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Inhalation Human Health Risk Assessment: Case Study of a South African International Airport

Makhosazana Dubazana (545715)

A dissertation submitted to the Faculty of Science and the School of Geography, Archaeology and Environmental Studies in fulfilment of the Master of Science.

Supervised by

Dr Raeesa Moolla

Abstract

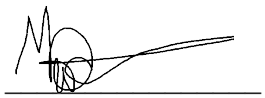
There has been an increase in public health concerns due to the impact of airport-related emissions on public and occupational health. Many studies have evaluated the potential health risk of a wide range of toxic pollutants within an airport. However, there has not been enough work done to analyse the potential human health impact of benzene, toluene, ethylbenzene, and xylene (BTEX), which occurs within airport environments in significant amounts. Besides, BTEX compounds are known to have a wide range of health impacts, where humans exposed to these compounds for an extended period or over their lifetime are known to develop symptoms such as wheezing and headaches, which are associated with the general effects of BTEX on the nervous system.

Furthermore, benzene exposure is associated with the development of leukaemia. This study aimed to assess the human health risk of BTEX compounds on hypothetical subpopulations groups of residents living near a privately-owned South African airport chosen for this study as well as on-site employees. The study utilised the US EPA guidelines on Human Health Risk guide materials and methods.

The results of the average ambient air emissions are 2.69, 7.43, 1.53, and 5.36 ug/m^{-3} for benzene, toluene, ethylbenzene, and xylene, respectively. The ambient emissions were higher during the winter sampling campaign, with total BTEX concentrations ranging from 13.93 to 44.36 ug/m^{-3}. BTEX seasonal and spatial variations were evident: concentrations dispersed from the southwest (lowest concentrations) to the northeast (highest concentration) end in the autumn and winter. On the other hand, in spring and summer, there were emission hotspots on either side of the runway. The results of the final risk assessment displayed similar spatial distributions to benzene emission; the highest cancer risk is at the emissions hotspots at the airport drop-off area and parking. The cancer risk was above the US EPA guideline of 1 x 10^{-6} for all locations. The residential subpopulation groups have an average cancer risk of 6.44 x10^{-05}, while on-site employees have an average cancer risk of 2.66 x 10^{-06}. The results of the general health risk measured through the Hazard Quotient were below 1 for most subpopulation groups, excluding the subpopulation group younger than six months. With the prolific increase in air traffic transportation and the probable deterioration of air quality, the resultant associated health risk for populations in and around airports may intensify, which is a cause for concern and further investigation.

Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



Makhosazana Dubazana

Student number 545715

Signed on this 17 day of January 2020 in Johannesburg

Acknowledgements

At the beginning of this thesis, I had experienced Post Traumatic Stress Disorder. In light of this, I would not have managed to get this far without the help and support of family, friends, the Wits Counselling and Career Unit, and professional assistance. Therefore, I would like to acknowledge and thank the following people and organisations for their assistance and contribution to my journey in undertaking a Masters in Geography and Environmental Studies:

- My supervisor Dr Raeesa Moolla for her guidance and support throughout my studies and allocating me the research grant;
- The National Research Foundation for funding my studies through the grant;
- My brother Thokozani Dubazana for his time and assistance in getting me to and from the study site;
- My immediate and extended family for the constant support and availing their home to me;
- To the South African international Airport used in this study, for availing their time of your resources for assistance on this project.

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List of Abbreviations

AMSTERDAM	Advanced Modelling System for Transport, Emissions, Reactions, and Deposition of Atmospheric Matter
ACRP	Airports Cooperation Research Program
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene
CMAQ	Community Multi-Scale Air Quality Model
EIA	Environmental Impact Assessment
EDMS	Emission and Dispersion Modelling System
FAA	Federal Aviation Administration
FAO	Federal Aviation Administration Office of Environment and Energy
GSE	Ground Support Equipment
HHRA	Human Health Risk Assessment
HIA	Health Impact Assessment
HQ	Hazard Quotient
ICAO	International Civil Aviation Organisation
ILCR	Incremental Lifetime Cancer Risk
IRIS	Integrated Risk Information Systems
LADD	Lifetime Average Daily Dose
LAWA	Los Angeles World Airport
LAX	Los Angeles International Airport
LTO	Landing and Takeoff Cycle
RAIS	Risk Assessment Information System
TPIA	Toronto Pearson International Airport
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

WHO	World Health Organisation

Chapter 1: Background and Introduction

1.1 Background

Modern-day atmospheric pollution at the earth's surface has been documented to have numerous health effects on humans (Kim *et al*., 2012; Royal College of Physicians, 2016; Barrett *et al*., 2012; NHS, 2016). The Royal College of Physicians (2016) articulated that the United Kingdom's to air pollution was linked more than 400,000 deaths. The same sentiment was shared by research institutions such as the Council of Scientific and Industrial Research in Southern Africa (Wright and Oosthuizen, 2009). Air pollution in the year 2007 was noted to have been the cause of 3,7 % of deaths from all cardiopulmonary diseases, and 5,1 % of these deaths were attributed to cancer of the trachea, bronchus, and lungs in adults and children over the age of 3 (Wright and Oosthuizen, 2009).

South African studies that address the effects of air pollution on human health have been conducted in pollutant source areas, from large industrial zones such as the South Durban Industrial area to areas such as the Vaal Triangle and Witbank area as well as high traffic zones in South African cities (Wright and Oosthuizen, 2009). However, little work has been done around airports, despite the increasing global public health concerns around the impact of emissions related to airport operations on general public health (Kim *et al*., 2012).

Cape Town International airport appointed SRK Consulting to conduct an Environmental Impact Assessment (EIA) in which they managed to conduct one of the first airport emission inventories at a South African Airport. As part of the EIA, they conducted a Human Health Risk Assessment (HHRA) for Cape Town International Airport. Following the HHRA, Burdzik (2016) conducted a desktop Health Impact Assessment (HIA), which addressed health implications related to airport activity. In the HIA, Burdzik (2016) concluded that they are no adverse health impacts associated with the realign projects constructions and post-construction emissions. With only one HHRA having been carried out at a South African airport, there have been a few studies conducted across the world.

In its Master Plan project, the Los Angeles World Airports (LAWA) looked at assessing the airport's impact from a social, environmental, and economic perspective. This project included an EIA for the airport in which a section of the EIA highlighted the probable health impact of air pollution-related to the airport's operation and proposed on-site projects

(LAWA, 2004). The results from the study concluded that there was not a significant risk for all receptors in the Los Angeles World Airport HHRA.

On the other hand, the Toronto Pearson International Airport (TPIA) conducted an Air Quality Assessment for the airport, which was followed by an HHRA (Intrinsik, 2015). A report by Intrinsik (2015) looked at the probable health impact of air pollution around and within TPIA for a hypothetical group of employees and residents. It revealed that exposure to annual average concentrations of acrolein, benzene, and formaldehyde exceeded the US EPA acceptable risk limit of $1x\ 10^{-6}$ calculated using emission estimates for the year 2020.

Several studies have looked at health concerns related to airport activity across Europe and many parts of the world (Franssen *et al*., 2002; Lindberg *et al*., n.d.; Tesseraux, 2004; Visser *et al*., 2005; Yim *et al*., 2013). The results from a study conducted by Frannsen *et al*. (2002) concluded that emissions from the Schiphol airport were below the guidelines. However, the participants from a survey they conducted brought to light the participants' general concerns over the respiratory health effects from airport emissions. Looking at the impact of aircraft emission on adjacent local communities, Tesseraux (2004) found airport emissions do impact local communities. However, the emissions in nearby communities were typical in urban environments. On the contrary Tesseraux (2004) and Frannsen *et al*. (2002) found no significant contribution of airport emission on local emissions. Yim *et al*. (2013), on the other hand, found that 90% of early deaths in the UK occur due to airport-related emissions. Another study in which Visser *et al.* (2005) looked at the incidence of cancer near the Amsterdam airport where they utilised the Amsterdam cancer registry found that in the core zone of the study area, which is closest to the airport, cancer incidences were slightly higher than in the remaining study area. These studies above shed light on some studies that have been conducted to evaluate the health impact of airport emissions. However, this is still a developing research field with site-specific insights.

Using a case study, this study will add to the discussion of public health research concerning airport-related emissions by conducting a HHRA on a small set of pollutants known to be associated with aircraft emissions, namely: benzene, toluene, ethylbenzene, and xylene (BTEX) (Maison and Harrison, 2014; Zhu *et al*., 2011). The BTEX group of compounds have been the subject of many HHRA in a variety of microenvironments such as paint shops, refuelling stations, roadsides, landfills, offices, homes, and public spaces (Brcić, 2004;

Demirel *et al*., 2014; Hinwood *et al*., 2007; Karakitsios *et al*., 2007; McKenzie *et al*., 2012; Pallavi Saxena, 2012). Within many of these studies – such as in the case of Mckenzie *et al*. (2012) – the resultant health impact of benzene is not at the prescribed US EPA of $1x\ 10^{-6}$.

1.2 Rationale

Studies that have looked at the human health impact of emissions from airports and aircraft have focused on an array of emissions, with most studies having varying conclusions on the health impact of airport-related emissions. An HHRA is merely a snapshot of the health impact, which can be attributed to the current state of the study site. There has been a general increase in air travel in the last few decades; therefore, the potential environmental and health impact of the aviation sector will increase. This study will be used as a case study to study the inhalation health effects of a few airport-related pollutants. It will look at a group of volatile organic compounds known as the BTEX group of compounds, namely benzene, xylene, ethylbenzene, and toluene. BTEX compounds occur at significant levels, are associated with many sources within the airport environment, and are associated with many long-term health effects. The long-term health effects of BTEX compounds are outlined below.

1.2.1 The health effects associated with long term exposure to benzene

Benzene is a naturally occurring substance in petroleum and used as an ingredient in some solvents and cleaning products (Luis Antonio and Georgina, 2014). Benzene is commonly emitted through exhaust fumes, oil spills, painting, and household or industrial cleaning products. Benzene is a carcinogenic compound and exposure to this compound is linked to the occurrence of Leukaemia in receptors (Duffy and Nelson, 1997; Guo *et al*., 2004; Liu *et al*., 2014). Long term exposure can have effects on the central nervous systems and immune systems. It may hurt bone marrow and may result in anaemia.

1.2.2 The health effects associated with long term exposure to toluene

Toluene is used in industrial settings for blending with gasoline and as a solvent. Toluene mixes well with air, and thus air can be harmfully contaminated quickly. The most common exposure scenarios are the manufacturing of toluene, during the use of paints, coating, thinners, and cleaners. Long term exposure to toluene may cause effects on the central nervous system and increase induced hearing loss. It was concluded through animal studies

that long term exposure might affect human reproduction and development (Bolden *et al*., 2015).

1.2.3 The health effects associated with long term exposure to ethylbenzene

Ethylbenzene has an aromatic odour, and it mixes well with air. However, the harmful contamination of an area will be reached slowly. Toluene is found in paints, inks, and exhaust fumes. Indoor ethylbenzene ambient air levels are often higher than outdoor levels because frequent sources are often indoors. Long term exposure to ethylbenzene may result in impaired functions of the liver and kidney, and it may impact the central nervous system.

1.2.4 The health effects associated with long term exposure to xylene

Xylene is an aromatic hydrocarbon compound with three isomers: ortho-xylene, meta-xylene, and paraxylene. This compound is heavier than air and can exist as pockets on the floor, which can be harmful to children crawling. Xylene is widely used in many industries as well as in dental and medical areas and products such as vehicle oils, paints and paint thinners, polishes, waxes, antifreeze, sealants, adhesives, gasoline, pesticides, disinfectants, and cigarettes. Toluene is known to be more harmful in children than in adults, and long-term exposure may have effects on the central nervous system, can result in visual impairment, and can have damaging effects on significant organs (Sciencing, 2018).

There are many ways that people can be exposed to BTEX emissions, with the International Civil Aviation Organization (2011) and Jung *et al*. (2010) noting that BTEX is one of the most prominent group of pollutants that is present in an airport. BTEX compounds serve as an excellent example of the need to evaluate the health impact of airport-related emissions. The public health impact can vary based on many factors, including the overall size of the airport or emission sources and the general composition of the pollution (Kim *et al*., 2012; Yim *et al*., 2013). It is essential to evaluate health impact across age groups, as children and the elderly are more prone to health risks. Generally, an HHRA can be conducted for three exposure pathways, mainly absorption through the skin, ingestion, and inhalation. Out of all the three pathways, the inhalation exposure pathway is assumed to be the most impactful pathway (WHO, 2014). Exposure pathways through adsorption and ingestion are considered not to be worthwhile in quantifying risk. Therefore, the following risk assessment will focus on evaluating the inhalation health risk of subpopulation groups defined by age.

1.3 Contributing to Existing Knowledge

The need to understand and qualify the impact of emissions related to the aviation sector has grown in the past few years. Kim *et al*. (2012) conducted a literature review to evaluate current literature and studies that evaluate airport air quality and public health studies through the Airports Cooperation Research Program (ACRP) with the goal of deriving information that can be useful for airport operations. The ACRP was established in 2005 and is sponsored by the Federal Aviation Administration (FAA) which is a regulatory body that promotes civil aviation safety. The ACRP's mandate is to provide the aviation industry with unbiased, reliable research in order to solve common problems experienced in the aviation sector, learn about new technologies, as well as assess innovations in service and operations. The ACRP continues to conduct research related to airport quality and public health. Most of the studies that the ARCP have evaluated were conducted for the purpose of fulfilling regulatory requirements as in the case of the Cape Town International Airports EIA project.

Some studies have been conducted for research purposes, such as the study conducted by Visser *et al*. (2005) that evaluated the incidence of cancer cases near an airport. Another study conducted by Yim *et al*. (2013) and Stettler *et al*. (2011) evaluated airport air quality and public health impact of UK airports. Yim *et al*. (2013) utilised a concentration-response function to estimate early deaths associated with airport emissions. Other studies evaluated the impact of noise from airports on public health (Correia *et al*., 2013; Hansell *et al*., 2013).

Not many studies have been conducted that have focused solely on the potential health impact of BTEX in an airport. However, BTEX has been the focus of public health studies conducted in many micro-environments, such as refuelling stations, roadsides, and paint shops (Moolla *et al.*, 2015 a; Tunsaringkarn *et al*., 2012; Demirel *et al*., 2014). This case study will serve to broaden the understanding of the potential impact of BTEX emissions in an airport environment. It is contributing to two sets of scientific knowledge, namely the research of BTEX emissions within a variety of micro-environments, as well the growing body of knowledge on airport air quality and health impacts.

1.4 Aim and Objectives

The aim of this research is to perform an Inhalation Air Pollution HHRA for on-site employees and residential subpopulation groups (children younger than 6 months, children 6

months to 6 years, children six years to 16 years, and adults aged 16 and older) living near a privately owned airport which flies , domestic and small international flights, in order to:

1. Determine the BTEX concentrations within and around the airport.

2. Characterise risk by defining the probability of long-term health effects through utilising the Hazard Quotient (HQ) and Incremental Lifetime Cancer Risk (ILCR) Assessments and the influence of risk across the following groups:

(i) On-site employees

(ii) Children, younger than 6 months old

(iii) Children 6 months to 6 years

(iv) Children 6 years to 16 years

(v) Adults (16 years or older)

1.5 Structure of the Thesis

The document is structured into 6 chapters. Chapter 1 provided an introduction to the study, outlining the rationale and the expected contribution to existing knowledge . Chapter 2 presents the literature review in order to frame the research that has been done in this field. Chapter 3 is the Methods and Materials chapter and explains the methodological approach. Chapter 4 outlines the findings from the experiment while chapter 5 discusses the findings of chapter 4. The study ends with chapter 6, which outlines the key findings, recommendations, and areas for further research.

Chapter 2: Literature Review

2.1 Methods Used to Evaluate the Public Health Impact Related to Environmental Containments

The effects of environmental pollutants on human health are commonly investigated using three methods, namely: (1) Human Health Risk Assessments; (2) Epidemiological studies and; (3) a relatively new field called Health Impact Assessments. These are standard methods of assessing either the potential or current state of a population's health due to exposure to various environmental and social determinants (Gulis and Fujino, 2015).

HIA and HHRA are predictive methods. Epidemiology is evidence-based, taking into consideration the current health state of the pollution (World Health Organization, 2010). The World Health Organisation (WHO) has defined "epidemiological as the distribution and determinates of health-related states or events. In specified populations and the application of this study to control health problems" (WHO, 2000). The methods in epidemiology vary according to the health effect and the causes that are being studied. Gulis and Funhjio (2015) state that the information used in epidemiology studies is rarely utilised to influence decision making at a macroscope level but can be used at a microscope level to assist employers or community leaders and local governments in understanding health implication of current health determinants, either environmental or social. The HIA, however, is a tool which can be used effectively for decision-makers as its focus is on improving the quality of policy decisions, which is a multi-scale investigation of health effects (WHO 2016, Gulis and Fujino, 2015).

Cole and Fielding (2007) mostly unpacked HIA methods, defining HIA as a multidisciplinary approach that looks at assessing the probable health effects of proposed projects and policies. An HIA integrates social and economic determinants and utilises results from epidemiology and HHRAs (Gulis and Fujino, 2015). However, an HHRA is a quantitative predictor process for estimating future as well as current adverse health effects due to exposure to the contaminated medium, for single or multiple chemicals (US EPA, 2014). Unlike HIA, it has set guidelines and procedures which do not leave room for bias imputing. However, an HHRA is based on numerous uncertainties that affect the overall results (Cole and Fielding, 2007; US EPA, 2014). Furthermore, due to the nature of the quantitative analysis, it is much simpler to account for uncertainties (World Health Organization, 2016).

All three methods have been used to analyse or predict potential health impacts of airport operations. Epidemiological studies conducted within an airport environment look at the prevalence of disease or illness for population groups living in the vicinity of an airport or working within the airport environment. An example of such a study is a study conducted at Amsterdam Schiphol Airport which investigated whether populations living near the airport are at higher risk of developing cancer than the overall Dutch community (Visser *et al*., 2005). The results showed that the incidence of cancer within the Schiphol region was no different from national incidences (Visser *et al*., 2005). However, the core region nearest to the airport had increased incidences of respiratory-related cancer.

Many other types of epidemiological studies conducted research around hospitalisation for cardiovascular diseases and investigated the correlation between hotspots for hospitalisation and noise contours (Correia *et al*., 2013; Hansell *et al*., 2013). In addition, these studies found that increased noise pollution was related to hospital admissions and mortality related to cardiovascular illnesses. Although the cause was unclear, there was a relationship between noise pollution and cardiovascular illnesses. Epidemiological studies work well in creating a link to the past or the current state of health for a defined population group and to past and current exposure levels for various environmental pollutants. Furthermore, epidemiological studies like HIAs and exposure studies qualitatively account for risk.

Exposure studies work on solely quantifying the concentrations within the living environment of receptors. Jung *et al*. (2010) assessed the personal exposure of residents within the vicinity of an airport by quantifying the concentrations of BTEX outdoors and indoors. The researchers found that concentrations measured at the airport were like concentrations measured in residents' homes. Jung *et al*. (2010) further reported on indoor and outdoor ambient concentrations in an air quality study which was used to measure exposure.

However, an HHRA would go further in quantifying risk by estimated HQ and ILCR, which are commonly used in an HHRA. Having established that there has been evidence that shows that airport activity and resultant air pollution may have an impact on general human health, it is necessary to analyse epidemiology, HIA, and HHRA at airports. HHRA has been used by several airports to quantify emission risk (Intrinsik, 2015; LAWA, 2004). The discussion will now focus on defining HHRA and the method used for this assessment.

2.2 Human Health Risk Assessments

Several HHRAs have been conducted using guidelines from the US EPA and the WHO's Guidelines on Human Health Risk Analysis (Kim *et al*., 2015; US EPA, 2014; Golder Associates, 2015; Instrink, 2015). An HHRA is defined as "a scientific study that evaluates the potential for the occurrence of adverse health effects from exposure of people to chemicals of concern present in the surrounding environment media (air, water or soil), under existing or predicted conditions" (Intrinsik, 2015). HHRAs follow a process that has a few fundamental steps outlined in the process flow chart in Figure 2.1: Hazard Identification, Hazard Characterisation, Exposure Assessment, and Risk Characterisation.

2.2.1 Hazard Identification

The first part of the HHRA starts with framing the questions for investigation in the Hazard Identification (World Health Organization, 2010). It begins by defining the problem statement, which stipulates the scope of the assessment and gives the direction to health assessors as to the pollutant that will be under investigation. Secondly, it looks at the related health effects of the chemicals being investigated (US EPA, 2014). Lastly, the health effects of the chemicals of interest are further evaluated in the Hazard Assessment.

2.2.2 Hazard Assessment

The Hazard Assessment looks at identifying hazardous elements by looking at the probable health effects humans may be prone to due to exposure to selected toxic chemicals and investigating the relationship between concentration levels and health effects (US EPA, 2014; World Health Organization, 2010, 2014). This step is supported by policy guidelines and legal emission restrictions for the chemical of concern which will provide minimum exposure guidelines and levels of acceptable risk.

2.2.3 Exposure Assessment

The Exposure Assessment looks at different ways humans are exposed to the defined risk. In this step, the assessor considers elements such as frequency of exposure, duration, and distance of receptors to the source. Furthermore, the assessor also looks for ways in which they can account for pollutant concentrations through direct measurements of pollutants in the carrier medium (Intrinsik, 2015; US EPA, 2014; WHO, 2014). The results obtained from the Exposure Assessments are then used in performing a Risk Characterisation.

