized systems fall in two main categories:

1. Wall Effect in Fixed Bed
2. Wall Effect in Fluidized Bed

Objectives

- To Investigate the effect of Liquid and Solid Properties on terminal velocityand bed expansion characteristic in liquid fluidized bed.

- To study the bed characteristics and to develop a theoretical model to account for wall effect in narrow fixed and fluidized beds.

Overview

- The expansion characteristics of fluidized beds and the settling rates of suspensions have been for last half century and many empirical expressions have been suggested.

- In this current research project, their reliability is examined on the basis of the accuracy by which they represent the experimental data, and an attempt is made to develop a relation to cover the entire range of interest of both Galileo number and voidage.

- Existing equations dealing with the expansion characteristics of fluidized beds and the settling rates of suspensions were compared and the best generalized equationwhich is has been reported.

Table 1: Summary of published relations for effect of voidage on sedimentation and fluidization velocities.

Goals Achieved

- Fluidization characteristic methods are discussed in detail with the constants in the expression as a function of the properties of the system, including wall effects.
- The selected experimental data were compared with equations covering the wide range of both Galileo number and voidage including wall effect. (Empirical Equations)
- The influence of the column diameter, expressed in terms of the ratio of particle to vessel diameter d/D, has been incorporated in to relationship, to achieve a generalized equation that is applicable for the experimental data.

Nomenclature

Experimental Data and Analysis of Models

Models Showing Wall Effects For Fixed And Fluidized Beds
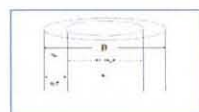
Theoretical models of fixed bed and fluidized bed of spherical particles for wall effects;

- The cylindrical column is hypothetically divided into two regions, core and wall region.
- In core the void fraction is uniform and equal to core void fraction eC while in wall zone, It varies from eC to unity adjacent to the wall where there is point contact and void fraction is unity.

Models Showing Wall Effects For Fixed And Fluidized Beds

The ratio of differences in the areas of cross-section can be equated to the ratio between the differences of void fractions as:

$$\frac{\varepsilon_x - \varepsilon_C}{1 - \varepsilon_C} = \frac{\Lambda_x - \Lambda_C}{\Lambda_T - \Lambda_C}$$

Void Fraction in the wall region is given as:

$$\varepsilon_w = \frac{\int_0^{\pi}\int_0^{d}\varepsilon_x\,x\,dx\,d\theta}{\int_0^{\pi}\int_0^{d}x\,dx\,d\theta}$$

When x =0, ex =1, and for x = d, ex = eC

The integration results:

$$\varepsilon_w = \frac{1 + \varepsilon_C}{2}$$

For an average value of void fraction the cumulative values are worked out by multiplying individual values of void fraction with its corresponding areas:

$$\varepsilon_{av} = \frac{\varepsilon_C \frac{\pi}{4}(D - 2n_0 d)^2 + \varepsilon_w\left\{\frac{\pi}{4}[D - (D - 2n_0 d)^2]\right\}}{\frac{\pi}{4}D^2}$$

On simplification;

$$\varepsilon_{av} = \varepsilon_C + (1 - \varepsilon_C)\frac{2n_0 d}{D}\left(1 - \frac{n_0 d}{D}\right)$$

Where;
D: Pipe diameter, d: Particle diameter, e : Voidage or Void fraction, n_0 : Index
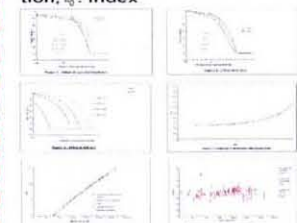
Discussion

- The above equation is for an average value of void fraction for any container, narrow or wide.
- The value of index no = 0.4 which is assessed for fixed and fluidized bed conditions.
- The value of index no is function of fluidization characteristics, Galileo number and d/D.
- The wall correlation model could be applied to a fluidization system from minimum fluidized velocity to fully expanded bed of voidage unity.

CONCLUSION

- The Equation is simple to obtain solutions for practical problems without the use of iterative procedures.
- The correlation coefficient between experimental and computed results is 0.99999.
- The Equation gives a simple and satisfactory relationship between particle concentration, or voidage, and sedimentation of fluidization velocity for systems composed of uniform spheres dispersed in a liquid.
- The equation has the advantage of being simple in form and of being applicable over a wide range of system properties and voidage. Other expressions, which have been proposed in the literature, are generally more complex or more restricted in their applications.

Recommendation

Implementation of the subject in Oil production will be beneficial in the following;

- The performance of the existing production, sweetening, dehydration and other separa tion processing units will be improved by including wall-effects.
- In future design calculations and computer simulations this advancement has to be integrated to yield correct and precise results.

A2.2B: Certificate of "Wall Effects in Fixed and Fluidized Beds", ECI conference "Computational Fluid Dynamics in Chemical Reaction Engineering IV."

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Oct. 3, 2005

CERTIFICATE OF PARTICIPATION

This letter certifies that **Khairyah Al-Hamad (Kuwait Oil Company, Kuwait)** attended and participated in the ECI conference "**Computational Fluid Dynamics in Chemical Reaction Engineering IV**." The conference was held from June 19 – 24, 2005 in Barga, Italy.

Engineer Al-Hamad presented the following paper at the conference:
Wall Effects in Fixed and Fluidized Beds

Please do not hesitate to contact me if any further confirmation is necessary.

Regards,

Kevin M. Korpics
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WCSET 2008

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In technical presentation, recognition and appreciation of research contributions to the ICCM 2008 : International Conference on Computational Mathematics

ArdilC. Chair
WCSET 2008

Venice, Italy
October 29-31, 2008

A3.1: Certificate of Conference "5th International Symposium on Naturally Occurring Radioactive Material"

NORM V Symposium
UNIVERSIDAD DE SEVILLA
E.T.S. ARQUITECTURA
DEPARTAMENTO DE FISICA
APLICADA 2
Av. de la Reina Mercedes 4
E-41012 Sevilla, Spain

NORM V
5ᵗʰ International Symposium
on NORM

5ᵗʰ International Symposium on
Natural Occurring Radioactive
Material
March 19ᵗʰ – 22ⁿᵈ, 2007
SEVILLE, SPAIN
http://www.congreso.us.es/normv
e-mail: normv@us.es

The Organizing Committee of the 5th International Symposium on Natural Occurring Radioactive material (NORM V)

CERTIFIES

that **Khairyah AL-Hamad** attended the 5ᵗʰ International Symposium on Natural Occurring Radioactive Material (NORM V), held in Seville, Spain during 19ᵗʰ-22ⁿᵈ March, 2007.

On behalf of the Organizing Committee

G. Manjón
Secretary

R. García-Tenorio
Chairman

Organized by the Universidad de Sevilla in cooperation with

IAEA
International Atomic Energy Agency
The International Atomic Energy Agency.