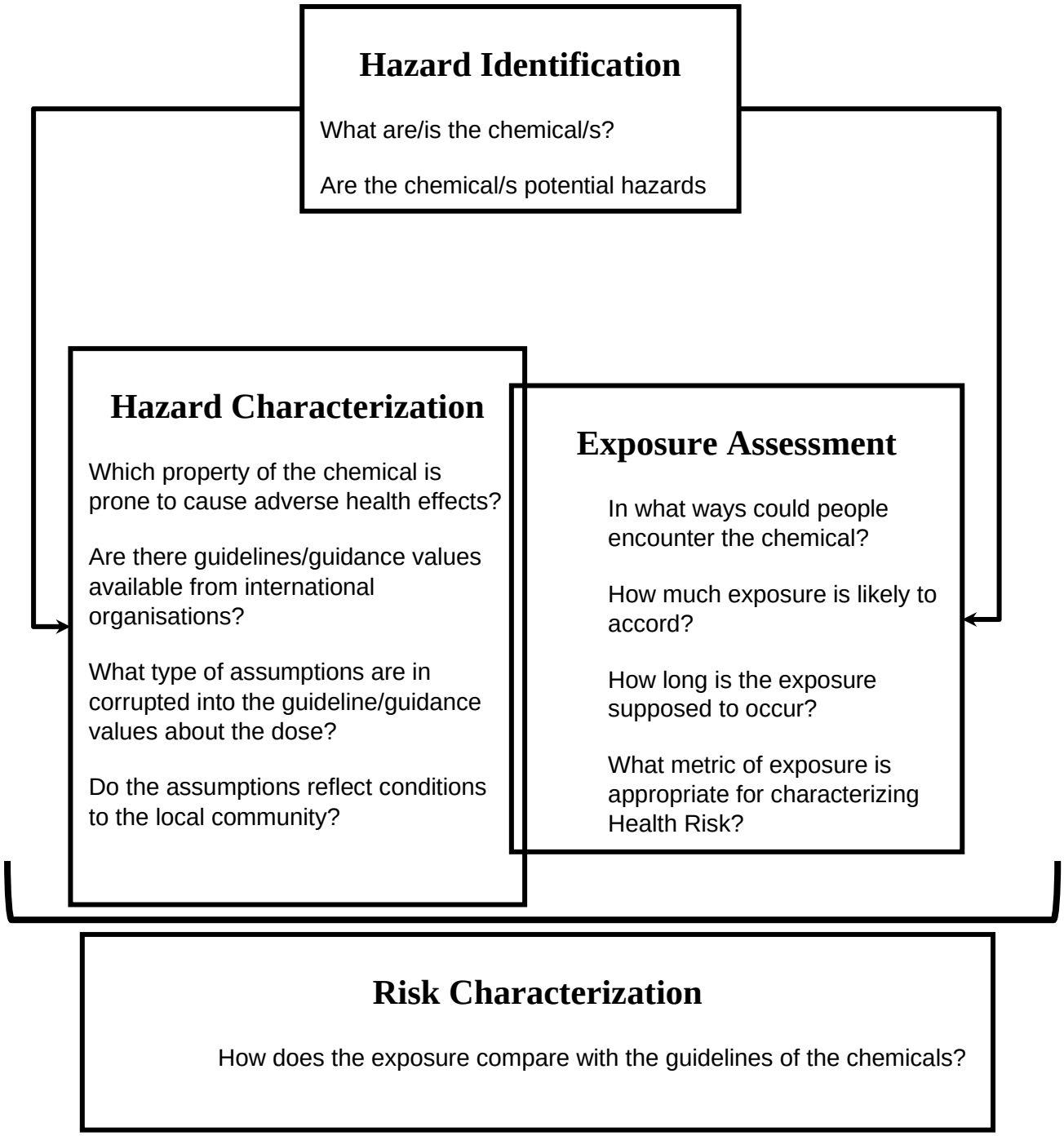


Figure 2.1: Human Health Risk Assessment process. Source: adapted from US EPA (2014).

2.2.4 Risk Characterisation

Risk Characterisation is a process in which risk is qualitatively and quantitatively expressed (Fowle and Dearfield, 2000; US EPA, 2014; World Health Organization, 2010). The risk is expressed as a function, using concentration-response equations for health outputs such as cancer risk and general health effects using the Incremental Lifetime Cancer Risk equations

(ILCR), the Hazard Quotient (HQ), or a Concentration Ratio to calculate cancer risk and general health impact (Intrinsik, 2015; World Health Organization, 2010).

2.3 Human Health Risk Assessments Conducted at Airports

HHRA studies have been amongst the popular types of health studies used to evaluate the potential health implications that airport-related activity poses on surrounding communities and for on-site employees (Intrinsik, 2015; Kim *et al*., 2012; LAWA, 2004). Table 2.1 outlines some of the HHRA conducted for airports.

Table 2.1: Human Health Risk Assessment conducted for airports

Year	**Airport**	**Emission Accounting Method/ Health evaluation method**	**Findings**	**Reference**
2004	Los Angeles World Airport	Develop Inventory and Modelling/ HHRA	No significant risk	LAWA (2004)
2013	Hartsfield-Jackson Atlanta International Airport	Aircraft PM2.5 modelled take-off and landing phases/ HHRA	PM2.5 emissions are responsible for 1.4 of premature deaths for adults >25 years.	Rissman *et al*. (2013)
2015	Toronto Pearson International	Developed emission inventory and modelled emissions/	For estimated emissions in 2022 Benzene was above the $1x\ 10^{-06}$ US	Intrinsik (2015)

	Airport	HHRA	EPA guideline.	
Not provided	John Wayne and proposed Orange County International Airports	Developed emission inventory/ HHRA	Cumulative Excess Cancer is 3.31 x 10^{-04} and 3.15 x 10^{-04} for Orange County and John Wayne airport respectively.	Lindberg *et al*. (n.d.)
2016	Cape Town International Airport	Developed an Emission Inventory/ EIA/HHRA	Significant risk during construction but risk is not significant post-construction.	Unknown
2015	12 Airports in California	Carbon Monoxide (CO)/ HHRA	One standard deviation increase in daily CO leads to an increase of $540 000 in hospital costs for 6 million people for respiratory and heart-related admissions.	Schlenker and Walker (2016)

HHRAs were conducted through two types of studies at the Los Angeles World Airport and Toronto Pearson International Airport (LAWA, 2004; Intrinsik, 2015). The first study conducted as part of phase 1 in Figure 2.2 is air quality pollution evaluation. During this part, the researchers either developed emissions inventory to model emissions or measured to account for emissions related to airport activity (Kim *et al*. 2012). The concentrations accounted for in the air quality study were then used as inputs for the HHRA as done at the Toronto Pearson International Airport (Intrinsik, 2015; LAWA, 2004). This study will look at

the various air quality studies conducted in and around airports by examining various air quality methods and emissions typical in an airport.

2.4 Methodological Approach of the Human Health Risk Assessment in an Airport Environment

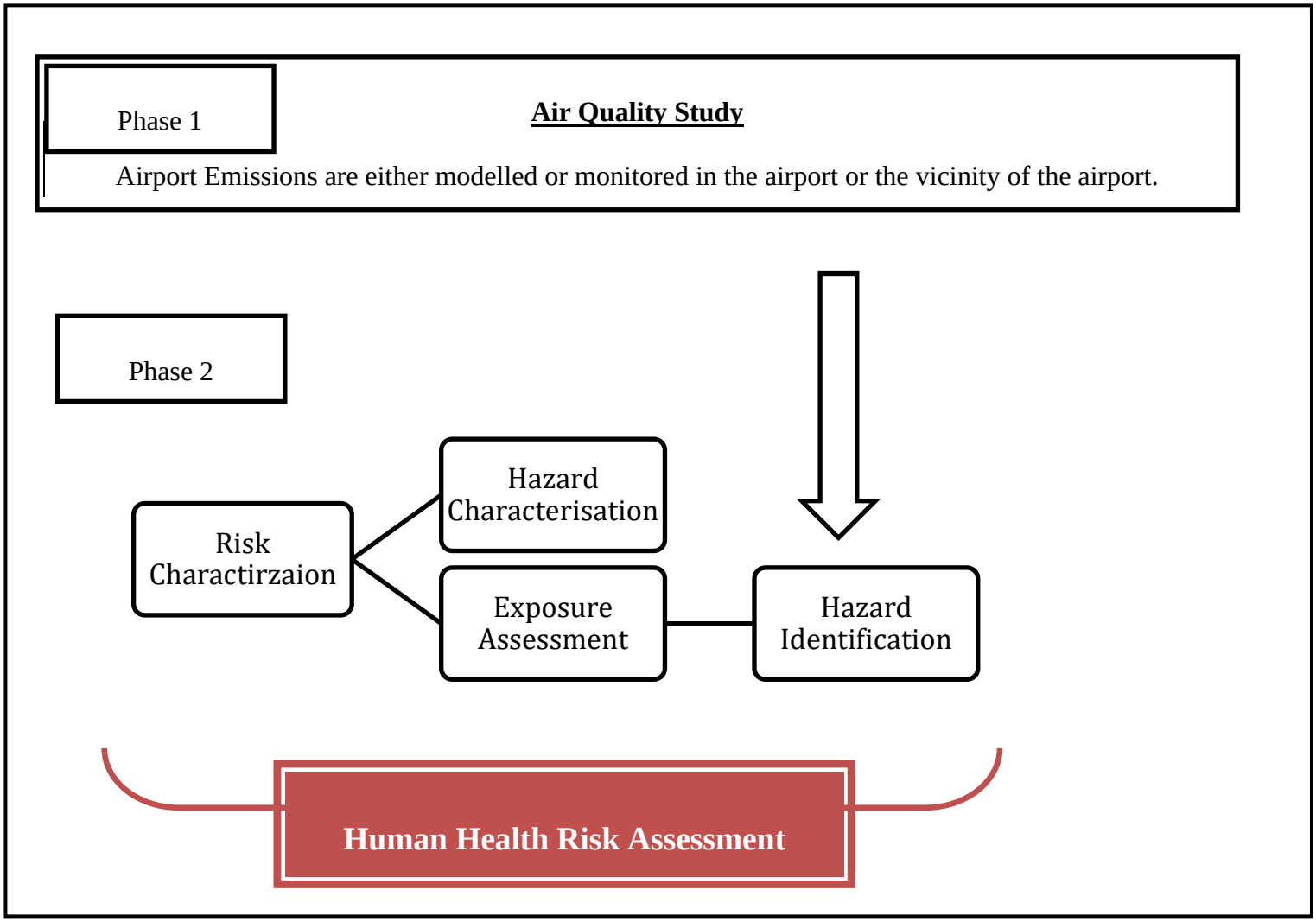


Figure 2.2: Process flow of a Human Health Risk Assessment at an airport showing how an Air Quality Study (phase 1) links with the general steps of a Human Health Risk Assessment (phase 2)

2.5 Air Quality Methodological Approaches

An airport is a complex environment, commonly characterised by fuel farms, administrative buildings, airport terminals, parking lots, aircraft hangars, taxiways, waste sites, and runways (FAO, 2003; ICAO, 2011; Kim *et al.*, 2012). All the characteristics of an airport are

associated with numerous types of emissions. A massive consideration for emission sources in airports is the aircraft, which have been noted to account for up to 97% of the annual landing and take-off emissions (ICAO, 2011; Kurniawan and Khardi, 2011; Mazaheri *et al*., 2011). Kurniawan and Khardi (2011) have noted that when the environmental impact of aircraft emissions is evaluated, this is done globally in the cruising phase of the aircraft as well as locally in the landing and takeoff phase. In the interest of this project, this study will consider regional air pollution analysis, which focuses on the landing and takeoff phase of the aircraft affecting the local air pollution at an airport.

In previous studies, they have either made direct measurements using various types of air monitoring equipment or modelling techniques which are endorsed by the ICAO and FAA FAA (FAO, 2003; ICAO, 2011; Kim *et al*., 2015). Table 2.2 provides a list of air quality studies that have been conducted in Northern America and Europe. Alongside these studies is an outline of the emissions studies and the technique used in each study.

2.5.1 Quantifying emissions through modelling

The method chosen for an airport air quality study is dependent on the scale of the project and resources available (ICAO, 2011; Kim *et al*., 2012). Emission modelling is one of the common ways airports conduct their Air Quality studies. Although they are cost-effective, they require a specialist with adequate skills and experience in modelling emissions. As such, this method has been widely used by consulting companies and research groups in conducting air quality analyses at airports as seen in Table 2.2, where studies such as (Golder Associates, 2015; Loader, 2013; LAWA, 2004) have been conducted by a consulting company.

The ICAO has provided guidelines for several emission modelling approaches which vary depending on the number of input parameters needed. However, theoretically, emission modelling is an extensive process which includes a process of accounting for emissions at the airport, by identifying sources of emissions and building an inventory. This is followed by the spatially and temporally modelling of emissions (ICAO, 2011; Kim *et al.,* 2012). In emission accounting, two types of datasets are required, namely emission factors and activity logs for all the sources. The extent of information required in this method leaves room for uncertainties, although this method is built to support large entry of data that is publicly available. Once all emission sources and possible emission types are identified, an emission

Table 2.2: Airport Air Quality Studies conducted at different airports, with varying methods, approaches, and emissions

Year	Airport of interest	Variables/Context	Analysis	Authors
2004	O'Hare Airport	Impact of Jet Fuels on Air Quality	Modelling using EDMS	Tesseraux, (2004)
2005	Atlanta International Airport	PM $_{2.5}$ and PM_{10}, Ozone, Gaseous matter, SO_2 and NO_x	Modelling using EDMS	(Unal et al., 2005)
2006	United Kingdom	Impact of different sources in an airport on Local Air Quality.		Peace et al., (2006)
2006	Zurich Airport	Impact of NO_x CO and VOCs on emissions		(Schu¨rmann et al., 2006)
2009	The United States and Canadian Airports	Impact of airport air quality on local emissions	(CMAQ)	(Ratliff et al., 2009)
2010	European Airports: Budapest Airport, Frankfurt Airport, London-Heathrow Airport, London-Gatwick Airport, Manchester Airport, Paris Airports, Madrid-Barajas Airport, Barcelona Airport, Palma de Mallorca Airport, Geneva International Airport, Vienna Airport, Zurich Airport, Athens International Airport	Effects of Airport operation on Local air quality	Monitoring	Airports Council International (2010)
2011	Los Angeles World Airport	Ultrafine particles PM $_{2,5}$ Black carbon	Monitoring	Zhu et al. (2011)
2012	Heathrow Airport	NO and NO_2	Monitoring	Rand et al. (2012)
2013	Hartsfield-Jackson Atlanta International Airport	$PM_{2.5}$	Modelling using AMSTERDAM	Rissman et al. (2013)
2013	Zurich Airport Emission Inventory.	Air Quality monitoring at the airport.	Modelling and monitoring of NO_x	(Duchene and Fuller, 2011)

EDMS: Emission and Dispersion Modelling System; CMAQ: Community Multi-Scale Air Quality Model; AMSTERDAM: Advanced Modelling System for Transport, Emissions, Reactions, and Deposition of Atmospheric Matter technology. Source: FAO, 2003; ICAO, 2011; Kim *et al*., 2012, 2015.

inventory is built and used in modelling emissions. A variety of modelling technology exists, as outlined in Table 2.3.

Table 2.3: Outline of conventional dispersion models with respective sponsors and developers

Model	**Model developer**	**Sponsoring organisation**
EDMS	FAA	United States
ADMS-Airport	CERC	United Kingdom
ALAQS-AV	Eurocontrol	France
LASPORT	Janicke Consulting	Germany and Switzerland

The outputs from these models are spatial and temporal, which allows researchers to readily associate pollutants to a specific receptor for an HHRA. The Los Angeles World Airport (2004) and Intrinsik (2015) have used spatial and temporal outputs to identify areas of high concentrations and, subsequently, at-risk populations. The emissions from modelled results are then used in the HHRA to calculate the probable health risk effects of the general population or the at-risk personal (FAO 2003; LAWA, 2004; ICAO, 2011; Intrinsik, 2015). Emission modelling gives insights not only into the static view of risk but it also allows for a dynamic view through time and spaces while allowing one to make future predictions of emissions.

Emission Modelling comes with its challenges and falls victim to the accuracy of information provided by the airport (Kim *et al*., 2012). Furthermore, due to the nature of the method, it does not take into consideration the relationship between emission sources, which can affect the results of the air quality study (Kim *et al*., 2012; FAO, 2003). Despite these pitfalls, emission models have been a favourable method for air quality studies as they are less

expensive than monitoring and give researches more analytical power while allowing one to break down emissions to specific sources, unlike the monitoring.

Monitoring has not been used extensively in airport air quality studies and health risk assessments because it poses several challenges. One such challenge that may be important in the context of conducting Risk Assessments is that monitoring does not provide source-specific emissions (Masiol and Harrison, 2014). Source-specific emission data can be of importance considering health risk assessments in identifying risk areas and employing mitigation strategies (Masiol and Harrison, 2014). The results produced by a monitoring campaign can be profoundly affected by the incorrect use of the equipment and the incorrect choice in equipment (Kim *et al*., 2015). Nevertheless, monitored data is trusted to validate modelled emission and can be used as background concentrations in models (Kim *et al*., 2015; Peace *et al*., 2006). Unlike monitoring, the modelling process gives researchers the ability to study the probable impact of airport emissions on the surrounding local air quality, which predicts emissions around the airport for up to 10 kilometres.

2.5.2 Impact of airport source emissions on local air quality

The impact of airport activity on local air quality has been of concern in the past few years. In 2010 the ideal situation was created, where emission sources were segregated to investigate the influence of airport-related sources on urban pollution. This was the case in Europe in April 2010, when flights were grounded due to a volcanic ash eruption that formed a cloud of ash in the atmosphere. With the aircraft's grounded, this offered a perfect opportunity for airport air quality researchers to investigate the influence of aircraft emissions on surrounding communities. Several European regional airports participated in the study of an extensive network of monitoring sites which were used across Europe to investigate Nitrogen Oxides (NOx) emissions (Loader, 2013). The results of the study concluded that changes in airport operations did not influence local air quality and the contribution of airport emissions to local air quality was slight.

Loader (2013), Carslaw *et al*. (2006), and Adamkiewicz *et al*. (2010) found similar results in their studies. Carslaw *et al*. (2006), looked that the influence of NOx from airports on local air quality found that at 1 - 1,5 km from the airport boundary the airport's contribution to local air quality reduced by 5-fold. However, emissions from the airport were detected at least 26 km from the airport. The local air quality for areas around the airport was found to be

very similar to those in urban environments. The highest concentrations of NOx were near road terminals and the NOx emissions were influenced by traffic-related activity. In most cases, it is challenging to correlate airport operations with local air quality, but little work has been done in this area. In the case of Airports Council International (2010) and Loader (2013), no apparent link exists between aircraft movement and ambient concentrations. However, meteorological conditions will have an influence on airport emission which, in turn, impact on local air quality which will influence dispersion patterns of emissions from sources (Helmis *et al*., 2011; Kim *et al*., 2012). Helmis *et al*. (2011) noted that background flow had an influence on concentration levels at sampling sites, with close to 50% influence of concentrations and its composition.

2.5.3 Pollutants from an airport

An airport's air composition is defined by air pollutants from a variety of sources. The primary sources that have been identified by the ICAO (2011) and Federal Aviation Administration Office of Environment and Energy (2003) in their research are aircraft, ground support equipment (GSE), vehicles around the airport, combustion from fire training, tyre burning, and painting. Table 2.4, as adopted from (Kim *et al*., 2015), shows some sources typical in an airport environment, with the likely pollutants emitted from the source as well as the pollutants of interested for Health concerns. Some of the criteria pollutants identified from various sources are Carbon Dioxide (CO), Hydrocarbons, Volatile Organic Compounds (VOCs), Nitric Oxides, Sulphides, and Particular Matter (PM10, PM2.5). Most of these pollutants have been the subject of airport air quality research, as seen in Table 4.2, although there have not been a wide variety of studies that focus on BTEX compounds within an airport environment. A study by Jung *et al.* (2010) focused on the exposure of populations living near an airport to BTEX compounds. They found that VOCs were emitted 30 % more during the Landing and Takeoff Cycle (LTO) than any other aircraft cycle (Jung *et al*., 2010).

2.5.4 Volatile Organic Compound monitoring at an airport

BTEX compounds have been the focus of many HHRAs in the past few decades (Hinwood *et al*., 2007). The BTEX group of aromatic hydrocarbons is one of the most universally present emissions in the atmosphere, due to the numerous sources, BTEX is associated with, namely: vehicles, refuelling stations, burning fossil fuels, and solvents. These sources are also

identified within an airport environment (ICAO, 2011), making BTEX an appropriate group to investigate within the context of an airport.

A study by Loader (2013) included BTEX compounds in an air quality study conducted at Heathrow International Airport at an onsite monitoring station. Loader (2013) choose to analyse BTEX compounds out of the group of VOCs that may be present in the airport environment because of the ease at which they can be sampled using diffusion methods. Several sampling methods have been used in sampling BTEX emissions, from active to semi-active samplers, and passive diffusive sampling (Skov, 2001). Above all, diffusive methods of sampling are favourable for HHRAs because in a health assessment researchers are more concerned with cumulative exposure to pollutants over long periods, from a couple of days to a week (Skov, 2001). Diffusive methods have been widely used in the past to sample BTEX emissions in a variety of environments for exposure or health studies to air quality studies.