CSN CONSEJO DE
SEGURIDAD NUCLEAR
Consejo de Seguridad Nuclear.

Universidad de Huelva.

Workshop Certificate

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(ASST)

Sponsored by Scientific Organizations from the State of Kuwait, Arab Republic
of Syria & Republic of Lebanon

(State of Kuwait)

Certifies That

Eng. Khairyeh Qheefan Al-Hamad

Has Attended The Workshop On

" Environmental Impact Assessment "

Held at Kuwait Foundation for the Advancement of Sciences (KFAS)

In The State Of Kuwait During November 25 - 29, 2007

الأستاذ الدكتور علي عبد الله الشملان

Prof. Ali A. Al-Shamlan

عضو هيئة الإشراف

MEMBER - ADVISORY COMMITTEE (ASST)

شهادة إتمام حلقة دراسية

شهد المدرسة العربية للعلوم والتكنولوجيا

المؤسسات العلمية المساهمة في المدرسة من

دولة الكويت ـ الجمهورية العربية السورية ـ الجمهورية اللبنانية

(دولة الكويت)

أن م/ **خيرية قحيفان الحمد**

قد أتمت الحلقة الدراسية حول

" **تقييم المردود البيئي** "

التي عُقدت في مؤسسة الكويت للتقدم العلمي بدولة الكويت

خلال الفترة من 25 – 29 نوفمبر 2007

الدكتور جاسم محمد بشارة

Dr. Jasem M. Besharah

رئيس مجلس إدارة المدرسة بدولة الكويت

CHAIRMAN, KUWAIT OFFICE (ASST)

KUWAIT OIL COMPANY(K.S.C)   شـركة نفـط الكـويت (ش.م.ك)

Presented to:

Khairyah Al-Hamad

In appreciation of your participation in the C&MD HSE Award 2007.

With the Compliments of
The C&MD HSE Award Committee 2007

Mohammed Al-Fodari
Chairman of the Committee

Appendix B

Meteorological Data for year 2006

Table B.1: A Sample of an input meteorically data file to the ISCST3 Model generated by using PCRAMET

Year	Month	Day	HR	Wind Direction	Wind Speed (m/s)	Temp. (K)	Stability Class	Mixing Height (m)
6	1	1	1	181	1.00	282.0	7	549.0
6	1	1	2	178	1.00	281.5	7	549.0
6	1	1	3	214	1.54	278.7	7	549.0
6	1	1	4	233	2.57	278.7	6	549.0
6	1	1	5	233	1.00	278.2	5	20.4
6	1	1	6	262	2.06	278.2	4	79.1
6	1	1	7	275	1.54	278.2	3	137.8
6	1	1	8	273	2.06	280.9	2	196.6
6	1	1	9	247	2.57	283.2	2	255.3
6	1	1	10	251	1.00	285.4	1	314.0
6	1	1	11	264	2.57	287.6	2	372.8
6	1	1	12	196	3.60	289.3	2	431.5
6	1	1	13	203	3.60	290.4	3	490.3
6	1	1	14	209	3.60	290.9	3	549.0
6	1	1	15	212	4.12	291.5	4	549.0
6	1	1	16	224	3.09	290.9	5	567.0
6	1	1	17	211	2.57	289.3	5	593.8
6	1	1	18	207	2.57	288.2	6	620.6
6	1	1	19	214	1.00	285.9	7	647.4
6	1	1	20	207	1.00	284.3	7	647.2
6	1	1	21	230	1.54	283.2	7	701.1
6	1	1	22	232	1.00	282.0	7	727.9
6	1	1	23	250	2.57	281.5	6	754.7
6	1	1	24	250	1.54	280.9	7	781.5

A sample shown the structure of the upper air meteorological data file

used to compute the temperature inversion layer for one day for year 2006.

Complete listing of Fine Structure file
File: C:\Metgraph\ARCHIVE\06010111.38e

Started at   1 January 2006 11:38 UTC

Station :   582
Location :   29.24 N 47.97 E   56 m/MSL

Sounding type : PTU GPS
RS-number   : 445304107
Sounding processor serial number: 0

Ground check :   Ref   RS   Corr

 Pressure   :   2.3   0.0   2.3
 Temperature : -0.1   0.0 -0.1
 Humidity   :   4   0   4

Clouds   : 00901/
Special 1 : /////
Special 2 : /////

Telemetry noise level : 98 %

            P   T   U
Accepted (%) : 89.3   96.4 96.1
Replaced (%) : 9.3   2.2   2.5
Rejected (%) : 1.4   1.4   1.4

GPS data quality
   Valid raw wind ratio   : 87.0 %
   Valid raw wind on 5 ratio : 87.0 %
   Invalid raw wind on 4 ratio :   4.0 %
   Poor PDOP ratio   :   4.0 %
   Unidentified signals ratio :   0.0 %
   Mean satellite track count :   6.4
   Mean track count valid   :   7.1
   Gaps over 1 min   :   0.0 min

Reason for termination : Increasing pressure

Time Pressure Height Temperature RH Dewp Significance flags

   min s   hPa   gpm   deg C   % deg C Automatic Operator

 0 0 1018.0   56   18.0   25 -2.3 TU   TU
 0 2 1016.5   68   17.4   26 -2.3
 0 4 1015.7   75   17.1   27 -2.0
 0 6 1014.7   83   16.7   27 -2.4
 0 8 1013.7   91   16.7   27 -2.4
 0 10 1013.0   98   16.6   27 -2.4
 0 12 1012.0   106   16.5   27 -2.5