2.6 BTEX Characteristics

BTEX compounds are known as highly volatile pollutants due to their photochemical behaviour (Alghamdi *et al*., 2014; Pallavi Saxena, 2012; Pérez-Rial *et al*., 2009; Zalel *et al*., 2008). These compounds have a short atmospheric lifetime of 9.4, 1.9, 1.7, and 0.27 days for benzene, toluene, ethylbenzene, and xylene compounds, respectively. BTEX is removed from the atmosphere by the reaction of the BTEX compounds with Hydroxyl Radical (OH) during the day (Perez-Rial *et al*., 2009). This reaction increases during higher temperatures throughout the day. Zalel *et al*. (2008) noted that BTEX ambient concentrations have a strong correlation with solar radiance variations. There is a higher concentration in winter than in summer, where summer has a higher potency for higher solar irradiance (Algamadi *et al*. 2014; Pallavi Saxena, 2012).

2.6.1 Seasonal variation

BTEX compounds have been seen to have a notable seasonal variation with atmospheric stability having a significant influence on BTEX concentrations (Alghamdi *et al*., 2014; Pérez-Rial *et al*., 2009; Zalel *et al*., 2008). Toluene, ethylbenzene and xylene concentrations were noted to have higher evaporation rates in summer, where there is a decrease in atmospheric stability, as opposed to winter where there is increased atmospheric stability. In summer, Pérez-Rial *et al*. (2009) found that sampling in summer after rains yielded higher concentrations than days where there were no rains in summer. In most studies, it was found

Table 2.4: Airport sources and associated pollutant emissions (adopted from Kim, *et al.*, 2015)

Source Types	**Pollutants That Can Potentially Be Emitted**	**Main Pollutants of Interest for Health Concerns and Research**
• Aircraft main engines (jet, turboprop, and piston/GA) • APU	• Criteria: CO, HC/VOC, NOx, PM10, PM2.5, SOx • Criteria: Pb (only GA aircraft using AvGas) • HAPs: VOCs, aldehydes and ketones, PAHs, dioxins and furans • Ultrafine PM • Other PM species: black carbon, nitrates, sulfates	• Criteria: HC/VOC, NOx, PM2.5 • Criteria: Pb (only GA aircraft using AvGas) • HAPs: VOCs, aldehydes and ketones, PAHs • Ultrafine PM • Other PM species: black carbon, nitrates, sulfates
• GSE (baggage tractor, belt loader, service truck, etc.) • GAV (passenger vehicles, airport-owned vehicles, shuttle buses, etc.) • Construction: combustion (on-road and off-road equipment)	• Criteria: CO, HC/VOC, NOx, PM10, PM2.5, SOx • HAPs: VOCs, aldehydes and ketones, PAHs, dioxins and furans • Ultrafine PM • Other PM species: black carbon, nitrates, sulfates	• Criteria: CO, HC/VOC, NOx, PM2.5, SOx • HAPs: VOCs, aldehydes and ketones, PAHs

• Stationary sources: combustion (boiler/heater, incinerator, power generator, etc.) • Training fires	• Criteria: CO, HC/VOC, NOx, PM10, PM2.5, SOx • HAPs: VOCs, aldehydes and ketones, PAHs, dioxins and furans, metals, acids (metals and acids generally not associated with training fires) • Ultrafine PM • Other PM species: black carbon, nitrates, sulfates	• Criteria: CO, HC/VOC, NOx, PM2.5, SOx • HAPs: VOCs, aldehydes and ketones, PAHs, dioxins and furans
• Stationary sources: fugitive (maintenance, painting/coating, etc.) • Construction: fugitive (demolition, asphalt paving, wind erosion, dust re-entrainment from roadways, etc.)	• Criteria: PM10, PM2.5 • HAPs: VOCs • Other PM species: black carbon, nitrates, sulfates	• Criteria: PM2.5 • HAPs: VOCs

that BTEX concentrations were lower in summer than in winter due to atmospheric stability (Hoque *et al*., 2008).

2.6.2 Temporal variation (distribution of pollutant sources)

Wind patterns can vary seasonally and thus affect the seasonal dispersion patterns of emissions (Kim *et al*., 2015). Pérez-Rial *et al*. (2009) noted that when wind speed increases the BTEX concentrations decrease, which causes photochemical reaction to speed up. On the other hand, windspeed favours BTEX accumulation, which causes higher concentrations during windy months (Alghamdi *et al*., 2014). The mixing processes are also affected and can

redistribute pollutants through advection and convective transport on regional and long-range scales (Alghamdi *et al*., 2014).

BTEX emissions will start reacting at a distance from the sources; the photochemical behaviour of BTEX compounds have been evaluated through ratios between BTEX species (Alghamdi *et al*., 2014). In the case of the toluene to benzene ratio, Pérez-Rial *et al*. (2009) noted that differences in the ratios could indicate the pollutants' distance from vehicle sources. The outdoor BTEX concentrations are noted to be lower than indoor sources, and this can be attributed to the stronger influence of dispersion on pollutants on outdoor emissions (Jung *et al*., 2010; Masih *et al*., 2017).

2.6.3 Use of predictive methods to analyse and estimate BTEX ambient concentration

Jung *et al*. (2010) and Masih *et al*. (2017) sampled different microenvironments in order to evaluate the BTEX exposure. However, if the number of samples increases, this would drive up the cost for sampling and lab analysis. Therefore, the use of predictive methods, such as kriging can help alleviate the cost of sampling. Whitworth *et al*. (2011) experimented with the use of interpolation methods and kriging in evaluating benzene exposure comparing it to a predictive modelling technique. The results of the methods were mostly different. Due to minimal inputs into the kriging method, Whitworth *et al*. (2011) suggested that more sampling points be used. Concentration estimates are used in determining exposure levels for pollutions, and thus detailed sampling is not required. BTEX concentration is a common component of urban environments and has numerous health effects. That is why they have been the subject of many HHRA. The study will outline some of the common ways in which humans are exposed to BTEX and the associated health effects.

2.7 Outline of Human Health Risk Assessment for Exposure to BTEX Emissions

In light of the influences of environmental concentrations on BTEX, it is common practice for environmental concentrations to be used as the base for the exposure concentrations in an HHRA (US EPA, 2014; Masih *et al*., 2016, 2017). Several studies have been conducted in the past few years looking at the HHRA of BTEX in different microenvironments, such as paint shops, car parks, and waste sorting sites that can be found in an airport environment as outlined in Table 2.5.

Table 2.5: Human Health Risk Assessment for BTEX exposure in different environments

Year	Location	Context	Analysis	Author
2012	Buenos Aires, Argentina	Indoor occupational HHRA is an electromechanics repair shop, paint shops, laboratories, and sewing room	Passive diffusive monitors (3M-3500) Analysis using GC-FID	Lerner *et al*. (2012)
2012	Colorado, USA	HHRA for community living near natural gas resources	Used data collected in the state for short-term study and ongoing monitoring program	McKenzie *et al*. (2012)
2012	Bangkok, Thailand	HHRA amongst gasoline station workers for BTEX exposure	Charcoal Tubes	Tunsaringkarn *et al*. (2012)
2004	Hong Kong	ILCR of cooks, food service workers, housewives, and	Canisters and passive samplers	Guo *et al*. (2004)

		school children for exposure to VOCs		
2010	Montreal, Canada	BTEX exposure and associated health risk for automobile mechanics and painters	Atmospheric pressure chemical ionisation-tandem mass spectrometry (APCI-MS/MS) method	Badjagbo *et al*. (2010)
2007	Australia	Analysis of the increased risk factor of BTEX for four cities in Australia	Passive Samplers	Hinwood *et al*. (2007)
2006	Taiwan	The indoor air quality of photocopy centres and evaluation of the HHRA from inhalation exposure	Personal samples and area samples	Lee *et al*. (2006)
2007	India	Evaluate the contribution of	Background concentrations	Karakitsios *et*

		petrol stations to ambient air and the associated health risk	Passive Samplers COPERT and CALINE4 used to model roadside emissions	*al*. (2007)
2008	Kolkata	Occupational exposure and associated health risk to monoaromatic hydrocarbons and carbonyls for petrol station workers	Charcoal sorbent tube	Majumdar (neé Som) *et al*. (2008)
2010	La Plata, Argentina	Indoor and outdoor distribution and Risk Assessment of VOCs in industrial areas	Passive 3M monitors	Massolo *et al*. (2010)
2016	Tehran, Iran	Investigate the distribution and Risk Assessment associated with	Samples collected using a continuous monitoring device	Miri *et al*. (2016)

		BTEX	VOC71M-PID	
2016	Gorakhpur	Investigation of BTEX inhalation exposure and associated health risk	Samples were extracted with carbon disulphide by occasional agitation, and the aromatic fraction was subjected to GC-FID	Masih *et al*. (2016)
2017	Gorakhpur	Exposure profiles of residents in Gorakhpur	Activated charcoal tubes using a low flow SKC model 220 pumps	Masih *et al*. (2017)
2010	Kocaeli, Turkey	Health risk in a landfill environment	Stainless steel sampling tubes using SKC AirLITESample r	Durmusoglu *et al*. (2010)
2015	South Africa	Occupational exposure to BTEX in a bus refuelling station	Passive Sampling	Moolla *et al*. (2015 a)

2013	South Africa	Occupational exposure to Benzene and Toluene at a landfill site	Passive Sampling	Moolla *et al*. (2013)
2014	Turkey	Personal Exposure of school children to BTEX and NOx in an urban and suburban environment	Organic vapour monitors and Passive Sampling	Demirel *et al*. (2014)
2017	India	Exposure Profiles and seasonal variation of health risk	Pump	Masih *et al*. 2017)
2016	India	Health Risk Assessment	Pump	Masih *et al*. (2016)
2010	United States	Calculate Daily-Adjusted Life Years for exposure to BTEX in landfills	Pump	Durmusoglu *et al*. (2010)

The widespread concern over BTEX and its effects on human health are evident in the extensive investigations of HHRA. BTEX emission sources include vehicles and aircraft emissions, paint, solvents, and detergents – all prominent sources in an airport (Badjagbo *et al.*, 2010; Curtis *et al*., 2006; Majumdar (neé Som) *et al*., 2008; Massolo *et al*., 2010; Zalel *et al*., 2008). Table 2.6 outlines some of the studies and the estimated probable health effects for non-cancer risk using the HQ, cancer risk assessment, and ILCR. As noted, most studies have found that the estimated ILCR for exposure to benzene concentrations has been above the US EPA threshold of 1×10^{-06}. On the other hand, the HQ was above the threshold of 1 for two studies in the table below. However, Bolden *et al*. (2015) conclude that the four elements may have very harmful properties at exposure levels below guideline concentrations, recommending that a new approach be taken for looking at the risk associated to these elements.

Table 2.6: Outline of BTEX Human Health Risk Assessment and the respective Hazard Quotient and Incremental Lifetime Cancer Risk (variables of HQ and ILCR that are above-recommended guidelines are marked in bold)

Author	**HQ**	**ILCR**	**BTEX Concentrations**	**Microenvironments**
Durmusoglu *et al*. (2010)	<1	**6.75 x 10-05**	B=140.3 T=239.9 E=127.7 X=341.3	Residential area near landfill site
McKenzie *et al.* (2012)	**>1**	**3.03 x 10-06**	-	Neighbourhoods near natural gas resources

Masih *et al.* (2016)	**>1** (BTEX total) B=0.3, T=0.4, E=0.6, X=1	**7.6E-06 to 1.0 x 10-05**	B=15.91 T=28.21 E=3.88 X=2.84	Residential, industrial, agricultural and roadside
Miri *et al*. (2016)	<1	3.93E-07	-	Urban area Tehran, Iran
Demirel *et al*. (2014)	<1	**1 x 10-04**	-	School children in different microenvironments
Majumdar *et al.*, (2011)	**>1**	**3 x10-05**	-	BTEX in Metropolitan City
Tunsaringkarn *et al.* (2012)	<1	**1.75 x10-04**	-	Gas station workers

BTEX concentrations will vary across environments and microenvironments; therefore individual exposure to various chemicals will vary, and depending on the environments they encounter (Colman Lerner *et al*., 2012; Demirel *et al*., 2014; Masih *et al*., 2017; McKenzie *et al*., 2012). Demirel *et al*. (2014) found that individuals in urban areas had ILCR almost two times greater than those in suburban areas. This was due to the different micro-environments for the two groups. The group that was exposed to traffic and had passed a refuelling station on their way to school had high exposure to BTEX compounds which also resulted in higher risk. The other influence was the vicinity of the children's homes to significant sources of BTEX such as refuelling stations. Lerner *et al*. (2012) and Demirel *et al*. (2014) noted that a person's exposure to BTEX is linked to their home and/or working place. Environments like

refuelling stations and electromechanical repair shops or painting shops have higher BTEX concentrations, resulting in higher benzene ILCR (Lerner *et al*., 2012).

2.8 Conclusion

With a global increase in concerns over the effects of airport-related activity (Kim *et al*., 2012; Burdzik 2016), the global interest in investigating the environmental presence of BTEX emissions and the subsequent health effects are also increasing. Little work has been done in this dynamic area in, for example, an airport which has multiple sources of BTEX emissions from aircraft, mobile vehicles, paint shops, fuel farms, and activities such as fire and refuelling. Significant evidence is presented in other studies of the risk associated with BTEX in various microenvironments within the airport environment. This includes high vehicle or traffic areas, paint shops, waste sorting sites, and fuel farms. Little research has been documented that evaluates BTEX air quality or risk at the airport. Studies by Jung *et al*. (2010) and Loader (2013) has explicitly looked at BTEX emissions at an airport while other studies developed emission inventories to account for the BTEX emissions alongside other emissions. Emissions are accounted for either through modelling or monitoring in an airport environment.

With an overview of the literature that addresses health risk studies, physical and chemical properties associated with BTEX, as well as an outline of the air quality and health risk studies conducted at airports, this study will delve into the methods and materials used to conduct the HHRA at a South African international airport.

2.9 Study Site

The study site is a South African privately-owned airport which flies domestic flights to other major cities in the country, local private flights, as well as private international flights. The map in Figure 2 shows the location and boundary of the study airport in red. The airport is in the north-west of Gauteng in the City of Johannesburg Metropolitan. As of 2016, there were four main human settlements within an approximate 5 km boundary of the airport, namely: Blair Athlon Golf estate, Malatjie Informal Settlement, an unknown informal settlement, and Stonehaven Estate in the Southwest. There are numerous other small settlements and smallholder farms within this 5 km radius. There is also a growing industrial park southwest of the airport, not included in the map below.

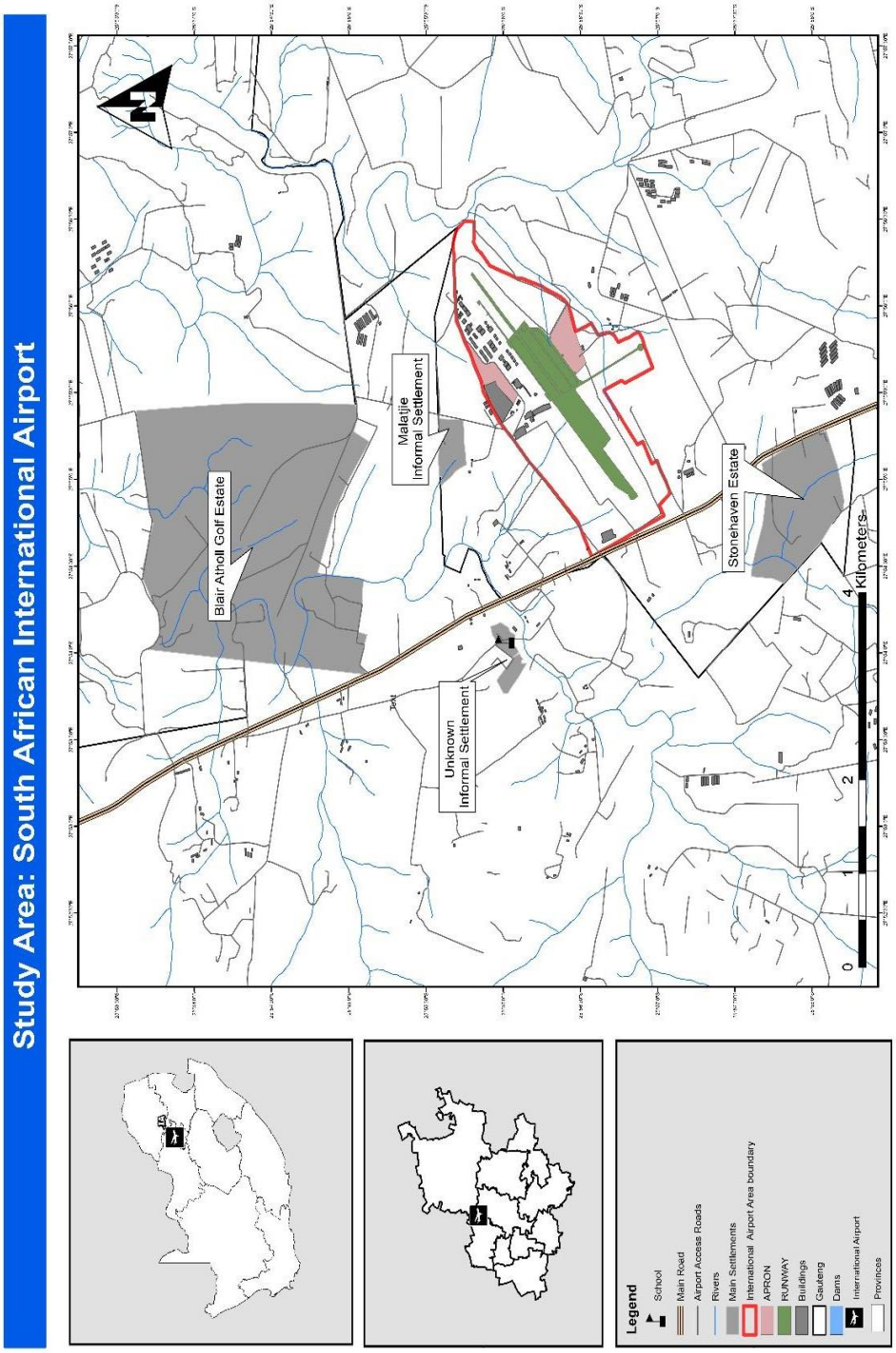


Figure 2.3: *Study Site Map of the South African International Airport* (a): location of the airport within the Gauteng Province; (b): relative location of the airport in the Gauteng province towards the west boundary of the province; (c): the airport and the main settlements in the area

Chapter 3: Material and Methods

3.1 Introduction

In conducting the Inhalation Health Risk Assessment, the methodological strategy that was followed was adapted from the United States Environmental Protection Agency (US EPA) and the WHO (US EPA, 2014; World Health Organization, 2010, 2016). The Los Angeles World Airport Master Plan Projects HHRA as well as the Toronto Pearson International Airport HHRA, which are sublimated mainly by the US EPA guidelines, have served to guide parts of the implementation of the methodological strategy (Intrinsik, 2015; LAWA, 2004). Deducing for the respective airport studies, an airport HHRA is conducted following two phases: an air pollution study, phase 1, which is followed by an HHRA as seen in Figure 2.2. Figure 3.1 outlines steps for the strategy followed in this HHRA.

3.2 Exposure Assessment

The Exposure Assessment forms an integral part of the HHRA as the information-gathering phase where the magnitude, frequency, and duration of human exposure to an agent in the environment is evaluated (US EPA, 2014). At this point, the assessor will look for potential receptors and pollutants, considering how the receptor and the pollutants come into contact and will decide on methods to use in order to quantify exposure. There are several ways to quantify exposure. In this case, a scenario-based evaluation was conducted where the concentrations of hazardous elements are measured separately from the receptors that had contact with the element (Badjagbo *et al*., 2010; Guo *et al*., 2004; Han and Naeher, 2006; McKenzie *et al*., 2012). The following section will discuss the procedure followed for the scenario-based exposure assessments, which include information gathering, BTEX emission estimations, selection of receptors, and inhalation assessment.