0 14	1011.7	108	16.5	27	-2.5
0 16	1011.3	112	16.4	27	-2.6
0 18	1011.0	114	16.4	27	-2.6
0 20	1010.5	118	16.3	27	-2.7
0 22	1010.0	122	16.3	27	-2.7
0 24	1009.3	129	16.3	27	-2.7
0 26	1008.0	139	16.2	28	-2.3
0 28	1006.8	149	16.0	28	-2.5 TU TU
0 30	1005.8	158	16.0	28	-2.5
0 32	1004.9	166	16.0	28	-2.5
0 34	1003.6	176	15.9	28	-2.6
0 36	1002.4	187	15.8	28	-2.6
0 38	1001.2	197	15.7	28	-2.7
0 40	1000.0	207	15.6	28	-2.8
0 42	998.7	218	15.5	28	-2.9
0 44	997.3	230	15.3	29	-2.6
0 46	996.1	240	15.3	29	-2.6
0 48	994.8	251	15.2	29	-2.7
0 50	994.1	257	15.1	29	-2.8
0 52	993.1	265	15.0	29	-2.9
0 54	991.9	275	14.9	29	-2.9
0 56	990.7	286	14.8	29	-3.0
0 58	989.0	300	14.7	30	-2.7
1 0	987.3	315	14.7	30	-2.7
1 2	986.6	321	14.6	30	-2.8
1 4	985.7	329	14.5	30	-2.8
1 6	984.5	339	14.4	30	-2.9
1 8	983.5	348	14.3	30	-3.0
1 10	982.5	356	14.2	30	-3.1
1 12	981.6	364	14.2	29	-3.6
1 14	980.1	376	14.0	30	-3.3
1 16	978.7	389	13.9	31	-2.9
1 18	977.7	397	13.8	30	-3.4
1 20	976.8	405	13.8	30	-3.4
1 22	975.4	418	13.6	31	-3.2
1 24	974.2	428	13.5	31	-3.3
1 26	973.2	436	13.4	31	-3.4
1 28	972.3	444	13.4	31	-3.4
1 30	971.1	454	13.2	31	-3.5
1 32	970.1	463	13.2	32	-3.1
1 34	969.2	471	13.2	32	-3.1
1 36	968.2	479	13.1	32	-3.2
1 38	967.3	487	13.0	31	-3.7
1 40	966.4	495	12.9	31	-3.8
1 42	965.4	504	12.9	31	-3.8
1 44	964.2	514	12.8	31	-3.9
1 46	963.3	522	12.7	30	-4.4
1 48	962.4	530	12.6	29	-4.9
1 50	961.4	538	12.6	29	-4.9
1 52	960.2	549	12.7	25	-6.8
1 54	959.1	559	12.7	21	-9.0
1 56	958.1	567	12.7	21	-9.0
1 58	957.0	577	12.7	21	-9.0
2 0	955.6	590	12.6	22	-8.5
2 2	954.6	598	12.5	21	-9.2
2 4	953.7	606	12.4	21	-9.3
2 6	953.0	612	12.4	21	-9.3
2 8	951.8	622	12.3	21	-9.4
2 10	950.9	630	12.2	21	-9.5
2 12	950.2	637	12.2	21	-9.5

2 14	948.8	649	12.1	21	-9.6
2 16	947.4	661	12.0	21	-9.6
2 18	946.0	673	12.0	21	-9.6
2 20	944.9	684	12.0	21	-9.6
2 22	943.7	694	12.0	21	-9.6
2 24	942.1	708	11.9	21	-9.7
2 26	941.4	714	11.8	21	-9.8
2 28	940.8	720	11.8	21	-9.8
2 30	939.8	728	11.7	21	-9.9
2 32	938.5	741	11.6	21	-10.0
2 34	937.3	751	11.5	21	-10.1
2 36	936.4	759	11.4	21	-10.1
2 38	934.8	773	11.2	21	-10.3
2 40	933.4	785	11.1	21	-10.4
2 42	932.3	796	11.0	22	-9.9
2 44	931.4	804	10.9	22	-10.0
2 46	930.2	814	10.8	22	-10.1
2 48	929.1	824	10.8	22	-10.1
2 50	928.4	830	10.6	22	-10.2
2 52	927.5	838	10.5	23	-9.7
2 54	926.4	848	10.5	23	-9.7
2 56	925.5	857	10.4	23	-9.8
2 58	924.6	865	10.4	23	-9.8
3 0	923.9	871	10.3	23	-9.9
3 2	922.6	883	10.2	23	-10.0
3 4	921.4	893	10.1	24	-9.5
3 6	920.5	901	10.0	24	-9.6
3 8	919.6	909	10.0	24	-9.6
3 10	918.5	919	10.0	24	-9.6
3 12	917.4	930	9.9	24	-9.7
3 14	916.7	936	9.9	24	-9.7
3 16	915.6	946	9.8	24	-9.8
3 18	914.5	956	9.8	24	-9.8
3 20	913.4	966	9.7	24	-9.9
3 22	912.5	974	9.7	24	-9.9
3 24	910.9	988	9.7	25	-9.4
3 26	909.6	1000	9.6	24	-10.0
3 28	908.5	1010	9.5	25	-9.5
3 30	907.4	1021	9.4	25	-9.6
3 32	906.3	1031	9.3	25	-9.7
3 34	904.9	1043	9.2	25	-9.8
3 36	903.6	1055	9.1	25	-9.9
3 38	902.9	1061	9.0	25	-10.0
3 40	901.8	1071	8.9	25	-10.1
3 42	900.7	1081	8.9	25	-10.1
3 44	899.9	1089	8.9	25	-10.1
3 46	898.5	1101	8.9	25	-10.1
3 48	897.0	1115	8.8	26	-9.6
3 50	896.4	1122	8.8	26	-9.6
3 52	895.5	1130	8.7	26	-9.7
3 54	894.4	1140	8.6	26	-9.8
3 56	893.3	1150	8.5	26	-9.9
3 58	892.2	1160	8.4	27	-9.5
4 0	891.3	1168	8.3	27	-9.6
4 2	890.3	1178	8.2	27	-9.7
4 4	889.2	1188	8.1	27	-9.8 T T
4 6	888.1	1198	8.1	28	-9.3
4 8	887.2	1206	8.1	28	-9.3
4 10	885.9	1218	8.1	29	-8.9
4 12	884.2	1234	8.0	29	-8.9

4 14	883.5	1240	7.9	29	-9.0	
4 16	882.9	1246	7.8	26	-10.5	
4 18	881.8	1256	7.8	23	-12.0	
4 20	880.7	1267	7.9	20	-13.7	
4 22	879.7	1277	7.9	17	-15.7	
4 24	878.8	1285	8.0	16	-16.3	
4 26	877.7	1295	8.1	13	-18.7	
4 28	876.4	1307	8.3	12	-19.5	
4 30	875.2	1319	8.3	12	-19.5	
4 32	874.3	1327	8.3	11	-20.5	
4 34	873.2	1337	8.3	11	-20.5	
4 36	871.8	1351	8.2	11	-20.6	
4 38	871.1	1357	8.2	11	-20.6	
4 40	870.5	1363	8.2	11	-20.6	
4 42	869.4	1373	8.2	11	-20.6	
4 44	868.4	1383	8.1	11	-20.6	
4 46	867.3	1393	8.0	11	-20.7	
4 48	866.4	1401	8.0	11	-20.7	
4 50	865.4	1411	8.0	11	-20.7	
4 52	864.3	1421	7.8	10	-22.0	
4 54	863.1	1433	7.7	10	-22.0	
4 56	862.0	1444	7.6	10	-22.1 T	T
4 58	861.0	1454	7.7	9	-23.2	
5 0	859.7	1466	7.7	9	-23.2	
5 2	858.9	1474	7.7	8	-24.6	
5 4	858.0	1482	7.8	7	-26.0	
5 6	857.0	1492	7.8	7	-26.0	
5 8	856.1	1500	7.8	7	-26.0	
5 10	855.3	1508	7.8	7	-26.0	
5 12	854.7	1514	7.7	7	-26.0	
5 14	853.6	1524	7.7	7	-26.0	
5 16	852.6	1534	7.7	7	-26.0	
5 18	851.8	1542	7.6	7	-26.1	
5 20	850.7	1552	7.5	7	-26.2	
5 22	849.9	1560	7.5	6	-27.9	
5 24	849.1	1568	7.5	6	-27.9	
5 26	848.0	1578	7.5	6	-27.9	
5 28	847.2	1586	7.5	6	-27.9	
5 30	846.2	1596	7.4	6	-27.9	
5 32	845.3	1604	7.4	6	-27.9	
5 34	844.5	1612	7.3	6	-28.0	
5 36	843.9	1618	7.3	5	-30.0	
5 38	842.7	1630	7.3	5	-30.0	