3.2.1 Information gathering and building a site conceptual model

Before conducting the air pollution analysis, the researcher had to have a clear understanding of the emissions sources around the airport. The researcher also had to understand the location of potential receptors relative to the sources in order to build a site conceptual model, noting the potential receptors and emission sources. The BTEX sources we identified during a site visit with one of the Airport Environmental and Risk Officers. This methodological approach based on the 2004 Los Angeles World Airport study in order to have a

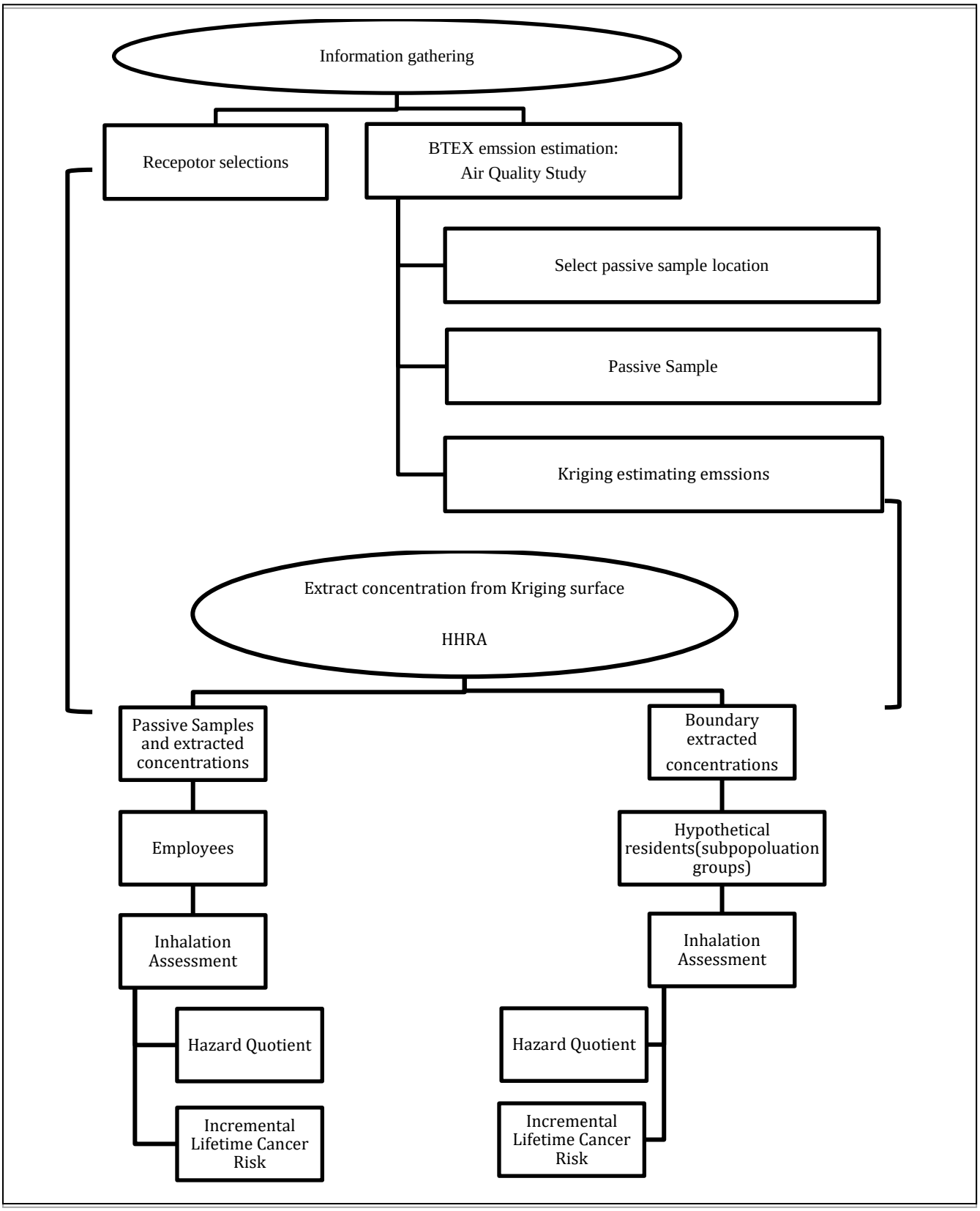


Figure 3.1: Process flow chart of the HHRA conducted at the South African International Airport with a scenario-based exposure assessment.

comprehensive understanding of all emission sources and potential at-risk personnel within and outside the airport. The visit helped in constructing a site conceptual model, as indicated below.

During the site visit, potential BTEX emissions identified are outlined in Figure 3.2. The identification of BTEX sources was based on sources that are commonly identified in the literature to be associated with BTEX. The emission sources were then categorised into three primary source types, area, mobile, and other sources. The potential sources of BTEX from mobile sources have been identified are; aircraft, GSE, and on-site and off-site vehicles which are airport and passenger vehicles. Aircraft and vehicle emissions are known to produce BTEX, with BTEX from aircraft emissions produced mostly during the landing and take-off cycle (Jung *et al*., 2010; Karakitsios *et al*., 2007; Zalel *et al*., 2008).

In an HHRA for gas station workers at a refuelling station, Tunsaringkarn *et al*. (2012) found that gas station workers who work in high traffic volume areas are prone to risk which is higher than the acceptable risk guidelines set by the US EPA. With area sources such as fuel farms, waste sorting sites, and airport hangers and airport buildings, there are several BTEX sources within these environments that are stationary. Han and Naeher (2006) note that BTEX compounds are emitted within stationary vehicles while parked. Taking this into consideration, the long-term parking areas in an airport can be a consistent source of emissions. The waste site can be a cause of concern because BTEX emissions have been associated with waste sites like landfills (Dumusoglu *et al*., 2010), although landfills are significantly bigger than on-site waste sites at airports. It is essential to investigate the site as a BTEX source because BTEX emissions can be of concern at any concentration. Other emission sources included items such as solvents, as well as emissions from the burning of an open veld around the airport. Veld fires were outlined by the airport as a concern because of its potential influence on the airport's emissions. The use of solvents indoors is also a concern as the concentration of BTEX is higher because of a lack of distribution of emissions. Massolo *et al*. (2010) outlined that the health risk for indoor benzene in industrial areas was two times higher than health risks estimated for outdoor emissions.

During the visit, several locations were selected for sampling using passive Radiello Samplers and taking into consideration the airport's areas of concern. Along the drive around the airport, sites that were linked to BTEX emissions where identified, such as the car park

area, the fire station, waste sorting site, and aircraft hangers. At each location GPS co-ordinates of the source was recorded using a mobile mapping application, SW Maps. The locations of the potential BTEX sources were exported from SW Maps as a KML file, imported into a QGIS and superimposed on a map of the study area in order for the researcher to see that the locations selected for sampling are spatially representative. These sites where narrowed done to the 17 sites as depicted in Figure 3.3, based on their vicinity to the airport's mobile sources, proximity to the boundary of the airport with settlements near it, and environments for onsite workers.

3.2.2 BTEX instrumentation

The airport air quality assessment included passive sampling and kriging methodologies in order to measure BTEX emissions at the airport and predict the estimated emissions at the airport. A Radiello Passive Sampler was used in sampling BTEX concentrations at the boundary of the airport. A Radiello Passive Sampler is a diffusive sampler which is filled with a thermally desorbable adsorbent (graphitised carbon Carbograph 4) (Pennequincardinal *et al*., 2005). A plastic covering was used to cover the sampler to prevent damage from extreme weather conditions such as wind and heavy rain, as seen in Figure 3.4 (a). Passive sampling is a technique that has been regularly used in quantifying emissions in a scenario-based exposure strategy (Skov, 2001).

Radellio Passive Samplers were used in the past in France to sample benzene concentrations; they are easy to use and easily implemented (Pennequincardinal *et al*., 2005). They can be deployed for a maximum of 14 days, which has made it a sampling method of choice for studies used in roadside BTEX sampling campaigns and occupational settings (Moolla *et al*., 2015 (a). The passive samplers are designed to be exposed to a variety of chemical compounds within a heterogenous atmosphere, where light and massive compound could not affect sampling rates and samples (Pennequincardinal *et al*., 2005). The passive samples have sampling detection limits for all BTEX compounds between 0.015 and 0.73 um/m^{-3}.

There may be concern about the influence of the exposure time, wind speed, temperature humidity, and back diffusion. Exposure time humidity is noted to have little effect on sampling; however, wind spread will influence the sampling rate because wind speeds influence the diffusive length. The wind speed will also influence the average direction and dispersion of exhaust emissions (Pecorari *et al*., 2015). Thus, it is essential to note the

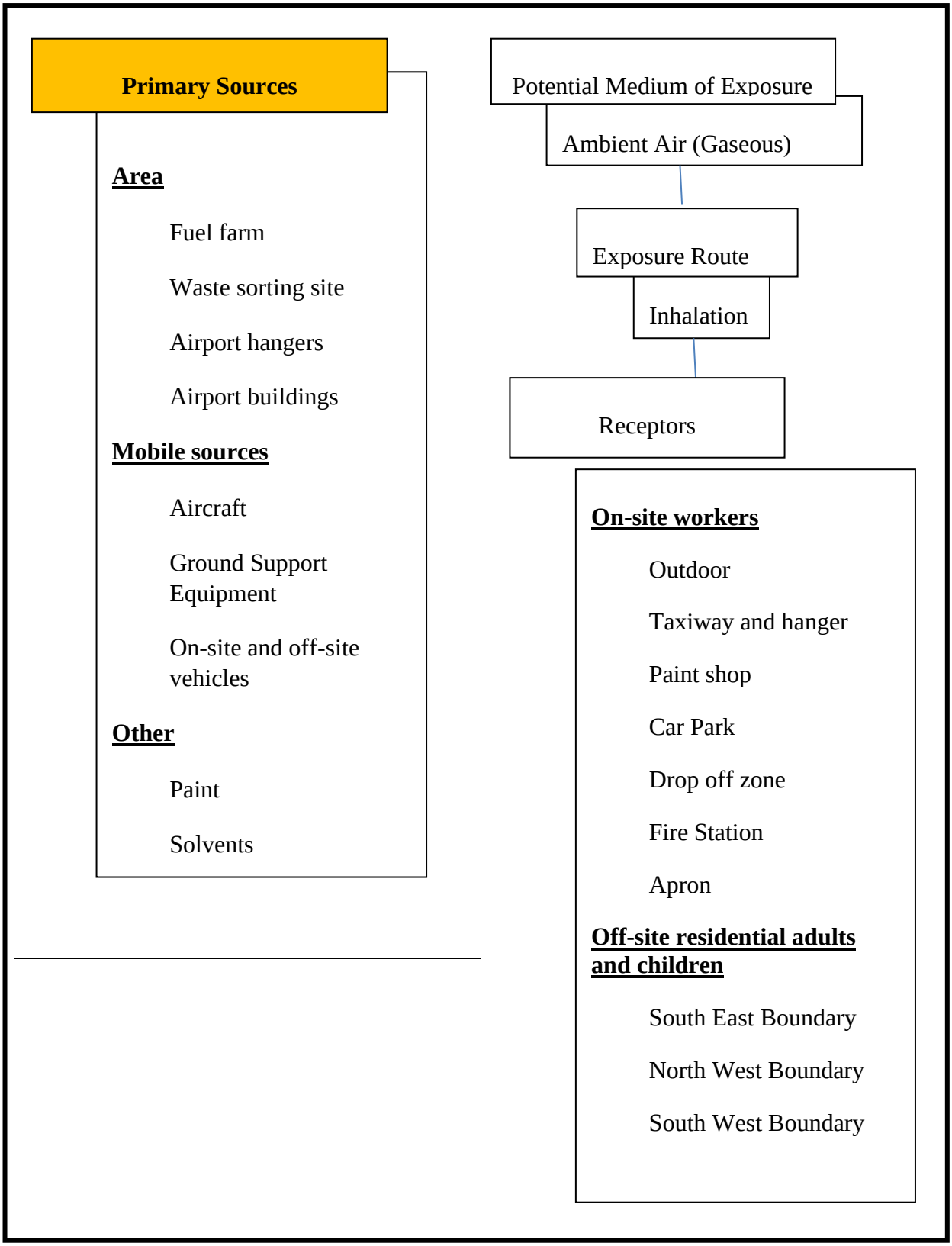


Figure 3.2: Site Conceptual model for a South African International Airport

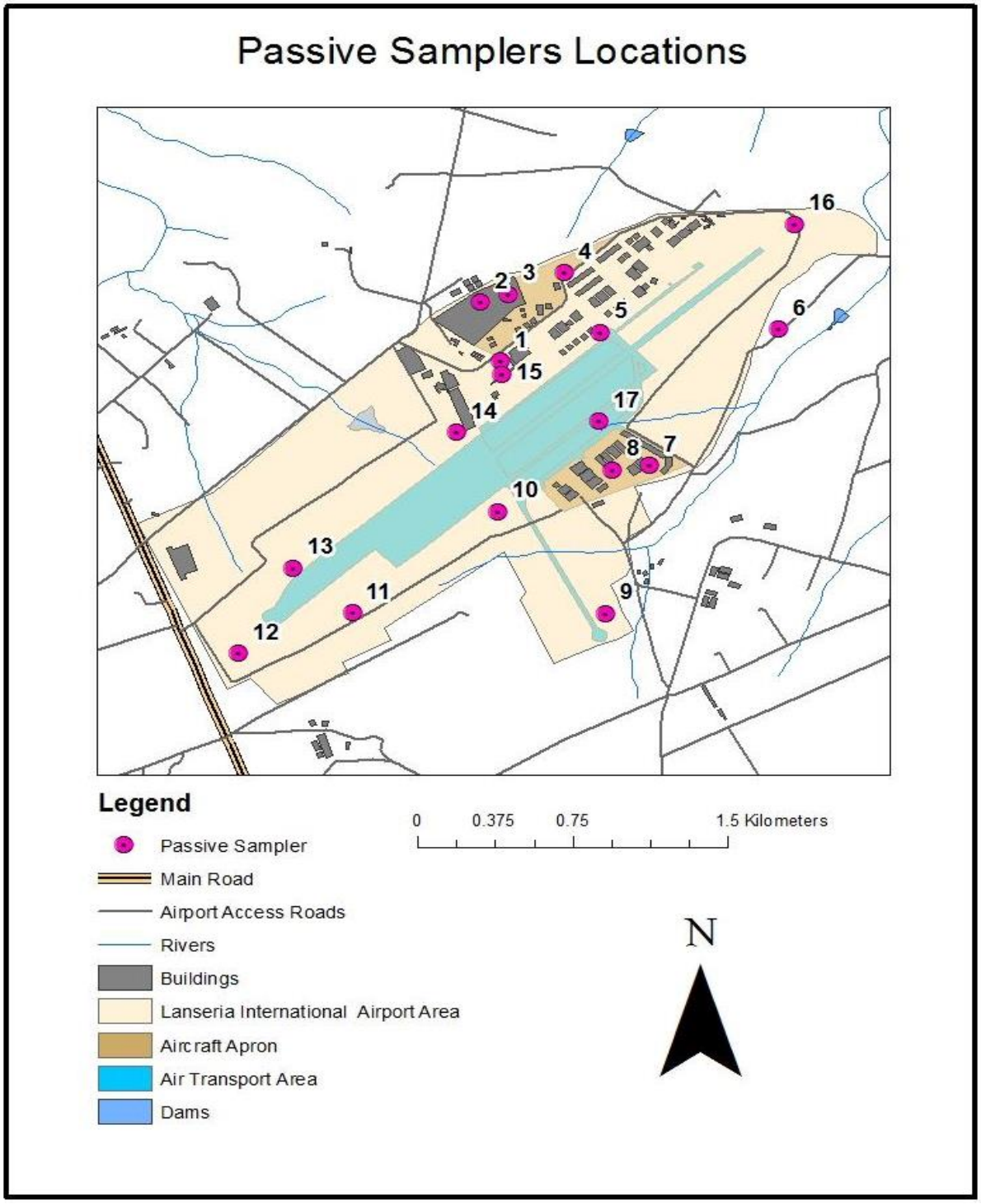


Figure 3.3: Map indicating the locations of samplers

(1) Drop-off zone; (2) Short term parking; (3) Long term parking; (4) Waste sorting site; (5) Taxiway by security booth; (6) Kelvin 5; (7) Opposite paint shop; (8) NAC fence; (9) Fire training site; (10) Fire station; (11) Gliding slope; (12) Runway approach; (13) Taxiway; (14) ExecuJet (hangers); (15) Gate 3 apron; (16) End of runway; (17) Taxiway south.

meteorological conditions of emissions during sampling. Common factors such as wind speed, relative humidity, wind direction, and solar insulation influenced the observed concentrations, as well as the temporal and seasonal variations noted.

The Radiello Passive Samplers were placed at the 17 sites, as seen in Figure 3.3. These locations were used for sampling in all four sampling campaigns. The sampling campaigns took place toward the last few months of each of the four of the Southern African seasons: spring, summer, autumn, and winter. In each campaign, the Radiello Passive Samplers were put up for a week at each location. When the samples were taken down, the thermally desorbable adsorbents were placed in sealed glass tubes, placed in a cooler box, and taken to ChemTech Lab for analysis.



Figure 3.4: Picture of the passive samples at various locations in the South African International Airport. (a) Sample with a plastic shield covering; (b) Diffusive sampler on the triangle. Source: images were taken by the author.

3.2.3 Kriging: Producing estimated BTEX emissions

The results from each sampling campaign were received via e-mail in a word document format. The results were manually transferred into an excel document that contained the name of each location as well as the x and y coordinates of each location. These were then imported into ArcMap 10.3/5. Using the x-y co-ordinate function in ArcMap, these were then

plotted. This enabled the researcher to associate each location with the resultant sampled emission. This was repeated for each sampling campaign. Each compound for each campaign was then interpolated using the ArcMap 10.5 geostatistical tool, kriging. Kriging is often used in risk assessments to map out the prediction of concentrations of contaminants between sampled locations and used to minimise the cost of sampling (Zhong, 2011; Whitworth *et al*., 2011). The kriging method was used to build a continuous raster surface with emissions on the entire surface of the airport area and, most importantly, to determine the boundary concentrations.

Kriging is a geostatistical tool which uses a set of known points in order to generate spatial surface otherwise known as a raster layer. The kriging tool fits a function to a number of points with a radius and determines the surface values within that radius. After estimating concentrations, the locations of receptors were defined, which is further discussed in section 3.2.4.

3.2.4 Selection of receptors and receptor locations

In selecting the location of receptors, some assumptions were made (the location of the airport also informed these assumptions). The location of the South African International Airport is the rural-urban environment, characterised mainly by game farms, commercial farms, informal settlements, and growing light industries around the southern boundary. Because of the surrounding land earmarked for development in the near future and due to the design of the assessment, it will be of value to conduct an HHRA along the boundary of the airport to see how the current airport operations may influence the health of current and future communities if operations and emissions were to stay the same. The HHRA was conducted for a hypothetical subpopulation, mainly on-site employees and resident subpopulations: < 6 months, 6 months to 6 years, 6 to 16 years, and adults. The Toronto Pearson International Airport's HHRA similarly used hypothetical subpopulation groups that were defined as life stages and were informed by Health Canada Guidelines (Intrinsik, 2015).

The frequency and duration of exposure were assumed to be for 24 hours a day for all seven days of the week and a 63-year lifetime for residents' subpopulation groups, as seen in Table 3.1. On the other hand, the frequency and duration of exposure for on-site employees were

assumed to be for an 8-hour working day for five days a week over a 63-year lifetime (Statistics South Africa, 2016). After describing the receptors, the receptor locations around the airport were defined. Figure 2.5 depicts the location of receptors. The receptor locations for residential and on-site employees were from location 1 to 21, and location 22 to 32, respectively. The residential receptor locations were defined in ArcMap using the Editor Construct Points tool, which allowed the research to define point with a 1 km distance between allowing the airport boundary with a 1 km between the points. The residential receptor locations were 1 km apart along the red airport boundary line. Secondly, the receptor locations for on-site employees were in the same area as the sample locations, with the addition of location 32, which was the fire training area. Location 22 to 32 was defined in ArcMap using the editors' tool to add points. The locations 22 to 31 were placed on top of the passive sampler locations using the editor tool in ArcMap.

3.2.5 Extracting BTEX concentrations from predicted surfaces

The author intended to derive BTEX emission estimates for receptors from the kriging surfaces using concentrations along the boundary for the residential subpopulation groups, and within particular areas in the airport for on-site employees. The kriging surfaces were converted to a raster layer, and then the concentrations were extracted at various locations as defined in Figure 3.5, using the Extract Multi Values to Points tool in ArcGIS 10.4, as seen in the example of the extraction in Figure 3.6.

For each of the seasons, the estimated emissions at the points defined from 1 to 32 had been extracted and the results of the extraction were in a points layer. The concentrations at each point were in the attribute tables of each points layer. These attribute tables were exported into CSV files and later imported into python for analysis. The predicted concentrations from 1 to 21 (red) were assumed to be the concentrations that the residential subpopulation groups were exposed to. The extracted concentrations from 22 to 32 are inside the airport boundary and were used for onsite employees. The passive sampler concentrations, along with the estimated emissions, will be used to calculate the inhalation risk assessment.

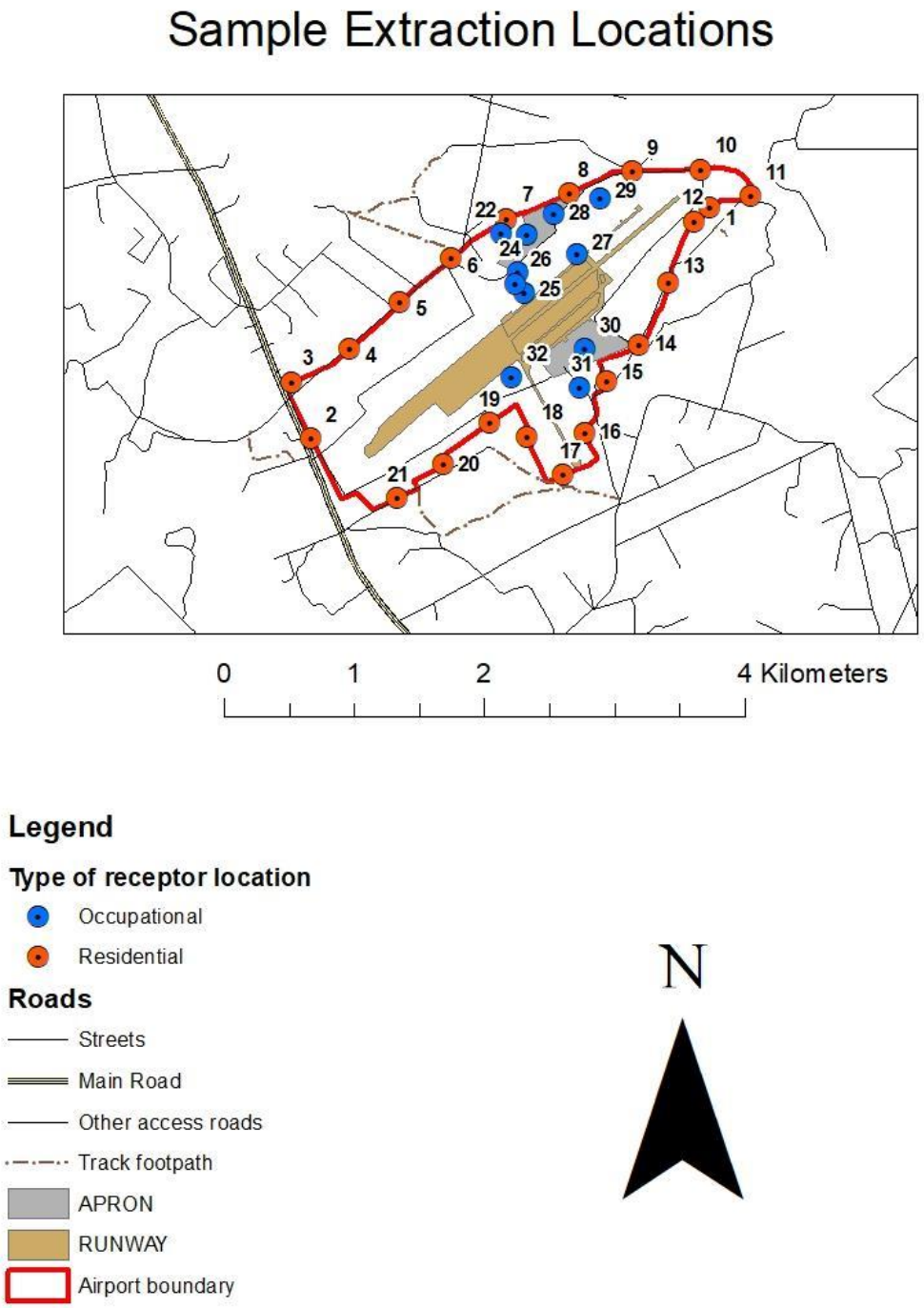


Figure 3.5: A map showing the locations of the selected receptors for the HHRA at the South African International Airport. The red circles represent the locations of hypothetical residential subpopulation groups, and the blue circles represent the on-site employees.

Table 3.1: List of hypothetical receptors according to different life stages with estimated exposure periods

.	**Subpopulation**	**Duration**	**Time-weighted average**	***Average bodyweight per subpopulation**
1	On-Site	1 hour	1 week; 1 – 12 hour/s	70
2	Residents < 6 months	At home 24/7	1 week	6
3	Residents 6 months to 6 years	At home 24/7	1 week	13.25
4.	Residents adults > 65	At home 24/7	1 week	70
5.	Children 6 to 11 years	In area 24/7	1 week	31.8
6.	Teens to young adults 11 to 21 years	In area 24/7	1 week	64.2
7.	Adult residents 22 to 64 years	In area 24/7	1 week	70/80

* Average weights were retrieved from the US EPA Exposure Factor Handbook chapter 8: Bodyweight

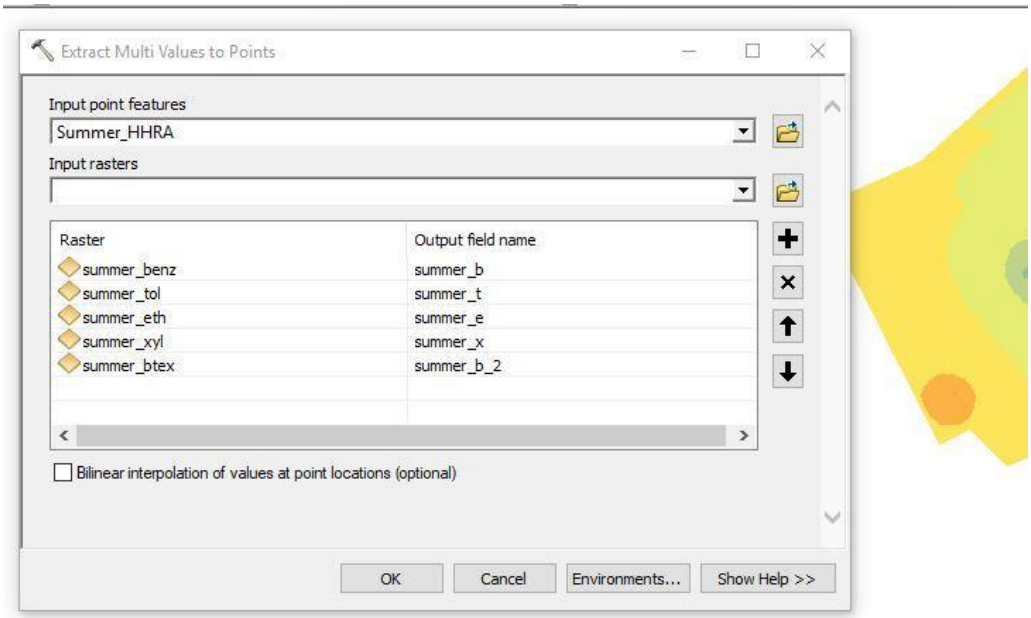


Figure 3.6: A screenshot of the Extract Multi Values to points used to extract BTEX concentrations from kriging surfaces for each compound in each season

3.3 Inhalation Assessment of BTEX for On-site Employees and Residential Subpopulation Groups

The inhalation assessment was used to measure the estimated lifetime exposure for subpopulation groups at the various receptor locations for all the selected subpopulation groups (US EPA, 2014; World Health Organization, 2010). Lifetime inhalation exposure is calculated using the Lifetime Average Daily Dose exposure equation 1. The information and assumption made in the exposure assessment were used as inputs to equation 1 presented below. The first assumption was that all on-site employees worked 8 hours a day, 5 days a week. The assumption made for the results of the inhalation assessment were used further in the Risk Characterisation equations (Intrinsik, 2015; US EPA, 2014; World Health Organization, 2010, 2014).

3.4 Risk Characterisation for On-site Employees and Residential Subpopulation Groups

In this section, the researcher integrated the information from the exposure assessment and the prescribed exposure limits to quantify risk using the risk calculations. The results were then compared with the prescribed guidelines provided by the US EPA and the WHO. The Risk Characterisation is defined through the HQ for the potential of general health defects for

all BTEX compounds, and on the other hand Cancer Risk for the carcinogenetic compound, benzene (Intrinsik, 2015; Majumdar *et al*., 2011; Tunsaringkarn *et al*., 2012).

Equation 1

$$LADD = (Cexp) \times (IR) \times (EL) \times (ED)/(BW) \times (TL)$$

Where:

- C_{exp} = exposure concentration ($\mu g/m^{-3)}$
- IR = inhalation rate (m^3 /h)
- EL = exposure length (h/day)
- ED = exposure duration (days in a week)
- BW = body weight (kg)
- TL = typical lifetime (days)

3.4.1 Hazard Quotient

Hazard Quotient (HQ) is an expression used to account for risk for a lifetime for non-carcinogenic compounds where an HQ > 1 indicates the great potential of health effects for the receptor and HQ < 1 is considered to have less likely effects (Hinwood *et al*., 2007, Intrinsik, 2015). The non-cancer risk assessment is carried out using the HQ for all the BTEX compounds of interest. The equation is as follows:

Equation 2

HQ = LADD / RFD

Where:

- LADD = Lifetime Average Daily Dose (mg/kg/day)
- *RFD = Reference Dose

*The RFC is retrieved from the US EPA Integrated Risk Information Systems (IRIS) adopted from the Risk Assessment Information System (RAIS).

3.4.2 Cancer risk

Cancer risk assessments were carried out on the carcinogenic compound benzene. ILCR was calculated using equation 5. This then defines the likeliness of individuals being prone to cancer risk.

Equation 3

$$CR = LADD \times SF$$

Where:

- CR = Cancer Risk
- LADD = Lifetime Average Daily Dose (mg/kg/day)
- *SF = Slope Factor

3.5 Inclusion and Exclusion Criteria

The HHRA was conducted for a single international airport in South Africa. The HHRA aims to study the localised potential human health impact of this particular airport on surrounding communities and on-site employees. Emissions around the airport were only considered along the boundary of the airport, which will result in conservative risk assessment results.

3.6 Ethical Considerations

A scenario-based exposure assessment was conducted in order to avoid ethical implications that are attributed to health impact studies. Some of the implications involve obtaining consent from receptors to participate in the study and interviews that may be intrusive. This type of sampling is considered less intrusive for employees and residents, whereas with active sampling, the airport staff was concerned it will be alarming and give rise to unnecessary concerns from staff and passengers. Using the hypothetical subpopulation groups may pose limitations when studying how the receptors' behavioural attributes to risk; however, this methodological approach has been used before and can produce a fair risk assessment.

3.7 Statistical Analysis

The researcher utilised Python programming for statistical analysis using a range of visualisation and statistical packages such as PANDAS, NumPy, SEABORN, MATLAB, and statistics. The graphs produced in the document were made in excel. The researcher ran through significant statistical reporting numbers such as the mean, max, min, and standard variation for each sampling campaigns, using the describe function in python. The describe function provides the general statistical descriptions of all numerical columns. The researcher also explored the relationship between the BTEX elements and the BTEX element per season by using the Pearson correlation test. The research utilised the panda function, CORR and defined the variables in the function method as Pearson and left the min_period as default. The same analysis was repeated for the extracted locations. Furthermore, the researcher looked into the difference in the sampled and predicted emission at the sampled points to see if there were any statistically significant variations in these numbers.

3.8. Weather Conditions

At the airport, there was a weather station maintained by the South African weather station. The research had requested weather data, specifically, wind speed, wind direction and temperature data. The research received the data in excel sheets for the months in which the sampling campaigns took place. The research received a full set of weather conditions for May , July and January. and only Temperature data for September. Each of the sheets in the excel document where saves as CSV files. To be imported into python. Similar to the statistical analysis above some packages where used. The CSV files were imported into python and save as data frames for wind and wind speed. The tables were transposed to have one column, with two index day and time and the wind speed or direction. The python package Windrose was installed, a windrose is a graphical tool used by meteorologist to give the overall view of wind patterns in a specific location(Roubeyrie, n.d.). The function WindroseAxes is used to produce the windroses.

Chapter 4: Results of the Study

4.1 Introduction

This chapter presents the research findings based on the analysis of BTEX concentration under lab conditions, exposure assessment, and potential HHRA for on-site employees and residents within the vicinity of the airport aged 6 months and older. An HHRA was conducted for hypothetical subpopulation groups, namely: on-site employees and resident subpopulation groups < 6 months, 6 months to 6 years, 6 years to 16 years, and adults. The HHRA was conducted using a scenario-based exposure assessment where the duration of exposure was measured separately from the concentrations in the air. This chapter presents the findings from the methodologies presented in chapter 3. Firstly, the results of the exposure assessment will be presented. This outlines the passive sampling results, the results from kriging (predictive isoconcentration maps), and the results of the extracted concentrations from the predictive surface for each campaign at the selected receptor location. The concentrations were used as inputs to the inhalation assessment equations. Furthermore, inhalation assessment was conducted for on-site employees from the results of the passive samples. Finally, a risk assessment will be presented for both on-site employees and residents using the HQ as well as the cancer risk. In addition, the results of the statistical analysis will be presented

4.2 Exposure Assessment

Before moving into the risk assessment, this study will consider the air quality assessment results, which includes the results of the air sampling, predictive mapping for each campaign, and the yearly average before looking at the results from the extractions of concentrations from the predictive surface for various receptor locations.

4.2.1. Results for the Passive Sampler Concentrations

The BTEX concentrations for all four sampling campaigns are shown in Figure 4.1. The results show that the highest concentration across all four seasons and all compounds are at location 7 (across the paint shop). Toluene is highest at this location for all seasons, with concentrations ranging from 15.08 µg/m^{-3} to 30.59 µg/ m^{-3}, as compared to concentrations ranging from 1.73 µg/m^{-3} to 30.59 µg/m^{-3} across all seasons for all the locations. The lowest concentrations for xylene are in spring; concentrations are below the sampling limit of 0.

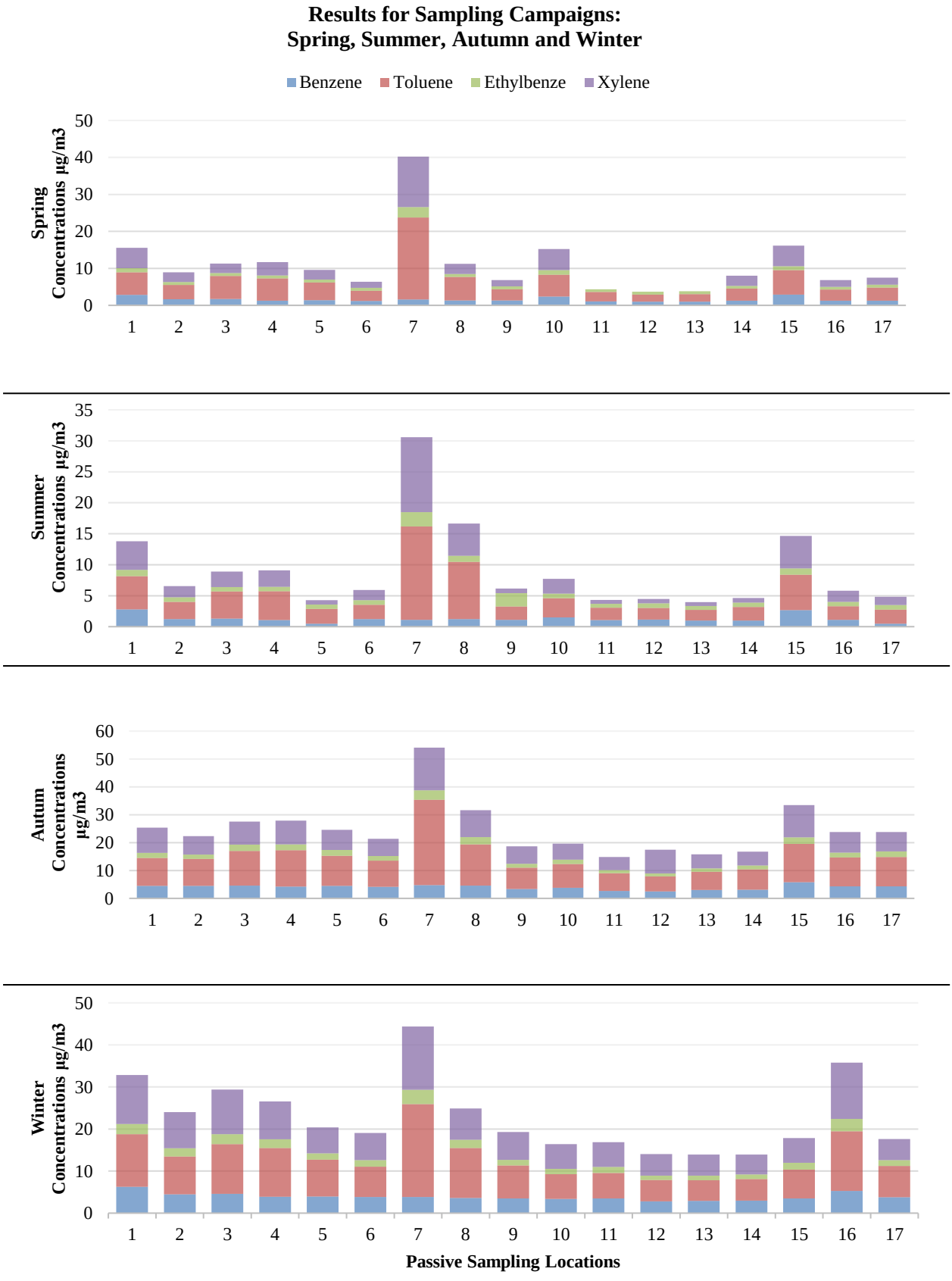


Figure 4.1: Graphs for BTEX passive sampling concentration results.

µg/m^{-3}. Xylene ranges from 0.7 µg/m^{-3} to 13.66 µg/m^{-3} in spring and across all four seasons it ranges from 0.7 µg/m^{-3} to 15.29 µg/m^{-3} with the highest concentrations recorded at location 7. On the other hand, benzene is highest at location 1 (the drop off the zone) in winter at 6.24 µg/m^{-3}, and concentrations ranged from 0.49 µg/m^{-3} to 6.24 µg/m^{-3} across all four seasons. Ethylbenzene has the smallest range with concentrations ranging from 0.73 µg/m^{-3} to 2.92 µg/m^{-3}. Overall, the total BTEX concentrations are highest in autumn and winter with spring and summer concentrations being almost half that of winter and autumn concentrations. Location 7 is an outlier and therefore will not be used in kriging. The predictive kriging concentrations maps were used to observe the spatial variation of concentrations.

4.2.2. Predictive isoconcentration maps for BTEX compounds

a. Predictive isoconcentration maps for benzene

The predictive isoconcentration maps for benzene are shown in Figure 4.2. The autumn campaign concentrations (Figure 4.2 a.) decrease toward the runway approach along the south-west boundary of the airport while concentrations are the highest (4.53 µg/m^{-3} to 4.74 µg/ m^{-3}) around the buildings toward the northern boundary. The winter campaign (Figure 4.2 b) has its lowest concentration range from 2.82 µg/m^{-3} to 3.36 µg/m^{-3} in the south-east boundary near the runway approach. The highest concentrations (4.48 µg/m^{-3} to 4.91 µg/m^{-3}) are at the northeast boundary. In the spring campaign (Figure 4.2 c) the highest concentrations are over the airport building and drop off zone with concentration ranging from 2.36 µg/m^{-3} to 2.91 µg/m^{-3}. In the summer campaign (Figure 4.2 d), the highest concentrations are also found in the drop off zone at 1.36 µg/m^{-3} to 1.76 µg/ m^{-3}. The lowest concentrations are in the centre of the airport over the apron area (0.49 µg/m^{-3} to 0.89 µg/ m^{-3}).

b. Predictive isoconcentration map for toluene

In the autumn campaign, predictive isoconcentration maps for toluene are shown in Figure 4.3, with the concentration highest in a distinct spot along the runway near the hangers north of the airport ranging from 11.64 µg/m^{-3} to 12.67 µg/m^{-3}. The lowest concentration, 5.44 µg/m^{-3} to 6.22 µg/m^{-3}, is towards the runway approach along the south-west boundary of the airport. In the winter (Figure 4.3 b), the highest concentrations of 4.48 µg/m^{-3} to 4.491 µg/m^{-3} were along the northeast boundary moving toward the end of the runway.

c. Predictive isoconcentration map for ethylbenzene

The predictive isoconcentration surfaces for ethylbenzene are shown in Figure 4.4. In autumn and winter, respectively (Figure 4.4 a and b), the concentrations are lower toward the runway approach and highest in the northeast end of the airport. However, in autumn (Figure 4.4 a) the concentrations are highest over the centre of the runway. In spring and summer, the concentrations are highest in the centre of the airport and decrease toward the northeast and south-west boundaries. In spring and summer, the ethylbenzene concentrations are highest over the airport building as well as over the fire station area in spring and the paint shop and NAC area in winter (Figure 4.4 b).

d. Predictive isoconcentration map for xylene

The predictive isoconcentration maps for xylene are seen in Figure 4.5. In autumn (Figure 4.5 a), concentrations are highest over the airport's building and fire stations. There is a small difference between the general xylene concentration in the entire airport and the hotspots. The highest concentration is in the 9.35 $\mu g/m^{-3}$ to 10.56 $\mu g/m^{-3}$ range, and the general airport has a concentration ranging from 6.82-10.56 $\mu g/m^{-3}$. In winter (Figure 4.5 b) the xylene concentrations are highest at the northeast boundary and lowest at the south-west boundary. In spring (Figure 4.5 c) the concentrations are highest around the airport's building and fire station area and lowest at the south-west boundary. In summer (Figure 4.5 d) concentrations are highest over the paint shop area and the airport building area.

e. Predictive isoconcentration map for total BTEX

When combining the concentrations for all four elements, the general spatial distribution of the BTEX group of compounds is shown in Figure 4.6. In autumn (Figure 4.6 a) concentrations are highest toward the northeast boundary and lowest toward the south-west boundary. In winter (Figure 4.6 b) concentration are highest over the parking area and the north-west boundary. In winter the lowest concentration is along the south-west end of the runway close to the approach. In spring the concentrations are highest over the fire station and the airport building area. The lowest concentration is along the south-west boundary and the northeast boundary. In summer the concentrations are highest around the airport building and car park area and the paint shop area. The following section will consider the annual average of all four elements and the combined distribution of the BTEX compounds.