Table B.2: A Sample of Kuwait Climatologically data for year 2006

CLIMATOLOGICAL SECTION

HOURLY VALUES OF STATION : 1500

DATE   01 st

MON   JAN   YEAR   2006

TIME	VISIBILITY	CLOUDS	WIND DIR	WIND SPD	DRY BULB	DEW POINT	QFF	PRES WX	WET BULB	VAPOUR	REL. HUM.	QFE	QNH
local	km	octas	degree	m/s	degrees C	degrees C	hpa	coded	degrees C	hpa	%	hpa	hpa
0000	10.0	0	250	03	09.2	04.2	1024.7	00	07.0	08.3	71	1017.7	1023.4
0100	10.0	0	000	00	08.7	01.1	1024.6	00	05.6	06.6	59	1017.6	1023.3
0200	10.0	0	000	00	08.0	03.1	1024.3	00	05.9	07.6	71	1017.3	1022.9
0300	10.0	0	230	02	05.2	03.0	1024.3	00	04.3	07.6	86	1017.2	1022.8
0400	08.0	0	250	03	05.4	03.0	1024.4	10	04.4	07.5	84	1017.3	1022.9
0500	10.0	0	000	00	05.0	03.0	1025.0	00	04.2	07.6	87	1017.9	1023.5
0600	10.0	0	280	02	04.7	02.7	1025.3	00	03.9	07.4	87	1018.2	1023.0
0700	08.0	0	290	02	04.8	03.8	1025.8	10	04.4	08.0	93	1018.7	1024.3
0800	10.0	0	290	02	07.8	02.8	1026.2	00	05.7	07.5	71	1019.2	1024.8
0900	10.0	0	270	03	09.8	02.8	1027.0	00	06.8	07.5	62	1020.0	1025.7
1000	10.0	2	000	00	11.9	03.0	1027.3	00	08.0	07.6	55	1020.3	1026.0
1100	10.0	1	280	03	14.3	02.3	1026.8	00	09.0	07.2	44	1019.9	1025.6
1200	10.0	2	320	04	15.8	01.5	1025.7	00	09.5	06.8	38	1018.8	1024.5
1300	10.0	2	320	04	17.0	-01.4	1025.0	00	09.3	05.5	29	1018.1	1023.8
1400	10.0	3	330	04	17.5	-00.4	1024.6	00	09.8	05.9	30	1017.8	1023.5
1500	10.0	3	330	04	18.0	-02.2	1024.8	00	09.6	05.2	25	1018.0	1023.7
1600	10.0	3	340	03	17.8	-01.8	1024.8	00	09.6	05.4	26	1018.0	1023.7
1700	10.0	4	330	03	15.8	00.2	1025.1	00	09.1	06.2	35	1018.2	1023.9
1800	10.0	3	330	03	14.7	01.4	1025.3	00	08.9	06.7	40	1018.4	1024.1
1900	08.0	0	000	00	12.7	03.6	1025.6	05	08.6	07.9	54	1018.7	1024.4
2000	08.0	0	000	00	11.0	03.5	1026.0	05	07.7	07.9	60	1019.0	1024.7

Appendix C

Input &Output of ISCST3Model

A Sample of input and output of ISCST3 Model results of SO$_2$ emission emitted from flaring in West Kuwait Oilfield Area

```
*****************************************

**

** ISCST3 Input Produced by:

** ISC-AERMOD View Ver. 4.5

** Lakes Environmental Software Inc.

** Date: 10/15/2007

** File: D:\All KOC model area\WK Model\Latest WK\SO2\Modify with 3 mesh\wkso23m.INP

**

*****************************************

**

**

*****************************************

** ISCST3 Control Pathway

*****************************************

**

**

CO STARTING
```