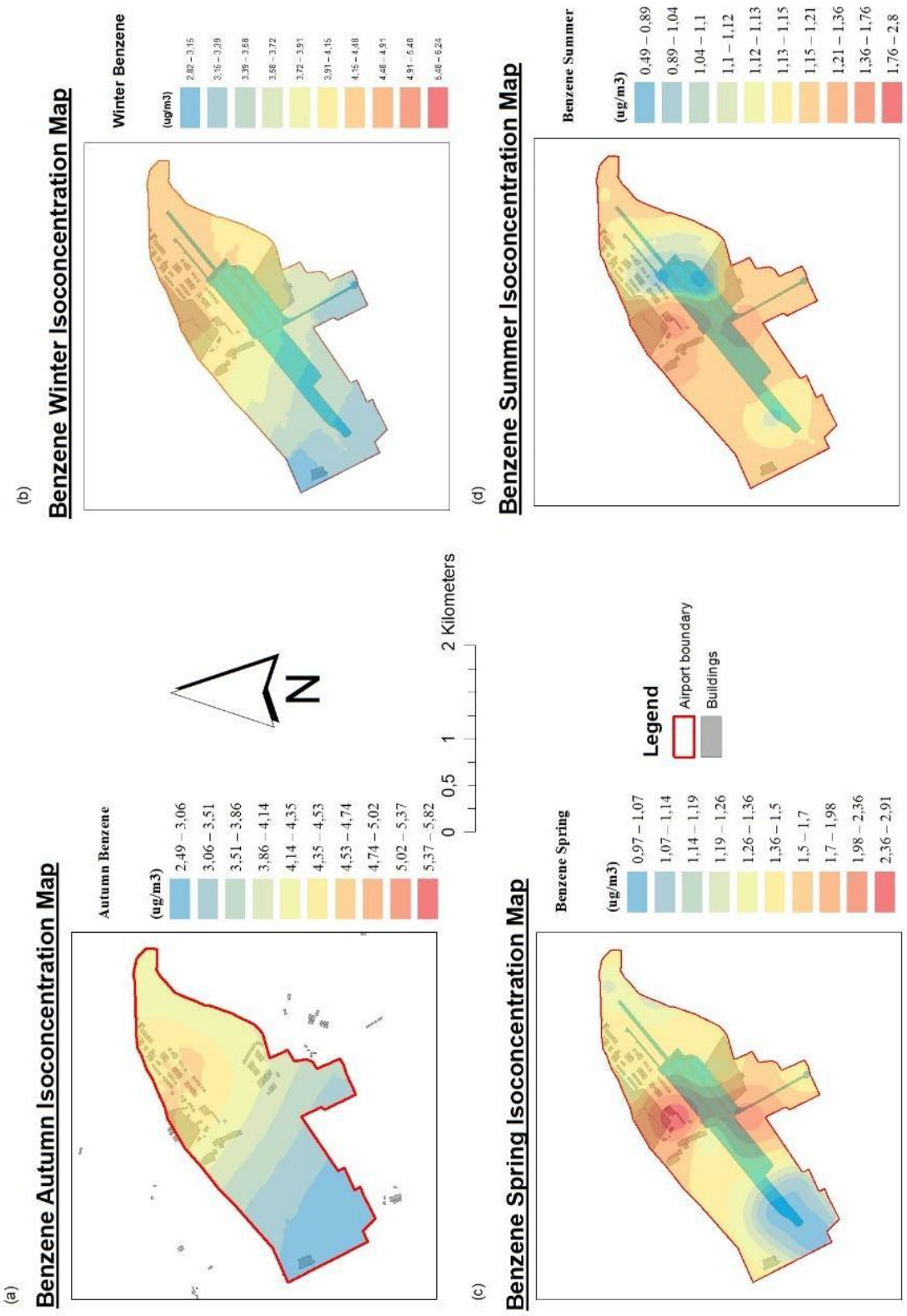


Figure 4.2: Kriging results for benzene concentrations for all four campaigns/seasons

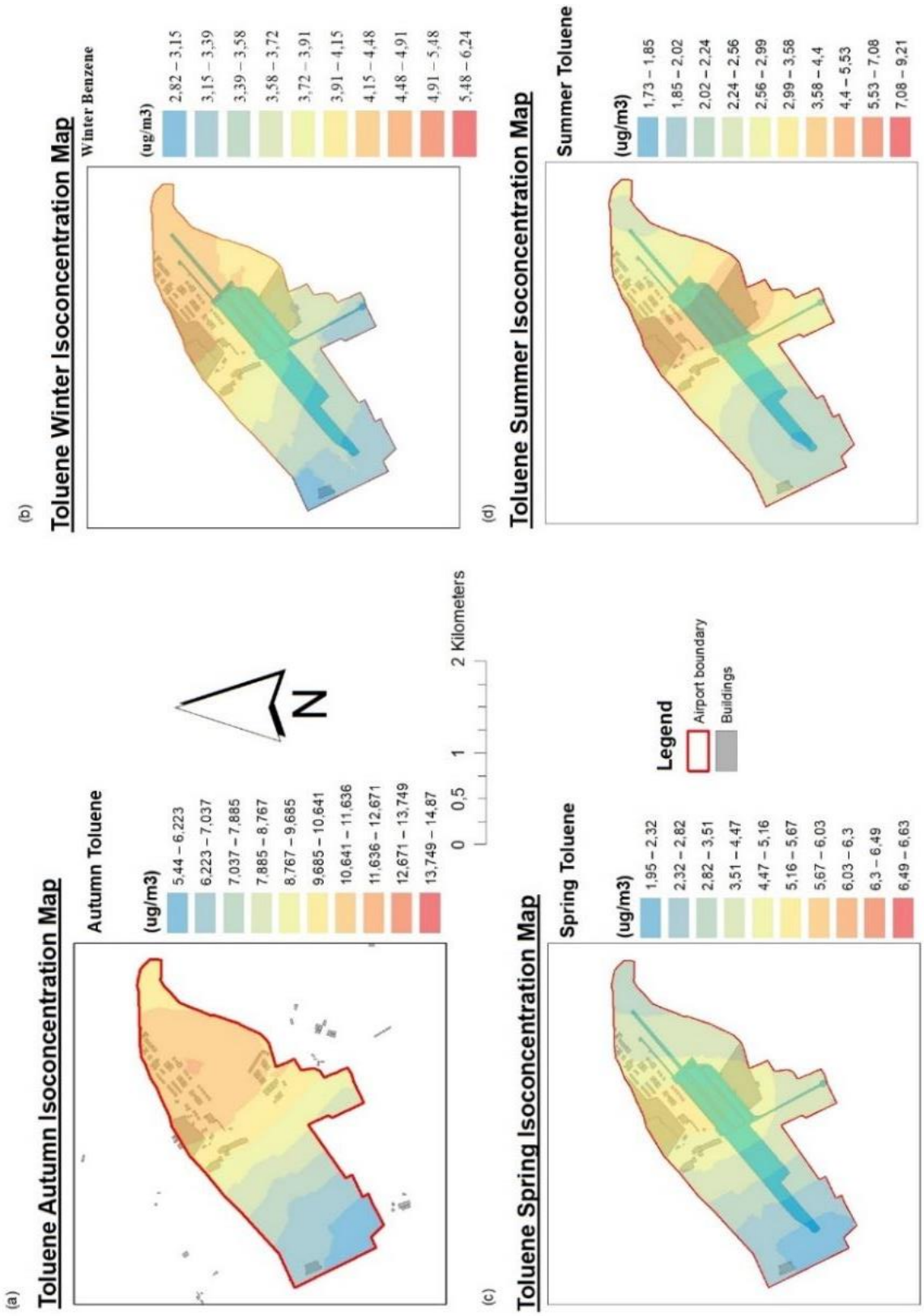


Figure 4.3: Kriging results for toluene concentrations for all four campaigns/seasons

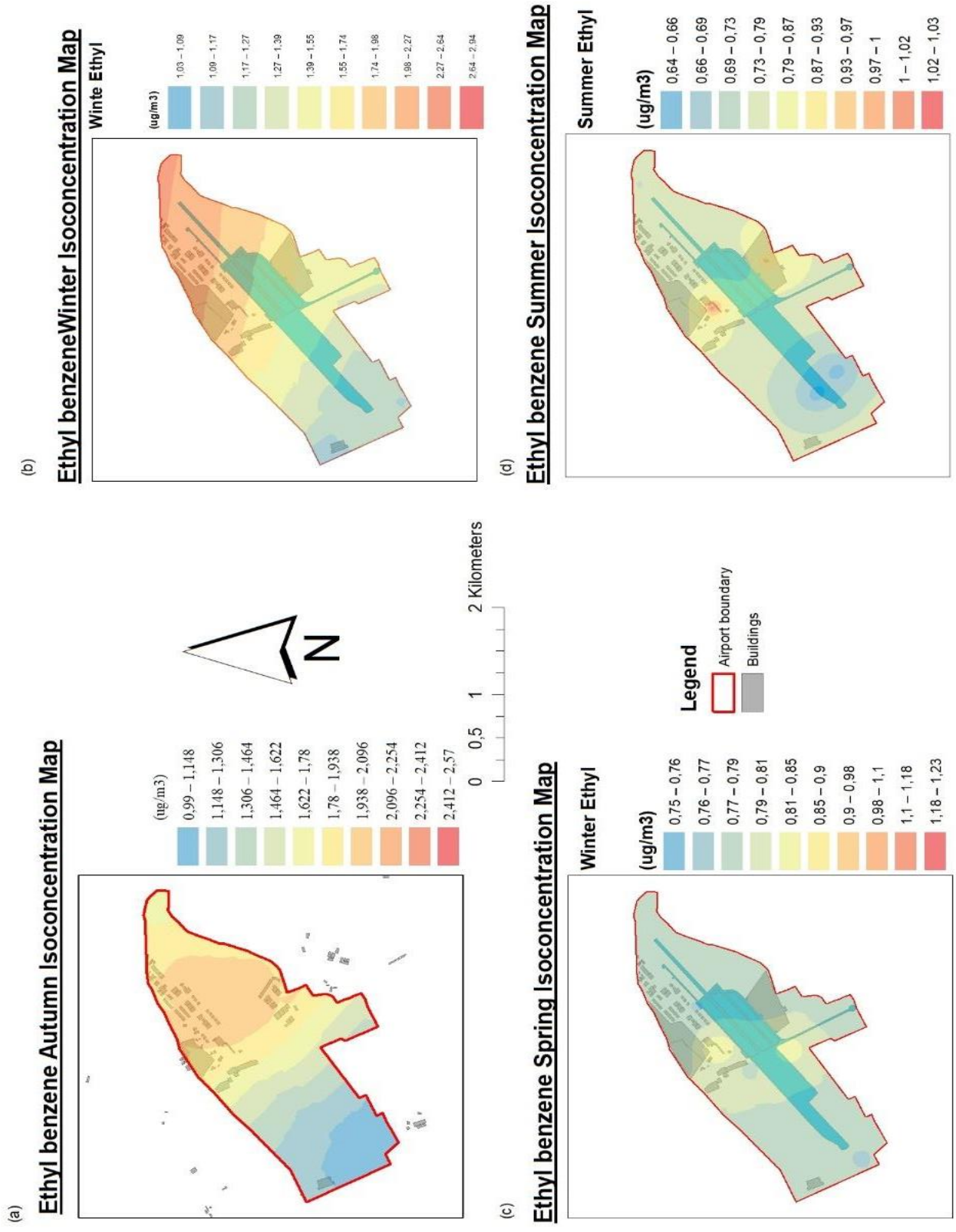


Figure 4.4: Kriging results for ethylbenzene concentrations for all four campaigns/seasons

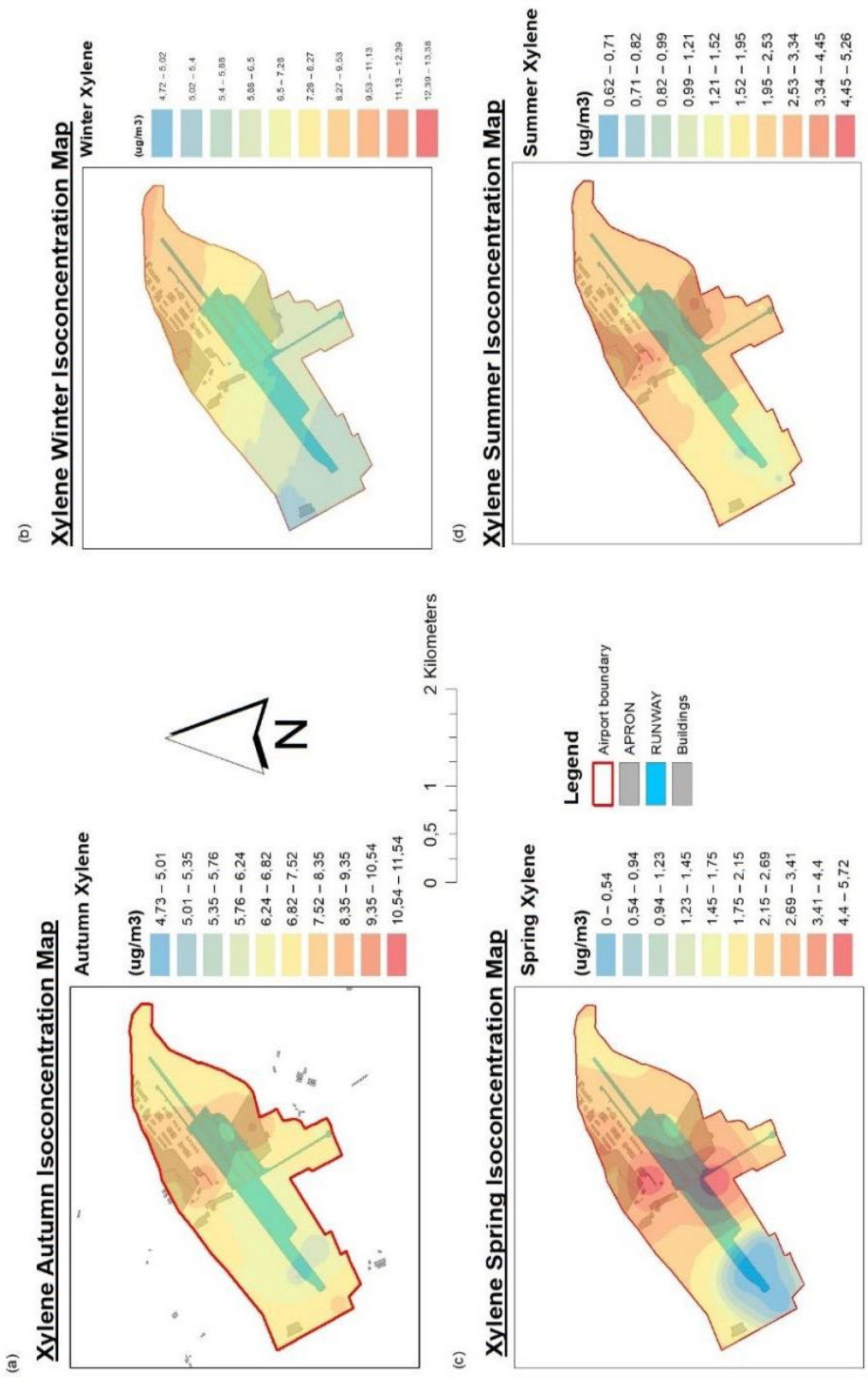


Figure 4.5: Kriging results for xylene concentrations for all four campaigns/seasons

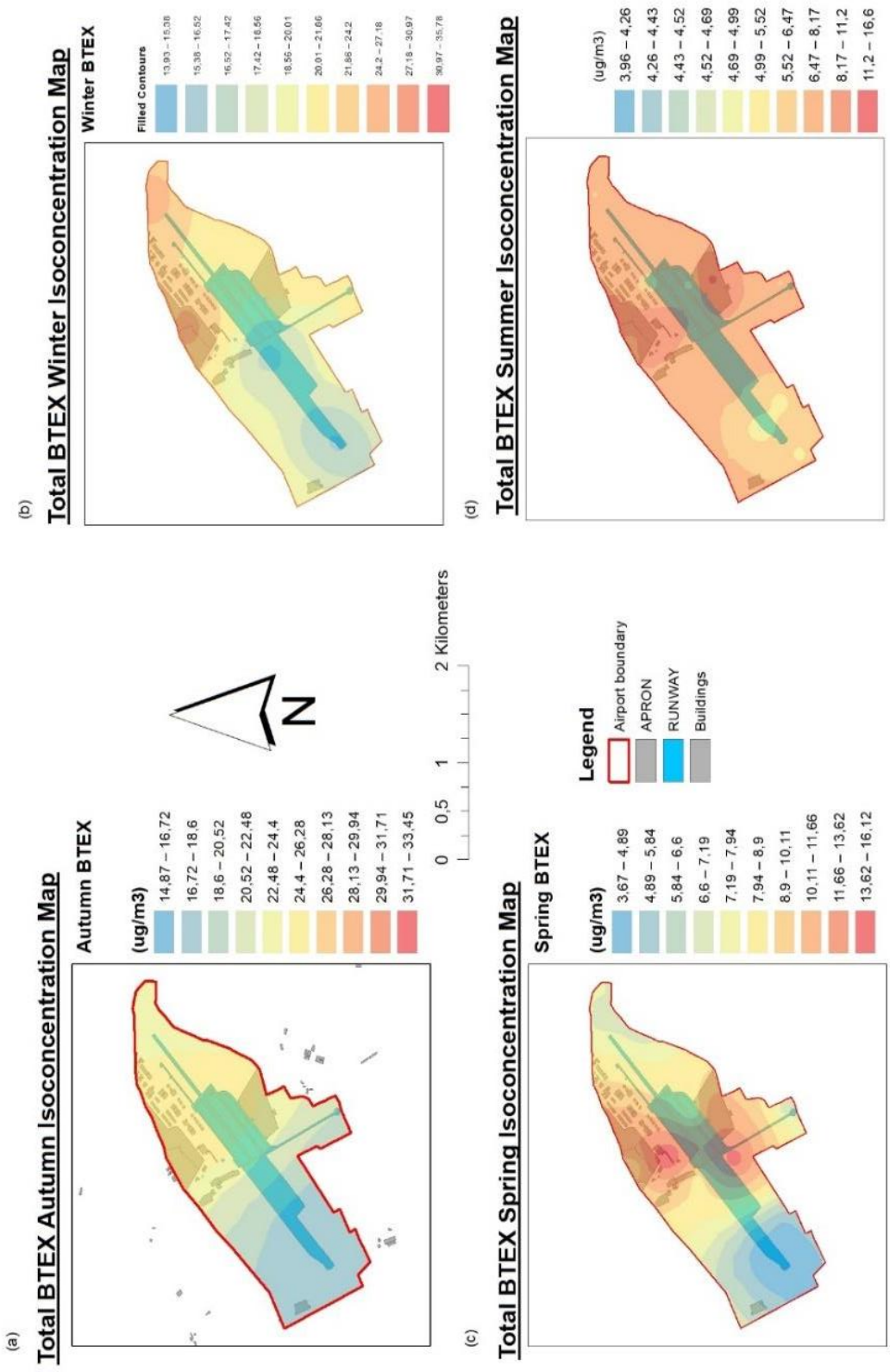


Figure 4.6: Kriging results for total BTEX concentrations for all four campaigns/season

4.2.3 Concentrations for estimated emission extracted from the kriging surface

Extracted concentrations were taken from all the results of the kriging predictive concentration maps produced from the average concentrations from all four campaigns, as seen in Annex 1. Table 4.1 shows the average concentrations over the four campaigns which have been used in conducting the inhalation assessment. Not all results are included for all receptor locations. For most of the occupational risk assessments, the passive sampler concentrations were used instead. The extracted concentrations range from 0.93 $\mu g/m^{-3}$ to 7.63 $\mu g/m^{-3}$, which is within the range presented from the sampled average of 0.91 $\mu g/m^{-3}$ to 10.57 $\mu g/m^{-3}$. The overall highest concentrations are at location 25 for toluene. When looking at the benzene concentration, the highest concentration is at the extracted point 25 near the car park at 3.21 $\mu g/m^{-3}$. The lowest concentrations are at the security booth at the extracted point 21 at 2.01 $\mu g/m^{-3}$. Toluene ranges from 3.98 $\mu g/m^{-3}$ to 7.63 $\mu g/m^{-3}$ and ethylbenzenes range from 0.99 $\mu g/m^{-3}$ to 1.44 $\mu g/m^{-3}$. Xylene ranges from 3.77 $\mu g/m^{-3}$ to 7.04 $\mu g/m^{-3}$. The above-extracted concentrations were assumed to be the concentrations residents are exposed to and, therefore, were used in the inhalation risk assessment.

4.3 Results of the Human Health Risk Assessment for Residents and On-site Employees

When characterising risk, the HQ for non-cancer risk (equation 2) and for benzene cancer risk (equation 3) were used. The results from the inhalation assessment and the estimated LADD have been used as inputs to the equations. The main difference for variables across the residential subpopulation groups would be the average weight of individual groups, but all other variables are the same. The following section will present the following LADD, ILCR, and HQ – first for on-site employees and secondly for residential subpopulation groups.

4.3.1. Occupational exposure and Human Health Risk Assessment

a. Lifetime Average Daily Dose for occupational exposure

The estimated LADD for extracted concentrations ranges from 4.13E-05 to 2.66E-04 mg/kg/day and the LADD for sampled concentrations for onsite employees ranges from 3.47 x 10^{-05} to 7.84 x 10^{-04} mg/kg/day (see Table 4.2. In Table 4.2, the highest LADD corresponds with the highest concentration at location 25 for toluene. The highest estimated LADD is at location 7. Looking at the carcinogenic element benzene, the highest LADD for the extracted surfaces is at location 25, representing the car park location.

Table 4.1: Estimated ambient air concentrations for BTEX at the extracted locations

	Extracted points	**Total BTEX**	**Benzene**	**Toluene**	**Ethylbenzene**	**Xylene**
Residential (boundary concentration)	(1.)	15.36	2.76	6.67	1.37	5.18
	(2.)	11.73	2.09	3.98	0.95	4.00
	(3.)	13.08	2.18	4.31	0.98	4.14
	(4.)	12.86	2.34	4.63	1.04	4.23
	(5.)	13.81	2.54	5.38	1.13	4.56
	(6.)	15.43	2.80	6.58	1.29	5.13
	(7.)	16.94	2.93	7.63	1.38	5.26
	(8.)	16.68	2.84	7.61	1.41	5.59
	(9.)	15.83	2.84	7.35	1.44	5.42
	(10.)	15.73	2.78	6.92	1.41	5.30
	(11.)	15.02	2.76	6.58	1.38	5.28
	(12.)	15.17	2.76	6.70	1.37	5.09

	(13.)	14.81	2.70	6.73	1.33	4.88
	(14.)	15.48	2.69	6.76	1.28	4.88
	(15.)	15.77	2.61	6.92	1.27	4.79
	(16.)	14.29	2.46	6.10	1.16	4.40
	(17.)	13.61	2.37	5.56	1.11	4.34
	(18.)	14.02	2.40	5.52	1.09	4.48
	(19.)	13.58	2.42	5.29	1.07	4.43
	(20.)	12.00	2.17	4.44	0.97	3.77
	(21.)	11.72	2.05	4.03	0.93	3.87
On site employees	(25.)	17.14	3.02	7.15	1.34	5.89
	(27.)	15.54	2.77	7.51	1.38	4.80
	(31.)	15.61	2.59	6.68	1.23	4.84

Table 4.2: Lifetime Average Daily Dose for on-site employees

Type of emission	**Sample number**	**Benzene LADD**	**Toluene LADD**	**Ethylbenzene LADD**	**Xylene LADD**

estimates		**mg/kg/day**	**mg/kg/day**	**mg/kg/day**	**mg/kg/day**
Extracted samples	25	1.05 x 10-04	2.49 x 10-04	4.68 x 10-05	2.06 x 10-04
	27	9.66 x 10-05	2.62 x 10-04	4.80 x 10-05	1.67 x 10-04
	31	9.03 x 10-05	2.33 x 10-04	4.30 x 10-05	1.69 x 10-04
Passive sample locations	1 (24)	1.43 x 10-04	2.96 x 10-04	6.17 x 10-05	2.69 x 10-04
	2 (22)	1.03 x 10-04	2.21 x 10-04	4.99 x 10-05	1.71 x 10-04
	3 (23)	1.07 x 10-04	3.04 x 10-04	6.17 x 10-05	2.09 x 10-04
	4 (29)	9.17 x 10-05	3.07 x 10-04	5.72 x 10-05	2.08 x 10-04
	5 (28)	8.97 x 10-05	2.34 x 10-04	4.98 x 10-05	1.46 x 10-04
	6	9.03 x 10-05	1.90 x 10-04	4.63 x 10-05	1.39 x 10-04
	7	9.87 x 10-05	7.84 x 10-04	1.06 x 10-04	4.89 x 10-

					04
	8 (30)	9.37 x 10-05	3.69 x 10-04	6.42 x 10-05	2.19 x 10-04
	9	8.14 x 10-05	1.80 x 10-04	5.63 x 10-05	1.34 x 10-04
	10 (32)	9.56 x 10-05	2.05 x 10-04	4.13 x 10-05	1.72 x 10-04
	11	6.88 x 10-05	1.33 x 10-04	3.47 x 10-05	9.30 x 10-05
	12	7.24 x 10-05	1.57 x 10-04	3.71 x 10-05	1.14 x 10-04
	13	1.30 x 10-04	2.87 x 10-04	5.85 x 10-05	2.46 x 10-04

b. Occupational Human Health Risk Assessment

Table 4.3 shows the HHRA results for on-site employees. The HQ, the calculation of general health risk, for all locations and all elements is less than 1. On the other hand, the cancer risk calculation is above the US EPA guideline of $1x10^{-6}$.

Table 4.3: Cancer risk and Hazard Quotient for on-site employees from extracted concentrations at receptor locations. (The extracted locations are in brackets, and passive sample locations are in plain text.)

Type of emission	**Sample number**	**Benzene CR**	**HQ Benz**	**HQ Tolue**	**HQ Ethylbenzene**	**HQ Xylene**	**Total HQ**

estimates			**ene**	**ne**			
Extracted sample location	(25)	**2.87×10^{-06}**	0.03	0.00	0.00	0.00	0.03
	(27)	**2.64×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	(31)	**2.47×10^{-06}**	0.02	0.00	0.00	0.00	0.03
Passive sample locations	1 (24)	**3.90×10^{-06}**	0.04	0.00	0.00	0.00	0.04
	2 (22)	**2.82×10^{-06}**	0.03	0.00	0.00	0.00	0.03
	3 (23)	**2.91×10^{-06}**	0.03	0.00	0.00	0.00	0.03
	4 (29)	**2.50×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	5 (28)	**2.45×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	6	**2.46×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	7	**2.70×10^{-06}**	0.02	0.01	0.00	0.00	0.04
	8 (30)	**2.56×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	9	**2.22×10^{-06}**	0.02	0.00	0.00	0.00	0.02
	10 (32)	**2.61×10^{-06}**	0.02	0.00	0.00	0.00	0.03
	11	**1.98×10^{-06}**	0.02	0.00	0.00	0.00	0.02

	12	**1.76 x 10^{-06}**	0.02	0.00	0.00	0.00	0.02
	13	**1.88 x 10^{-06}**	0.02	0.00	0.00	0.00	0.02
	14	**1.98 x 10^{-06}**	0.02	0.00	0.00	0.00	0.02
	15 (26)	**3.55 x 10^{-06}**	0.03	0.00	0.00	0.00	0.04

4.3.2 Results for the exposure assessment and Human Health Risk Assessment for residents

a. Lifetime Average Daily Dose for the subpopulation group < 6 months

The LADD for residents younger than 6 months of age ranges from 1.58 x 10^{-03} to 1.30 x10^{-02} mg/kg/day, and the average across all four compounds is 6.15 x10^{-03} mg/kg/day (Table 4.4). The lowest LADD is found at point 21 (1.58 x10^{-03} mg/kg/day) along the south-west boundary of the airport opposite the industrial park. The highest LADD of 1.30 x10^{-02} is for toluene and is found at locations 7 and 8, which run along the fence line next to the parking bay. Benzene has a LADD range between 3.50 x10^{-03} and 4.99 x 10^{-03} mg/kg/day. The average LADD for benzene across all locations is 4.33 x10^{-03}.

Table 4.4: Lifetime Average Daily Dose for the residential subpopulation group < 6 months

Extracted locations	**Benzene LADD (mg/kg/day)**	**Toluene LADD (mg/kg/day)**	**Ethylbenzene LADD (mg/kg/day)**	**Xylene LADD (mg/kg/day)**
(1)	4.70 x 10^{-03}	1.13E^{-02}	2.34 x 10^{-03}	8.81 x 10^{-03}

(2)	3.56×10^{-03}	6.77×10^{-03}	1.62×10^{-03}	6.80×10^{-03}
(3)	3.71×10^{-03}	7.33×10^{-03}	1.67×10^{-03}	7.04×10^{-03}
(4)	3.99×10^{-03}	7.88×10^{-03}	1.76×10^{-03}	7.20×10^{-03}
(5)	4.31×10^{-03}	9.15×10^{-03}	1.93×10^{-03}	7.75×10^{-03}
(6)	4.76×10^{-03}	1.12×10^{-02}	2.19×10^{-03}	8.72×10^{-03}
(7)	4.99×10^{-03}	1.3×10^{-02}	2.35×10^{-03}	8.96×10^{-03}
(8)	4.83×10^{-03}	1.30×10^{-02}	2.40×10^{-03}	9.51×10^{-03}
(9)	4.84×10^{-03}	1.25×10^{-02}	2.45×10^{-03}	9.21×10^{-03}
(10)	4.72×10^{-03}	1.18×10^{-02}	2.39×10^{-03}	9.01×10^{-03}
(11)	4.69×10^{-03}	1.12×10^{-02}	2.34×10^{-03}	8.97×10^{-03}
(12)	4.69×10^{-03}	1.14×10^{-02}	2.33×10^{-03}	8.65×10^{-03}
(13)	4.60×10^{-03}	1.14×10^{-02}	2.26×10^{-03}	8.31×10^{-03}
(14)	4.57×10^{-03}	1.15×10^{-02}	2.17×10^{-03}	8.29×10^{-03}
(15)	4.44×10^{-03}	1.18×10^{-02}	2.15×10^{-03}	8.14×10^{-03}
(16)	4.19×10^{-03}	1.04×10^{-02}	1.98×10^{-03}	7.49×10^{-03}

(17)	4.03 x 10-^{03}	9.46 x 10-^{03}	1.88 x 10-^{03}	7.37 x 10-^{03}
(18)	4.08 x 10-^{03}	9.40 x 10-^{03}	1.86 x 10-^{03}	7.61 x 10-^{03}
(19)	4.11 x 10-^{03}	9.00 x 10-^{03}	1.83 x 10-^{03}	7.53 x 10-^{03}
(20)	3.69 x 10-^{03}	7.56 x 10-^{03}	1.65 x 10-^{03}	6.41 x 10-^{03}
(21)	3.50 x 10-^{03}	6.85 x 10-^{03}	1.58 x 10-^{03}	6.58 x 10-^{03}

b. Lifetime Average Daily Dose for the subpopulation group 6 months to 6 years

The LADD for residents aged between 6 months and 6 years ranges from 7.21 x 10^{-04} to 5.90 x10^{-03} mg/kg/day (Table 4.5). The lowest and highest LADD for this age group is at location 21 for ethylbenzene and location 7 for toluene. The LADD for benzene ranges from 1.59 x 10^{-03} to 2.27 x10^{-03} mg/kg/day. The highest LADD is at location 7 for toluene along the fence line opposite the parking bay. The average LADD for benzene across all residential extracted locations is 1.97 x10^{-03}.

Table 4.5: Lifetime Average Daily Dose for the residential subpopulation group 6 months to 6 years

Extracted locations	**Benzene LADD (mg/kg/day)**	**Toluene LADD (mg/kg/day)**	**Ethylbenzene LADD (mg/kg/day)**	**Xylene LADD (mg/kg/day)**
(1)	2.14E-03	5.16E-03	1.06E-03	4.01E-03
(2)	1.62E-03	3.08E-03	7.35E-04	3.10E-03

(3)	1.69E-03	3.33E-03	7.59E-04	3.20E-03
(4)	1.81E-03	3.59E-03	8.02E-04	3.28E-03
(5)	1.96E-03	4.16E-03	8.77E-04	3.53E-03
(6)	2.17E-03	5.09E-03	9.95E-04	3.97E-03
(7)	2.27E-03	5.90E-03	1.07E-03	4.08E-03
(8)	2.20E-03	5.89E-03	1.09E-03	4.33E-03
(9)	2.20E-03	5.69E-03	1.11E-03	4.19E-03
(10)	2.15E-03	5.36E-03	1.09E-03	4.10E-03
(11)	2.13E-03	5.09E-03	1.07E-03	4.08E-03
(12)	2.13E-03	5.19E-03	1.06E-03	3.94E-03
(13)	2.09E-03	5.21E-03	1.03E-03	3.78E-03
(14)	2.08E-03	5.24E-03	9.89E-04	3.77E-03
(15)	2.02E-03	5.35E-03	9.80E-04	3.71E-03
(16)	1.91E-03	4.72E-03	9.00E-04	3.41E-03
(17)	1.83E-03	4.31E-03	8.56E-04	3.36E-03

(18)	1.86E-03	4.28E-03	8.47E-04	3.47E-03
(19)	1.87E-03	4.10E-03	8.32E-04	3.43E-03
(20)	1.68E-03	3.44E-03	7.49E-04	2.92E-03
(21)	1.59E-03	3.12E-03	7.21E-04	3.00E-03

c. Lifetime Average Daily Dose for the subpopulation group 6 years to 16 years

The estimated LADD exposure for individuals in the subpopulation group aged between 6- and 16-years ranges from 2.16 x 10^{-04} to 1.77 x 10^{-03} mg/kg/day, as seen in Table 4.6. The highest LADD was found at location 7 for toluene and ethylbenzene, and the lowest LADD was found at location 21 for xylene. Benzene's LADD range was from 4.76 x10^{-04} to 6.79 x 10^{-04} mg/kg/day averaging at 5.90 x10^{-04} mg/kg/day.

Table 4.6: Lifetime Average Daily Dose for the residential subpopulation group 6 to 16 years

Extracted Locations	**Benzene LADD (mg/kg/day)**	**Toluene LADD (mg/kg/day)**	**Ethylbenzene LADD (mg/kg/day)**	**Xylene LADD (mg/kg/day)**
(1)	6.40E-04	1.54E-03	3.18E-04	1.20E-03
(2)	4.85E-04	9.22E-04	2.20E-04	9.26E-04
(3)	5.06E-04	9.97E-04	2.27E-04	9.58E-04

(4)	5.42E-04	1.07E-03	2.40E-04	9.80E-04
(5)	5.87E-04	1.25E-03	2.62E-04	1.05E-03
(6)	6.48E-04	1.52E-03	2.98E-04	1.19E-03
(7)	6.79E-04	1.77E-03	3.19E-04	1.22E-03
(8)	6.58E-04	1.76E-03	3.27E-04	1.29E-03
(9)	6.59E-04	1.70E-03	3.33E-04	1.25E-03
(10)	6.43E-04	1.60E-03	3.26E-04	1.23E-03
(11)	6.38E-04	1.52E-03	3.19E-04	1.22E-03
(12)	6.38E-04	1.55E-03	3.17E-04	1.18E-03
(13)	6.26E-04	1.56E-03	3.07E-04	1.13E-03
(14)	6.22E-04	1.57E-03	2.96E-04	1.13E-03
(15)	6.04E-04	1.60E-03	2.93E-04	1.11E-03
(16)	5.70E-04	1.41E-03	2.69E-04	1.02E-03
(17)	5.48E-04	1.29E-03	2.56E-04	1.00E-03
(18)	5.55E-04	1.28E-03	2.53E-04	1.04E-03

(19)	5.60E-04	1.23E-03	2.49E-04	1.02E-03
(20)	5.02E-04	1.03E-03	2.24E-04	8.73E-04
(21)	4.76E-04	9.32E-04	2.16E-04	8.96E-04

d. Lifetime Average Daily Dose for the subpopulation group young adults and adults

The LADD for the subpopulation group between the ages of 16 and 64 ranges between 1.37 x 10^{-04} and 1.12 x 10^{-03} mg/kg/day, as seen in Table 4.7. The highest LADD was found at location 7 for toluene and ethylbenzene, and the lowest LADD was found at location 21 for xylene. Benzene's LADD ranges from 3.01 x 10^{-04} to 4.30 x10^{-04} mg/kg/day, averaging at 3.73 x 10^{-04} mg/kg/day.

Table 4.7: Lifetime average Daily Dose for the adult residential subpopulation group

Extracted locations	**Benzene LADD (mg/kg/day)**	**Toluene LADD (mg/kg/day)**	**Ethylbenzene LADD (mg/kg/day)**	**Xylene LADD (mg/kg/day)**
(1)	4.05 x 10^{-04}	9.77 x 10^{-04}	2.01 x 10^{-04}	7.59 x 10^{-04}
(2)	3.07 x 10^{-04}	5.84 x 10^{-04}	1.39 x 10^{-04}	5.86 x 10^{-04}
(3)	3.20 x 10^{-04}	6.31 x 10^{-04}	1.44 x 10^{-04}	6.06 x 10^{-04}

(4)	3.43 x 10^{-04}	6.79 x 10^{-04}	1.52 x 10^{-04}	6.20 x 10^{-04}
(5)	3.72 x 10^{-04}	7.88 x 10^{-04}	1.66 x 10^{-04}	6.68 x 10^{-04}
(6)	4.10 x 10^{-04}	9.64 x 10^{-04}	1.88 x 10^{-04}	7.51 x 10^{-04}
(7)	4.30 x 10^{-04}	1.12E-03	2.02 x 10^{-04}	7.71 x 10^{-04}
(8)	4.16 x 10^{-04}	1.12E-03	2.07 x 10^{-04}	8.19 x 10^{-04}
(9)	4.17 x 10^{-04}	1.08E-03	2.11 x 10^{-04}	7.93 x 10^{-04}
(10)	4.07 x 10^{-04}	1.01E-03	2.06 x 10^{-04}	7.76 x 10^{-04}
(11)	4.04 x 10^{-04}	9.64 x 10^{-04}	2.02 x 10^{-04}	7.73 x 10^{-04}
(12)	4.04 x 10^{-04}	9.82 x 10^{-04}	2.01 x 10^{-04}	7.45 x 10^{-04}
(13)	3.96 x 10^{-04}	9.86 x 10^{-04}	1.94 x 10^{-04}	7.16 x 10^{-04}

(14)	3.94×10^{-04}	9.91×10^{-04}	1.87×10^{-04}	7.14×10^{-04}
(15)	3.82×10^{-04}	1.01×10^{-04}	1.85×10^{-04}	7.01×10^{-04}
(16)	3.61×10^{-04}	8.93×10^{-04}	1.70×10^{-04}	6.45×10^{-04}
(17)	3.47×10^{-04}	8.15×10^{-04}	1.62×10^{-04}	6.35×10^{-04}
(18)	3.51×10^{-04}	8.09×10^{-04}	1.60×10^{-04}	6.56×10^{-04}
(19)	3.54×10^{-04}	7.75×10^{-04}	1.57×10^{-04}	6.49×10^{-04}
(20)	3.18×10^{-04}	6.51×10^{-04}	1.42×10^{-04}	5.52×10^{-04}
(21)	3.01×10^{-04}	5.90×10^{-04}	1.37×10^{-04}	5.67×10^{-04}

4.3.3 Human Health Risk Assessment for residential subpopulation groups

The HQ and cancer risk assessment for the four subpopulation groups were conducted using equation 2 for HQ and equation 3 for cancer risk. The average risk assessments for these four groups are presented in Table 4.8. When looking at the HQ for BTEX compounds for the subpopulation below 6 months of age, the non-cancer risk exceeds 1 for most locations,

shown in red in Table 4.8. These numbers are highlighted in red. The cancer risk exceeds the threshold standard of 1 x 10^{-6} across all locations, as seen in Annex 2. The HQ results for the subpopulation group aged between 6 months to 6 years, 6 years to 16 years, and adults (as shown in Table 4.8 respectively) show that the HQ results for all the BTEX compounds are below 1. The HQ decreases from the 6 months to 6 years subpopulation group to the adult subpopulation group. On the other hand, the cancer risk for benzene for all the subpopulation groups is above the 1 x10^{-6} threshold. When looking at the individual subpopulation groups, 4.34 to 6.2 in every 100 000 children in the 6 months to 6 years subpopulation group have the potential of developing cancer. Across all locations, the highest potential for individuals of developing cancer in each subpopulation group is found at location 7, which is opposite the north end fence line near the short- and long-term parking.

Table 4.8: Average Incremental Lifetime Cancer Risk and Hazard Quotient for subpopulation groups < 6 months, 6 months to 6 years, 6 years to 16 years, and adults

	Cancer Risk Benzene	**HQ Benzene**	**HQ Toluene**	**HQ Ethylbenzene**	**HQ Xylene**	**Total HQ**
< 6 months	**1.18 x10^{-04}**	**1.08**	0.01	0.00	0.00	**1.09**
	1.26 x 10^{-05}	*0.12*	*0.03*	*0.01*	*0.01*	*0.13*
6 months to 6 year	**1.13 x10^{-04}**	**1.04**	0.12	0.02	0.04	**1.21**
	1.20 x10^{-05}	*0.11*	*0.02*	*0.00*	*0.00*	*0.14*
6 to 16 years	**1.61 x 10^{-05}**	0.15	0.02	0.00	0.01	0.17
	1.71 x10^{-06}	*0.02*	*0.00*	*0.00*	*0.00*	*0.02*

Adults	**1.02 x10^{-05}**	0.09	0.01	0.00	0.00	0.11
	1.08 x10^{-06}	*0.01*	*0.00*	*0.00*	*0.00*	*0.01*
Average	***6.44 x10^{-05}***	*0.59*	*0.04*	*0.01*	*0.01*	*0.65*

Italics: standard deviation

The number in bold represents the acceptable risk of 1 x10-6 US EPA for CR and 1 for HQ.

4.4 Statistical Analysis of Sampled vs. Estimated Extracted Concentrations

As discussed in chapter 3, section 3.7, samples are extracted from the predictive surfaces. When comparing the statistics of the extracted emissions with the ambient air passive samples, the sample ambient concentration does not vary much for benzene which has the lowest variation while toluene has the highest variation with a difference of 1.43 between the average extracted emissions and the sampled ambient emissions. Toluene has the highest standard deviation amongst the BTEX compounds for both extracted and sampled concentrations. The high standard deviation supports the fact that there is an anomaly at location 7 for toluene. The variation sampled location was observed in the extracted location, and when comparing the mean of both the extracted and sampled location, they are not far off. Therefore, the extracted location's concentrations are still representative of the overall emissions measured at the airport.

Furthermore, when comparing the passive sampled emissions (actual) to the extracted emissions (estimated), the Pearson Correlation Coefficient was used to test the relationship between the sampled emissions and extracted emissions. The Pearson correlation was conducted for the following locations: the short term parking, the long term parking, the drop-off area, gate 3 (apron), taxiway (security), waste sorting area, and NAC fence. In Table 4.9, benzene, xylene, and ethylbenzene have a high correlation which means the predicted emissions represent the area emission well. However, it is not represented so well for the toluene emissions. Siska and Hung (n.d.) argue that the actual vs predicted value correlation should be high for the predicted samples to be representative of the actual samples. The

extracted emissions have thus been used to conduct the HHRA for both residents and employees.