TITLEONE C:\Documents and Settings\KHAYRIA AL-HAMAD\Desktop\New Folder (2)\W

MODELOPT DFAULT CONC RURAL

AVERTIME 1 24 PERIOD

POLLUTID SO2

TERRHGTS FLAT

RUNORNOT RUN

CO FINISHED

**

****

** ISCST3 Source Pathway

****

**

**

SO STARTING

** Source Location **

** Source ID - Type - X Coord. - Y Coord. **

   LOCATION 3GC16 POINT 749489.000 3214100.000

   LOCATION GC17 POINT 765716.571 3194548.964

   LOCATION 2GC17 POINT 765589.120 3194560.883

LOCATION 3GC17 POINT 765476.694 3194568.175

LOCATION 4GC17 POINT 765431.121 3194752.512

LOCATION GC27 POINT 766743.430 3198025.470

LOCATION 2GC27 POINT 766530.090 3198024.970

LOCATION 3GC27 POINT 766327.850 3198474.630

LOCATION 4GC27 POINT 766438.850 3198425.380

LOCATION GC28 POINT 753157.300 3212342.220

LOCATION 2GC28 POINT 753746.920 3211400.300

LOCATION 3GC28 POINT 752287.070 3211214.970

LOCATION 4GC28 POINT 751331.940 3211040.290

LOCATION BS170 POINT 765894.736 3194422.358

LOCATION 2BS170 POINT 765799.718 3194440.094

LOCATION GC16 POINT 749960.334 3214311.613

LOCATION 2GC16 POINT 749742.881 3214389.536

LOCATION 4GC16 POINT 749624.479 3214516.970

** Source Parameters **

SRCPARAM 3GC16 1596.04 76.757 1673.150 13.100 0.410

SRCPARAM GC17 470.1332306 54.115 1673.150 13.100 0.254

SRCPARAM 2GC17 470.1332306 54.115 1673.150 13.100 0.254

```
SRCPARAM 3GC17 470.1332306 68.448 1673.150 13.100 0.410

SRCPARAM 4GC17 470.1332306 68.448 1673.150 13.100 0.410

SRCPARAM GC27 2638.189068 117.302 1673.150 13.100 0.900

SRCPARAM 2GC27 2638.189068 117.302 1673.150 13.100 0.750

SRCPARAM 3GC27 2638.189068 118.496 1673.150 13.100 0.900

SRCPARAM 4GC27 2638.189068 118.496 1673.150 13.100 0.900

SRCPARAM GC28 3773.770668 129.274 1673.150 13.100 0.914

SRCPARAM 2GC28 3773.770668 129.274 1673.150 13.100 0.914

SRCPARAM 3GC28 3773.770668 139.550 1673.150 13.100 0.914

SRCPARAM 4GC28 3773.770668 139.550 1673.150 13.100 1.066

SRCPARAM BS170 7547.541336 131.032 1673.150 13.100 0.410

SRCPARAM 2BS170 7547.541336 113.020 1673.150 13.100 0.410

SRCPARAM GC16 1596.03803 60.894 1673.150 13.100 0.254

SRCPARAM 2GC16 1596.03803 60.894 1673.150 13.100 0.254

SRCPARAM 4GC16 1596.03803 76.735 1273.000 13.100 0.410

EMISFACT 3GC16 MONTH 0.07 0.04 0.06 0.13 0.10 0.09

EMISFACT 3GC16 MONTH 0.07 0.21 0.12 0.04 0.05 0.02

EMISFACT GC27 MONTH 0.09 0.11 0.13 0.02 0.02 0.03

EMISFACT GC27 MONTH 0.12 0.10 0.11 0.06 0.17 0.05
```

```
EMISFACT GC28 MONTH 0.02 0.00 0.08 0.03 0.09 0.06

EMISFACT GC28 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT BS170 MONTH 0.02 0.00 0.08 0.04 0.09 0.06

EMISFACT BS170 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT GC17 MONTH 0.09 0.04 0.04 0.10 0.11 0.12

EMISFACT GC17 MONTH 0.11 0.13 0.09 0.04 0.07 0.06

EMISFACT 2GC17 MONTH 0.09 0.04 0.04 0.10 0.11 0.12

EMISFACT 2GC17 MONTH 0.11 0.13 0.09 0.04 0.07 0.06

EMISFACT 3GC17 MONTH 0.09 0.04 0.04 0.10 0.11 0.12

EMISFACT 3GC17 MONTH 0.11 0.13 0.09 0.04 0.07 0.06

EMISFACT 4GC17 MONTH 0.09 0.04 0.04 0.10 0.11 0.12

EMISFACT 4GC17 MONTH 0.11 0.13 0.09 0.04 0.07 0.06

EMISFACT 2GC27 MONTH 0.09 0.11 0.13 0.02 0.02 0.03

EMISFACT 2GC27 MONTH 0.12 0.10 0.11 0.06 0.17 0.05

EMISFACT 3GC27 MONTH 0.09 0.11 0.13 0.02 0.02 0.03

EMISFACT 3GC27 MONTH 0.12 0.10 0.11 0.06 0.17 0.05

EMISFACT 4GC27 MONTH 0.09 0.11 0.13 0.02 0.02 0.03

EMISFACT 4GC27 MONTH 0.12 0.10 0.11 0.06 0.17 0.05

EMISFACT 2GC28 MONTH 0.02 0.00 0.08 0.03 0.09 0.06
```

```
EMISFACT 2GC28 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT 3GC28 MONTH 0.02 0.00 0.08 0.03 0.09 0.06

EMISFACT 3GC28 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT 4GC28 MONTH 0.02 0.00 0.08 0.03 0.09 0.06

EMISFACT 4GC28 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT 2BS170 MONTH 0.02 0.00 0.08 0.04 0.09 0.06

EMISFACT 2BS170 MONTH 0.21 0.23 0.15 0.11 0.02 0.01

EMISFACT GC16 MONTH 0.07 0.04 0.06 0.13 0.10 0.09

EMISFACT GC16 MONTH 0.07 0.21 0.12 0.04 0.05 0.02

EMISFACT 2GC16 MONTH 0.07 0.04 0.06 0.13 0.10 0.09

EMISFACT 2GC16 MONTH 0.07 0.21 0.12 0.04 0.05 0.02

EMISFACT 4GC16 MONTH 0.07 0.04 0.06 0.13 0.10 0.09

EMISFACT 4GC16 MONTH 0.07 0.21 0.12 0.04 0.05 0.02

SRCGROUP ALL

SO FINISHED

**

****************************************

** ISCST3 Receptor Pathway

****************************************
```

```
**

**

RE STARTING

   GRIDCART UCART1 STA

                XYINC 739055.09 21 1983.43 3181731.00 21 2029.55

   GRIDCART UCART1 END

   GRIDCART UCART2 STA         -

                XYINC 745512.76 21 1260.78 3190033.72 21 1337.66

   GRIDCART UCART2 END

   GRIDCART UCART3 STA

                XYINC 761810.70 21 522.76 3190956.25 21 538.14

   GRIDCART UCART3 END

RE FINISHED

**

****************************************

** ISCST3 Meteorology Pathway

****************************************

**

**
```

ME STARTING

    INPUTFIL D:\2006MA~1\2006KW.met

    ANEMHGHT 10 METERS

    SURFDATA 2000 2006

    UAIRDATA 1 2006

ME FINISHED

**

****

** ISCST3 Output Pathway

****

**

**

OU STARTING

    RECTABLE ALLAVE FIRST

    RECTABLE 1 FIRST

    RECTABLE 24 FIRST

    MAXTABLE ALLAVE 50

** Auto-Generated Plotfiles

    PLOTFILE 1 ALL 1ST WKSO23M.IS\01H1GALL.PLT

217

PLOTFILE 24 ALL 1ST WKSO23M.IS\24H1GALL.PLT

PLOTFILE PERIOD ALL WKSO23M.IS\PE00GALL.PLT

OU FINISHED

```
**********************************
*** SETUP Finishes Successfully ***
**********************************
```

*** POINT SOURCE DATA ***

SOURCE ID	NUMBER PART. CATS.	EMISSION RATE (GRAMS/SEC)	X (METERS)	Y (METERS)	BASE ELEV. (METERS)	STACK HEIGHT (METERS)	STACK TEMP. (DEG.K)	STACK EXIT VEL. (M/SEC)	STACK DIAMETER (METERS)	BUILDING EXISTS	EMISSION RATE SCALAR VARY BY
3GC16	0	0.15960E+04	749489.0	3214100.0	0.0	76.76	1673.15	13.10	0.41	NO	MONTH
GC17	0	0.47013E+03	765716.6	3194549.0	0.0	54.12	1673.15	13.10	0.25	NO	MONTH
2GC17	0	0.47013E+03	765589.1	3194561.0	0.0	54.12	1673.15	13.10	0.25	NO	MONTH
3GC17	0	0.47013E+03	765476.7	3194568.3	0.0	68.45	1673.15	13.10	0.41	NO	MONTH
4GC17	0	0.47013E+03	765431.1	3194752.5	0.0	68.45	1673.15	13.10	0.41	NO	MONTH
GC27	0	0.26382E+04	766743.4	3198025.5	0.0	117.30	1673.15	13.10	0.90	NO	MONTH
2GC27	0	0.26382E+04	766530.1	3198025.0	0.0	117.30	1673.15	13.10	0.75	NO	MONTH

3GC27 MONTH	0	0.26382E+04	766327.9	3198474.8	0.0	118.50	1673.15	13.10	0.90	NO
4GC27 MONTH	0	0.26382E+04	766438.9	3198425.5	0.0	118.50	1673.15	13.10	0.90	NO
GC28 MONTH	0	0.37738E+04	753157.3	3212342.3	0.0	129.27	1673.15	13.10	0.91	NO
2GC28 MONTH	0	0.37738E+04	753746.9	3211400.3	0.0	129.27	1673.15	13.10	0.91	NO
3GC28 MONTH	0	0.37738E+04	752287.1	3211215.0	0.0	139.55	1673.15	13.10	0.91	NO
4GC28 MONTH	0	0.37738E+04	751331.9	3211040.3	0.0	139.55	1673.15	13.10	1.07	NO
BS170 MONTH	0	0.75475E+04	765894.8	3194422.3	0.0	131.03	1673.15	13.10	0.41	NO
2BS170 MONTH	0	0.75475E+04	765799.7	3194440.0	0.0	113.02	1673.15	13.10	0.41	NO
GC16 MONTH	0	0.15960E+04	749960.3	3214311.5	0.0	60.89	1673.15	13.10	0.25	NO
2GC16 MONTH	0	0.15960E+04	749742.9	3214389.5	0.0	60.89	1673.15	13.10	0.25	NO
4GC16 MONTH	0	0.15960E+04	749624.5	3214517.0	0.0	76.74	1273.00	13.10	0.41	NO

```
                    *** METEOROLOGICAL DAYS SELECTED FOR PROCESSING ***
                                   (1=YES; 0=NO)

        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1 1 1 1 1   1 1 1 1
1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1 1   1 1 1 1 1 1
```

        NOTE: METEOROLOGICAL DATA ACTUALLY PROCESSED WILL ALSO DEPEND ON WHAT IS INCLUDED IN THE
DATA FILE.

                    *** UPPER BOUND OF FIRST THROUGH FIFTH WIND SPEED CATEGORIES ***
                                   (METERS/SEC)

                    1.54,   3.09,   5.14,   8.23,   10.80,

                            *** WIND PROFILE EXPONENTS ***

            STABILITY   WIND SPEED CATEGORY

	CATEGORY	1	2	3	4	5
6						
.70000E-01	A	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01
.70000E-01	B	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01
.10000E+00	C	.10000E+00	.10000E+00	.10000E+00	.10000E+00	.10000E+00
.15000E+00	D	.15000E+00	.15000E+00	.15000E+00	.15000E+00	.15000E+00
.35000E+00	E	.35000E+00	.35000E+00	.35000E+00	.35000E+00	.35000E+00
.55000E+00	F	.55000E+00	.55000E+00	.55000E+00	.55000E+00	.55000E+00

*** VERTICAL POTENTIAL TEMPERATURE GRADIENTS ***
(DEGREES KELVIN PER METER)

	STABILITY			WIND SPEED CATEGORY		
	CATEGORY	1	2	3	4	5
6						
.00000E+00	A	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	B	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	C	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	D	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.20000E-01	E	.20000E-01	.20000E-01	.20000E-01	.20000E-01	.20000E-01
.35000E-01	F	.35000E-01	.35000E-01	.35000E-01	.35000E-01	.35000E-01

*** ISCST3 - VERSION 02035 ***   *** C:\Documents and Settings\KHAYRIA AL-HAMAD\Desktop\New Folder (2)\W
***   10/15/07

                                         *** THE MAXIMUM   50   1-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:
ALL   ***
                                  INCLUDING SOURCE(S):   3GC16   , GC17   , 2GC17   , 3GC17   , 4GC17
, GC27   , 2GC27   ,
        3GC27   , 4GC27   , GC28   , 2GC28   , 3GC28   , 4GC28   , BS170   , 2BS170   , GC16   , 2GC16
, 4GC16   ,

                                         ** CONC OF SO2   IN MICROGRAMS/M**3   **

RANK   CONC   (YYMMDDHH) AT   RECEPTOR (XR,YR) OF TYPE   RANK   CONC   (YYMMDDHH) AT
RECEPTOR (XR,YR) OF TYPE
- -
- - - - - - - - - - - -
    1.   11795.79880 (06080710) AT (765992.75, 3193108.75) GC   26.   8205.28027 (06081308) AT
(767038.31, 3192032.50) GC
    2.   11658.61130 (06082809) AT (767038.31, 3193108.75) GC   27.   8165.50537 (06082511) AT
(766515.50, 3193647.00) GC
    3.   11537.97750 (06082010) AT (765992.75, 3193108.75) GC   28.   8164.29248 (06080813) AT
(766515.50, 3193647.00) GC
    4.   11130.25980 (06082910) AT (766823.06, 3193908.25) GC   29.   8038.94580 (06082909) AT
(766823.06, 3193908.25) GC
    5.   10629.18360 (06081311) AT (764839.63, 3193908.25) GC   30.   8028.87500 (06082912) AT
(766515.50, 3194185.00) GC
    6.   10209.58980 (06082010) AT (765992.75, 3193647.00) GC   31.   7973.44189 (06081308) AT
(766823.06, 3191878.75) GC
    7.   10139.88380 (06082809) AT (767561.06, 3192570.75) GC   32.   7885.64453 (06082809) AT
(768083.81, 3192032.50) GC
    8.   9864.11133 (06080710) AT (765992.75, 3193647.00) GC   33.   7868.14600 (06082309) AT
(767038.31, 3194185.00) GC
    9.   9712.16016 (06081118) AT (764424.50, 3193108.75) GC   34.   7831.00391 (06082509) AT
(765992.75, 3193108.75) GC

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   10.    9550.98926 (06082009) AT ( 766515.50, 3193647.00) GC        35.    7827.52832 (06081810) AT
( 764424.50, 3194723.25)  GC
   11.    9391.49805 (06081018) AT ( 763378.94, 3193647.00) GC        36.    7795.27295 (06080708) AT
( 767561.06, 3195261.25)  GC
   12.    9269.53125 (06082514) AT ( 766823.06, 3193908.25) GC        37.    7768.18262 (06082110) AT
( 766946.00, 3194046.75)  GC
   13.    9182.39648 (06081909) AT ( 765685.25, 3195384.50) GC        38.    7739.91406 (06081212) AT
( 766515.50, 3193647.00)  GC
   14.    9044.61719 (06080708) AT ( 768083.81, 3195799.50) GC        39.    7737.47949 (06081118) AT
( 763901.75, 3192570.75)  GC
   15.    8997.49121 (06082515) AT ( 765992.75, 3193647.00) GC        40.    7734.30664 (06081311) AT
( 764424.50, 3193647.00)  GC
   16.    8941.38086 (06081018) AT ( 763901.75, 3193647.00) GC        41.    7720.32227 (06080710) AT
( 765992.75, 3192570.75)  GC
   17.    8793.40234 (06081308) AT ( 766515.50, 3192570.75) GC        42.    7705.96973 (06090711) AT
( 765470.00, 3194723.25)  GC
   18.    8726.80273 (06072219) AT ( 763378.94, 3195261.25) GC        43.    7645.59473 (06082812) AT
( 765992.75, 3193647.00)  GC
   19.    8687.98242 (06081018) AT ( 764424.44, 3194046.75) GC        44.    7634.25537 (06080708) AT
( 767038.31, 3195261.25)  GC
   20.    8461.03906 (06082317) AT ( 764424.50, 3193108.75) GC        45.    7618.23145 (06082011) AT
( 765685.25, 3194046.75)  GC
   21.    8404.96484 (06082309) AT ( 766946.00, 3194046.75) GC        46.    7579.31201 (06091210) AT
( 767038.31, 3193647.00)  GC
   22.    8402.29297 (06081308) AT ( 766515.50, 3193108.75) GC        47.    7557.87256 (06082714) AT
( 764424.50, 3194185.00)  GC
   23.    8289.43359 (06072908) AT ( 767561.06, 3194723.25) GC        48.    7552.19287 (06082910) AT
( 767038.31, 3193647.00)  GC
   24.    8243.37695 (06082713) AT ( 764947.25, 3194185.00) GC        49.    7511.20068 (06072219) AT
( 763163.69, 3195384.50)  GC
   25.    8230.91113 (06082710) AT ( 766515.50, 3193647.00) GC        50.    7455.06641 (06082811) AT
( 765992.75, 3193647.00)  GC

  *** RECEPTOR TYPES:  GC = GRIDCART
                       GP = GRIDPOLR
                                                                              DC = DISCCART
  *** ISCST3 - VERSION 02035 ***     *** C:\Documents and Settings\KHAYRIA  AL-HAMAD\Desktop\New Folder (2)\W
  ***        10/15/07
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                              *** THE MAXIMUM   50   24-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:

ALL   ***

                          INCLUDING SOURCE(S):   3GC16   , GC17   , 2GC17   , 3GC17   , 4GC17

, GC27   , 2GC27   ,

        3GC27   , 4GC27   , GC28   , 2GC28   , 3GC28   , 4GC28   , BS170   , 2BS170 , GC16   , 2GC16

, 4GC16   ,

                                ** CONC OF SO2   IN MICROGRAMS/M**3   **

RANK   CONC   (YYMMDDHH) AT   RECEPTOR (XR,YR) OF TYPE   RANK   CONC   (YYMMDDHH) AT RECEPTOR (XR,YR) OF TYPE

- -

     1.   1233.07727c(06082524) AT (765992.75, 3193647.00) GC   26.   945.75958 (06080324) AT (768206.81, 3191371.50) GC

     2.   1221.15002c(06082824) AT (765992.75, 3193647.00) GC   27.   933.38672c(06081324) AT (748972.19, 3214203.75) GC

     3.   1211.85217c(06082924) AT (766823.06, 3193908.25) GC   28.   929.73407c(06082324) AT (766823.06, 3193908.25) GC

     4.   1211.74536c(06082724) AT (764424.50, 3194185.00) GC   29.   927.15210 (06080324) AT (768083.81, 3191494.50) GC

     5.   1179.89795c(06081324) AT (764947.25, 3194185.00) GC   30.   919.42603 (06080324) AT (768606.56, 3191494.50) GC

     6.   1168.37927c(06082924) AT (766515.50, 3194185.00) GC   31.   914.21136c(06081224) AT (766515.50, 3193647.00) GC

     7.   1145.02197c(06081324) AT (764424.44, 3194046.75) GC   32.   912.28296 (06070824) AT (767561.06, 3192032.50) GC

     8.   1137.68555c(06081324) AT (764839.63, 3193908.25) GC   33.   910.82544 (06080324) AT (769467.56, 3190033.75) GC

     9.   1091.86963c(06081324) AT (764424.50, 3194185.00) GC   34.   896.84576 (06070824) AT (768083.81, 3191494.50) GC

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  10.     1071.76978c(06071924) AT ( 766515.50, 3193108.75)  GC        35.        893.26715c(06082524) AT
( 765992.75, 3193108.75)  GC
  11.     1060.99695c(06081124) AT ( 766515.50, 3193647.00)  GC        36.        892.32770c(06082024) AT
( 765470.00, 3193647.00)  GC
  12.     1058.50781c(06082224) AT ( 766515.50, 3193647.00)  GC        37.        883.95905c(06082724) AT
( 763901.75, 3194185.00)  GC
  13.     1058.00623c(06081124) AT ( 767038.31, 3193108.75)  GC        38.        883.63330c(06092124) AT
( 767038.31, 3193647.00)  GC
  14.     1044.47815c(06082424) AT ( 765992.75, 3193108.75)  GC        39.        878.65497 (06070824) AT
( 768206.81, 3191371.50)  GC
  15.     1025.63623c(06082724) AT ( 764947.25, 3194185.00)  GC        40.        874.18268c(06082724) AT
( 764424.44, 3194046.75)  GC
  16.     1020.02490c(06082324) AT ( 766946.00, 3194046.75)  GC        41.        869.62866 (06072724) AT
( 768083.81, 3192032.50)  GC
  17.     1018.28394c(06082324) AT ( 766515.50, 3193647.00)  GC        42.        863.93451c(06082124) AT
( 766515.50, 3193647.00)  GC
  18.      996.78986c(06091724) AT ( 765992.75, 3192570.75)  GC        43.        862.21014 (06080324) AT
( 767038.31, 3193108.75)  GC
  19.      987.72449c(06091724) AT ( 765992.75, 3193108.75)  GC        44.        860.45648c(06082224) AT
( 767038.31, 3193108.75)  GC
  20.      978.38165c(06071924) AT ( 767038.31, 3192032.50)  GC        45.        857.80548 (06080324) AT
( 769129.31, 3190956.25)  GC
  21.      972.62823c(06081824) AT ( 764947.25, 3194185.00)  GC        46.        849.61835 (06072724) AT
( 768606.56, 3191494.50)  GC
  22.      970.36719c(06082324) AT ( 766515.50, 3194185.00)  GC        47.        842.97125 (06072724) AT
( 767561.06, 3192570.75)  GC
  23.      965.03656 (06080324) AT ( 768083.81, 3192032.50)  GC        48.        836.72443c(06082424) AT
( 765992.75, 3192570.75)  GC
  24.      964.61444 (06080324) AT ( 768606.56, 3190956.25)  GC        49.        833.98309c(06072024) AT
( 767561.06, 3192032.50)  GC
  25.      957.10187 (06080324) AT ( 767561.06, 3192570.75)  GC        50.        825.79218 (06072524) AT
( 766515.50, 3193647.00)  GC

  *** RECEPTOR TYPES:  GC = GRIDCART
                       GP = GRIDPOLR
                       DC = DISCCART
                       *** ISCST3 - VERSION 02035 ***     *** C:\Documents and Settings\KHAYRIA  AL-
HAMAD\Desktop\New Folder (2)\W ***          10/15/07
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*** THE SUMMARY OF MAXIMUM PERIOD (8736 HRS) RESULTS ***

** CONC OF SO2   IN MICROGRAMS/M**3   **

NETWORK GROUP ID ID		AVERAGE CONC		RECEPTOR	(XR, YR, ZELEV, ZFLAG)		OF TYPE GRID-
ALL UCART3	1ST HIGHEST VALUE IS	159.16150	AT (	766515.50,	3193647.00,	0.00,	0.00) GC
UCART3	2ND HIGHEST VALUE IS	155.45119	AT (	767038.31,	3193108.75,	0.00,	0.00) GC
UCART2	3RD HIGHEST VALUE IS	149.70876	AT (	766946.00,	3192709.00,	0.00,	0.00) GC
UCART3	4TH HIGHEST VALUE IS	147.04054	AT (	766515.50,	3193108.75,	0.00,	0.00) GC
UCART3	5TH HIGHEST VALUE IS	144.62099	AT (	767038.31,	3192570.75,	0.00,	0.00) GC
UCART3	6TH HIGHEST VALUE IS	136.18684	AT (	767561.06,	3192570.75,	0.00,	0.00) GC
UCART3	7TH HIGHEST VALUE IS	132.34485	AT (	767561.06,	3192032.50,	0.00,	0.00) GC
UCART3	8TH HIGHEST VALUE IS	121.12387	AT (	768083.81,	3192032.50,	0.00,	0.00) GC
UCART3	9TH HIGHEST VALUE IS	120.03760	AT (	768083.81,	3191494.50,	0.00,	0.00) GC

10TH HIGHEST VALUE IS   117.48380 AT (768206.81,   3191371.50,   0.00,   0.00) GC
UCART2

*** RECEPTOR TYPES: GC = GRIDCART
                     GP = GRIDPOLR
                     DC = DISCCART
                     DP = DISCPOLR
                     BD = BOUNDARY

****
*** ISCST3 Finishes Successfully ***
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Appendix D
Existing Models and Their Brief Description

A list of existing models and their brief description is given as follows;

No.	Models Name and Description
1	**Industrial source complex short term (ISCST) (for microcomputers). Model** This EPA model is a steady-state Gaussian plume model which can be used to assess pollutant concentrations from a wide variety of sources associated with an industrial source complex. This model can account for settling and dry deposition of particulates, downwash, area, line, and volume sources, plume rise as a function of downwind distance, separation of point sources, and limited terrain adjustment. ISC is designed to calculate the average seasonal and/or annual ground level concentration or total deposition from multiple continuous point, volume, and/or areas sources.
2	**ADMS-3 (Atmospheric Dispersion Modelling System)** an advanced model for calculating concentrations of pollutants emitted both continuously from point, line, volume and area sources, or discretely from point sources. The model includes algorithms which take account of the following: effects of main site building; complex terrain; wet deposition, gravitational settling and dry deposition; short term fluctuations in concentration; chemical reactions; radioactive decay and gamma-dose; plume rise as a function of distance; jets and directional releases; averaging time ranging from very short to annual; condensed plume visibility; meteorological pre-processor.
3	**PLUVUEII** a model used for estimating visual range reduction and atmospheric discoloration caused by plumes resulting from the emissions of particles, nitrogen oxides, and sulfur oxides from a single source. The model predicts the transport, dispersion, chemical reactions, optical effects and surface deposition of point or area source emissions.
4	**EMS-HAP (Version 3.0)** (Emissions Modelling System for Hazardous Pollutants) an emissions processor that performs the steps needed to process an emission inventory for input into the ASPEN model or the ISCST3 model.
5	**Regional Modelling System for Aerosols and Deposition (REMSAD) [REMSAD]**

	REMSAD is a three-dimensional grid model designed to calculate the concentrations of both inert and chemically reactive pollutants by simulating the physical and chemical processes.
6	**UAM-IV - Urban Airshed Model IV [UAM-IV_Model]** (Summary adapted from EPA.) UAM-IV (Urban Airshed Model IV) an urban scale, three dimensional, grid type numerical simulation model. The model incorporates a condensed photochemical.
7	**Human Dimensions of Global Change Learning Modules [AAG_HDGC]** This project has developed ten teaching/learning modules through a collaborative process that involves module authors, participants in summer workshops, and project staff at Clark.
8	**Socioeconomic Data and Applications Center (SEDAC) Gateway [CIESIN_SEDAC_Gateway]** The SEDAC Gateway is a web-based search interface for simultaneous searching of local and distributed metadata catalogs. Through the Z39.50 information retrieval protocol.
9	**CALMET** is a diagnostic meteorological model and is widely used for prediction of 3-dimensional meteorological fields using surface and radiosonde observation data. It is also used in various air pollution dispersion modelling such as CALPUFF and CALGRID. CALMET, a diagnostic wind field and boundary layer model that interpolates wind fields from MM5 with available surface and upper air observations to produce hourly, gridded, three-dimensional wind and boundary layer parameter fields for the modelling period.
10	**CALPUFF** is a multi-layer, multi-species, non-steady state puff dispersion model which can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal. CALPUFF can use the three-dimensional meteorological fields computed by the CALMET model, or simple, single station winds in a format consistent with the meteorological files used to drive the ISC3 or the CTDM steady-state Gaussian models. CALPUFF contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, and sub grid scale terrain interactions.