Table 4.9: Extracted vs sampled concentration and the variance and Pearson correlation between the extracted vs sampled emissions

		Benzene	**Toluene**	**Ethylbenzene**	**Xylene**
Extracted concentrations	Mean	2.874271	7.220354	1.345885	5.567865
	Standard deviation (STD)	1.429793	3.142159	0.576979	2.567502
Sampled concentrations	Mean	2.963571	7.930000	1.403571	5.706786
	Standard deviation (STD)	1.549230	3.526439	0.642335	2.976910
	Pearson Correlation Coefficient (extracted vs. sampled)	0.941185	0.859259	0.912837	0.920689

4.5 Statistical Analysis of the Benzene and Toluene Ratios

Given the calculated benzene/toluene ratios in Table 4.10, it is evident that location 7 has the lowest ratio consistently throughout all the seasons. The average ratio is about 4.1 and most locations are well within this ratio.

Table 4.10: Benzene/toluene ratio for all sampling campaigns and for the yearly average concentrations

Rations	Spring B/T ratio	Summer B/T ratio	Autumn B/T ratio	Winter B/T ratio	Yearly average B/T ratio
1	0.47	0.52	0.45	0.50	0.48
2	0.43	0.43	0.47	0.49	0.47
3	0.28	0.30	0.37	0.39	0.35
4	0.21	0.23	0.33	0.34	0.30
5	0.29	0.21	0.41	0.45	0.38
6	0.42	0.54	0.44	0.53	0.48
7	0.07	0.07	0.16	0.17	0.13
8	0.21	0.13	0.31	0.30	0.25
9	0.44	0.52	0.44	0.45	0.45
10	0.39	0.48	0.44	0.57	0.47
11	0.43	0.53	0.42	0.58	0.49
12	0.50	0.59	0.46	0.56	0.52

13	0.50	0.56	0.46	0.59	0.52
14	0.38	0.45	0.42	0.57	0.46
15	0.44	0.47	0.43	0.51	0.45
16	0.41	0.50	0.42	0.37	0.40
17	0.36	0.22	0.41	0.51	0.42

4.6 Wind patterns and weather conditions.

The following are Figure 4.7 to 4.9 depicts wind patterns for the months of January, May and July represents the wind patterns of Summer, Autumn and Winter, respectively. In the summer month, January the winds blow predominately from the South-East directions. With windspeeds mainly ranging from 0.5 to 5.7 km/s. In summer we have some winds about 18% of the time blowing from the North-northeast direction. The temperature in January is 22˚C, the average maximum is 27.1˚ C while the average minimum is 16.3˚ C. Rainfall was recorded for the 5th, 7th , 8th, 13th and 20th. With significant rainfall on the 7th, with rainfall recorded throughout the day. In May the autumn month, winds are mainly coming from the South East, east and northeast directions, with the predominate wind speed ranging from 3.6 to 5.7 km/s. The average temperature in May was 14 ˚C with the average maximum being 21˚C and the average minimum of 6.9˚C. In July the winter month, and the predominate windspeed ranges from 0.5 to 2.10 km/s coming from the east. The average temperature in July is 12.9 C while the average max is 21.1˚C and the average minimum is 4.7.˚C. In September the spring month the average temperature record was 19.3˚C , the average maximum was 27.4˚C and the average minimum was 11.2˚C.

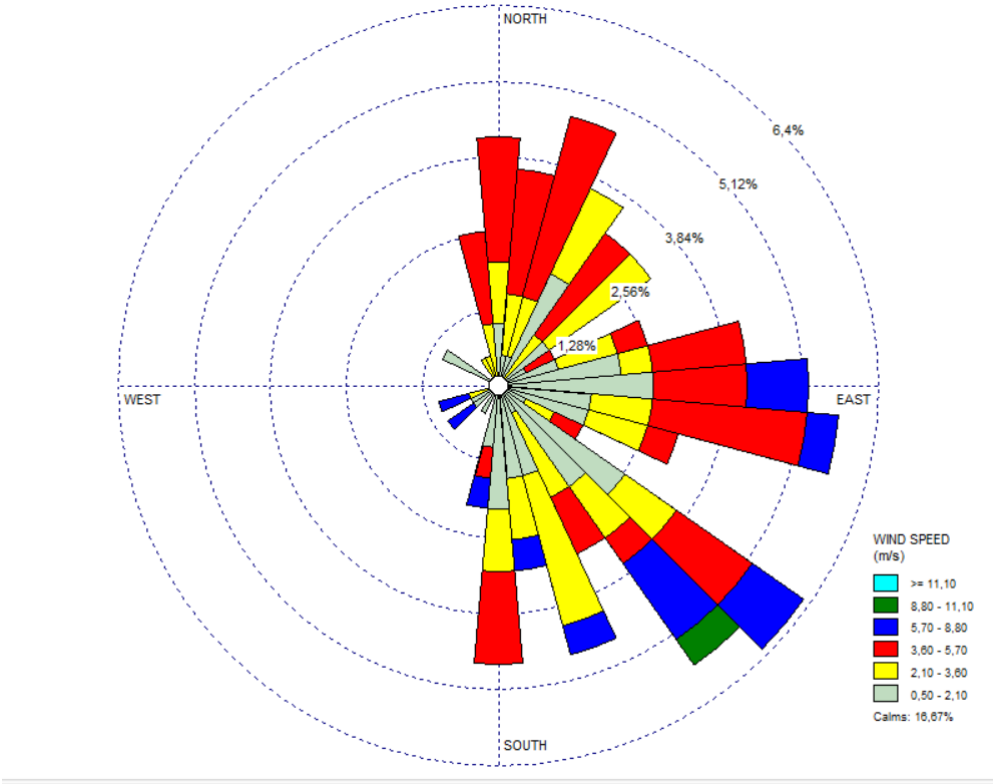


Figure 4.7: Windrose of the full month of January, representing the weather conditions in Summer.

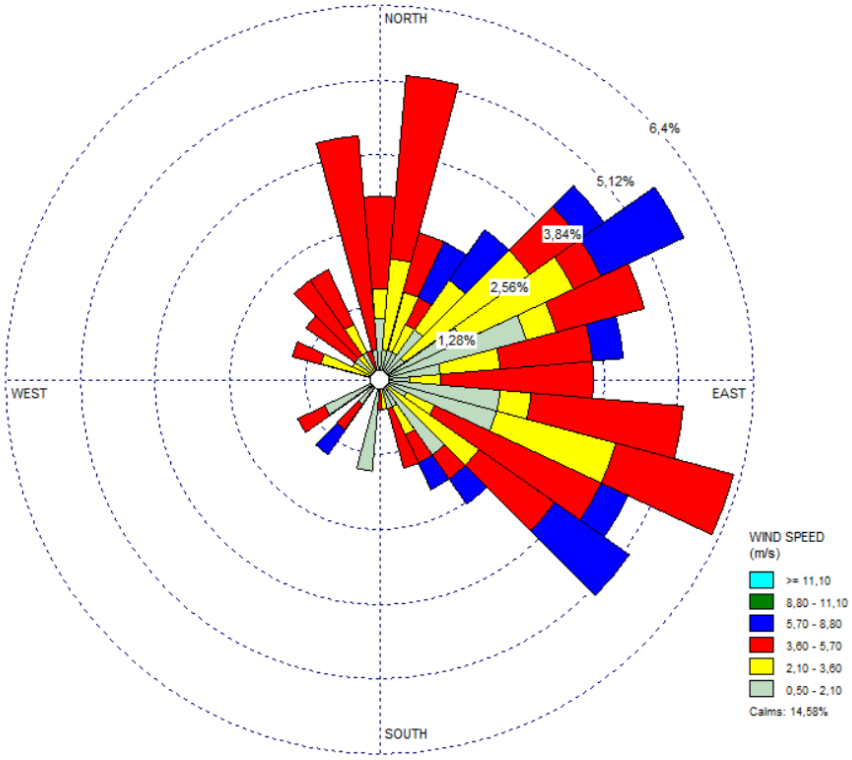


Figure 4.8: Windrose for a full month of May, which is representative of Autumn wind patterns.

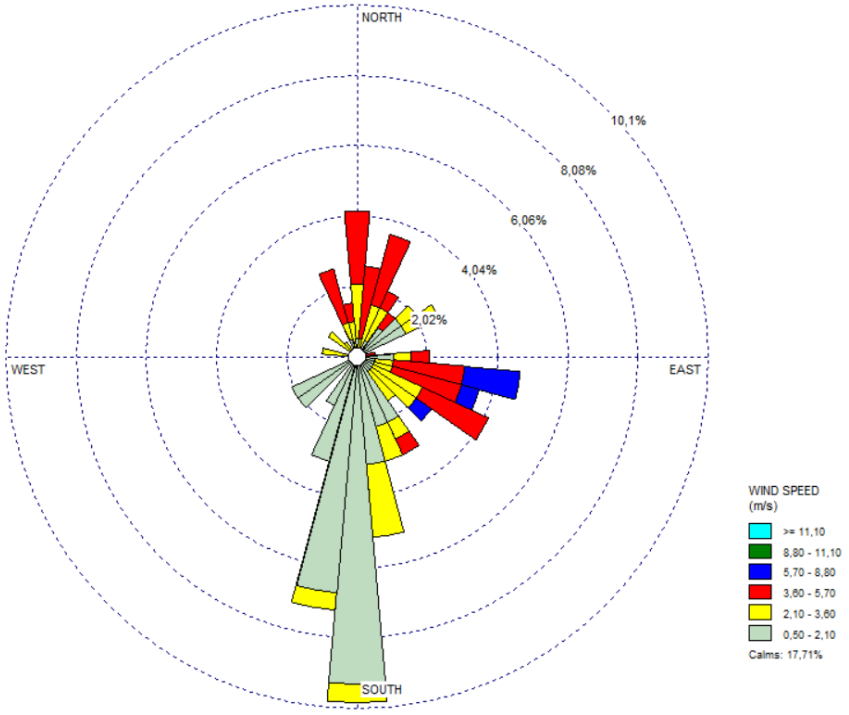


Figure 4.9: Windrose representing the wind patterns for a full July (Winter).

4.7 Conclusion

The results of the research methods used in conducting the HHRA were presented in this chapter. The results of the passive sampling campaign were presented with concentrations ranging from a detection limit of 0.7 µg/m^{-3} to 30.59 µg/m^{-3}. A higher concentration was found at location 7 of the passive sample locations and was omitted from the predictive mapping. This was followed by predictive mapping using kriging in order to see the spatial distribution of concentrations and predict concentrations across the entire surface area of the airport. These results were used to produce an output layer of concentration at the boundary of the airport to represent concentrations residents may be exposed to. Concentrations were also extracted at various locations within the airport to measure concentration levels for on-site employees. The highest concentration level for on-site employees was found at location 28. These results were used as input concentrations in calculating LADD, HQ, and cancer risk, respectively. The subpopulation group aged younger than 6 months had the highest LADD, HQ, and cancer risk overall. Employees at locations 26 and 15 had the highest cancer risk for extracted concentration and sampled concentrations. To highlight the relevance of the

study and to conceptualise the outcomes, the results will be discussed in the following chapter.

Chapter 5: Discussion of Results

5.1 Introduction

The researcher conducted an inhalation risk assessment at a privately owned South African airport. The methodological approach was able to satisfy the objectives placed forward in the introduction. In this chapter, these findings a discussion of the general passive sampled emissions results, the results from the predictive isoconcentration maps (extracted locations), the distribution and seasonal variation of the BTEX compounds. Subsequently, a comparison between the overall cancer risk and non-cancer risk results in this study and other BTEX HHRA studies which were either within an airport environment or one of the microenvironments that occur in an airport. Then finally, the results risk assessment in this study will compare to other studies in order inorder to establish how the Risk Assessment results in this study compare to other BTEX risk assessments across the globe.

5.2 BTEX emissions variation across passive sampling locations and extracted locations

5.2.1 BTEX results across the passive sampled results.

From all the passive sampled results, Location 7 is an outlier in chapter 4. This location exhibited a B/T ratio ranging between 0.07 and 0.17 for all sampling campaigns as compared to ratios at location 8 which range between 0.13 and 0.31 despite location 8 being within a 200-meter radius from location 7. Al well as both the passive sample locations 8 and 7 characterised by aircraft hangers and taxiways, the difference in the B/T ratios are indicative of different source influencing the BTEX emissions in the area. The primary distinctive BTEX source at location 7 is the paint shop. According to Miller *et al*. (2011) and Zalel *et al*. (2008), differences in B/T ratios might be indicative of different sources. The general area of location 7 consists of aircraft hangers and paint shops where aircraft are painted throughout the year. The average concentration sampled at this location is 2.83, 22.48, 3.04, and 14.02, for benzene, toluene, ethylbenzene, and xylene, respectively. The toluene concentration was about three times higher than the average across the airport. A study by Badjagbo *et al.* (2010) looked at the BTEX emissions within a paint shop and mechanics workshop and the evidence from this study points to the potential of multiple sources of emissions using the B/T ratio.

When looking into areas that had higher emission samples across all sampling points for each of the BTEX compounds, benzene had the highest average concentration at the passive sampled location 1. Location 1 is a drop-off zone where taxis drop airport passengers and idle while waiting for passengers. The average concentration for benzene at this location is 4.1, with a B/T ratio of 0.48, which does not vary much from the average ratio of 0.41. This ratio is indicative that the source of benzene is likely to be from similar emission sources for most of the sampling locations excluding location 7. Even with similar ratios, the concentrations at location 1 and across all sampling locations have an apparent seasonal variation. The seasonal and variation is discussed in the latter part of the discussion first, we will look at the results of the extracted locations.

5.2.2 BTEX results from the predicted iso concentration maps (extracted)

In the study, we made use of predictive mapping into order to estimate the emissions at the boundary of the airport, which was assumed to be emissions that residents are most likely to be exposed too. Looking specifically at the extracted locations along the boundary of the airport location 1 to 21 as mapped out in Figure 3.5. The extracted locations 7, 8, 9 10 along the north fence line and extracted location 14, 15 along the southeast end of the fence line of the airport, are were the highest accumulation of BTEX emissions are found at the airport. The assumed source of emissions for locations along the northern fence line is the carpark area, which houses may vehicles for long-term and short-term parking. On the south end of the fence line, the emissions source may be due from the roadside activity on the airport road and other as well as the sampled location 7 the paint shop. On both sides of the fence line, they are small settlements. The high emissions from this area, likely to also be influenced by household-related emissions. Not much is known about the source of power for the residents in these areas, but on the northern fence line the small settlement is informal and they may use paraffin and coal burning as a source of power. However, there is no way to prove this as the sampling was confined to the boundary of the airport. The extracted locations depended on the sampled locations. In our statistical analysis, we tested the relationship of the extracted and sampled locations only for the locations were an extraction was made and a passive sample was taken

5.2.3 Actual VS Extracted emission.

When testing the relationship between the sampled and the extracted emissions, we looked at the locations outlined below.

- Passive sampled location 1 = Extracted location 24
- Passive sampled location 2 = Extracted location 22
- Passive sampled location 3 = Extracted location 23
- Passive sampled location 4 = Extracted location 29
- Passive sampled location 5 = Extracted location 28
- Passive sampled location 8 = Extracted location 30
- Passive sampled location 10 = Extracted location 32

The Pearson correlation results of all fur BTEX emissions, strongly suggest that these a strong correlation between the sampled and the extracted emissions. Bar plots further evocate these results in figure 5.1 of the average BTEX emissions for each of the mentioned locations. Although we find that the difference between the actual and extracted emission for location 1/(24) for benzene and location 8/(30) for toluene are slightly different the overall emissions at these locations are quite similar. The strong correlation justifies the use of the extracted concentrations are representative concentration for human health exposure in areas that are not sampled. The seasonal, as well as spatial distribution, will be discussed in the following sections. The spatial distribution of emissions will be discussed using the kriging results represented in the isoconcentration maps

5.2.4 BTEX seasonal variation

BTEX compounds are known to vary seasonally (Alghamdi *et al*., 2014; Pérez-Rial *et al*., 2009; Zalel *et al*., 2008) concentrations of BTEX compounds are noticeably higher in the colder seasons (during the winter and autumn campaign as seen in Figure 4.6). The seasonal variation is further illustrated in Table 5.1 were the average concentrations of the BTEX for each sampling campaign is considered. The seasonal variation is noticeable. The BTEX concentrations for the summer and spring campaigns are almost half of the winter and summer samples. Winter in the Highveld of South Africa, where the study site is located, are characterised by high atmospheric stability (Tyson *et al*., 2000).

In the study weather data was collected for the sampling months, the results show a temperature difference between the summer and the winter months as 9,1˚C, where the average temperature in each month is 22 and 12,9˚C respectively. The higher concentrations during the autumn period sampling campaign may be due to increased wind speed, which is noted to favour BTEX accumulation (Alghamdi *et al*., 2014). In the study, we see that the predominate windspeed range from 3.7 to 5.7 km/s in May (autumn) was as the windspeeds in July (winter) range from 0.5 to 2.1 km/s. However, the sampling campaign took place in the latter part of the autumn season when temperatures are known to be colder, over the autumn season. BTEX compounds are also known to have a spatial variation which will be considered next.

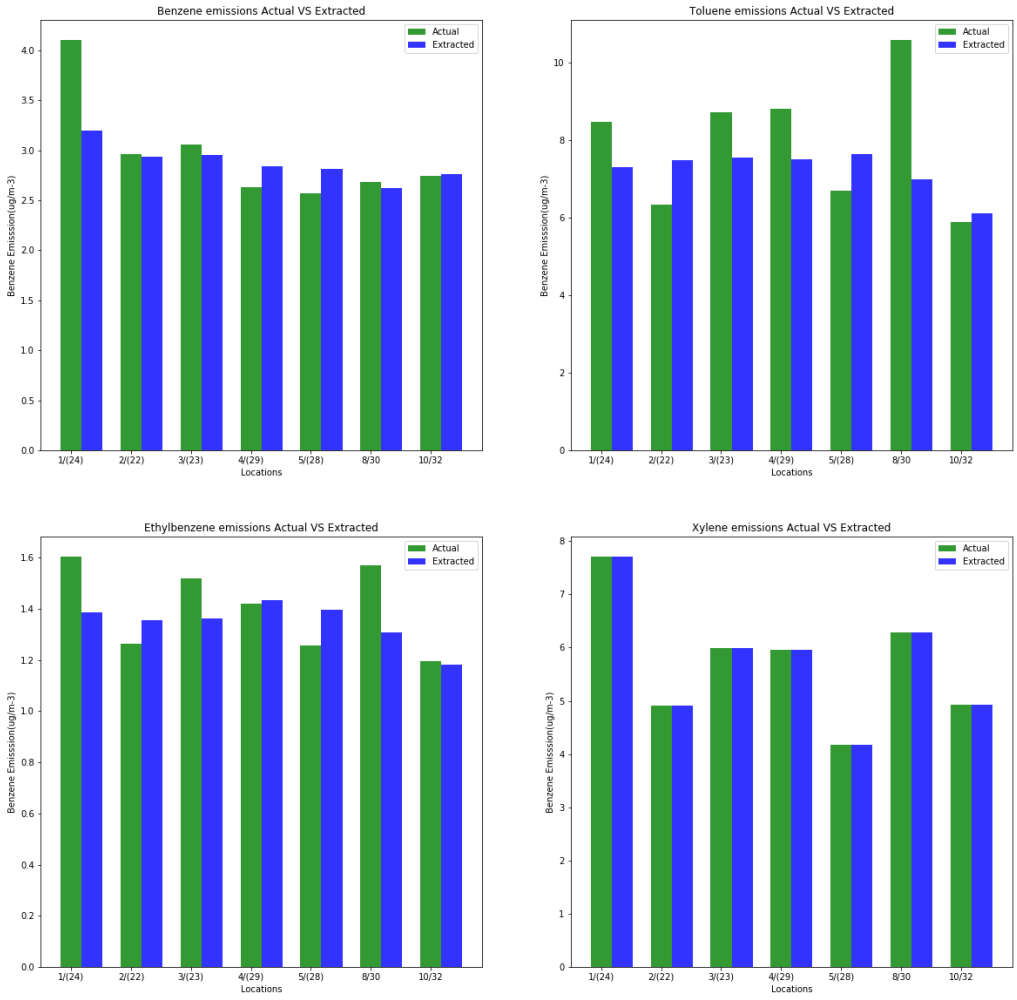


Figure 5.1: Results for Actual and Estimated Risk at Passive sampled locations at the airport.

Table 5.1: Average BTEX ambient sampled concentrations (in ug/m3) for the four sampling campaigns: spring, summer, autumn, and winter

	Benzene	**Toluene**	**Ethylbenzene**	**Xylene**	**Total BTEX**
Spring (average)	1.56	5.31	0.95	3.21	10.08
Summer (average)	1.32	4.22	0.99	3.45	9.98
Autumn(average)	4.04	11.01	1.84	7.76	24.65
Winter(average)	3.88	9.32	1.79	7.79	22.78
Overall average	2.69	7.43	1.53	5.4	16.62

5.2.5 BTEX concentration distribution

When one considers the general pattern of concentration across all four seasons, it is evident that the total BTEX isoconcentration during autumn and winter are highest toward the northeast area of the airport (Figure 4.6). In winter, emissions migrate toward the northeast boundary. In summer and spring, there are two hotspots identified for each season. In spring, the hotspots are above the drop-off area, and the fire station and in summer the hotspots are above the car park apron, the drop-off zone, and along the paint shop area. The hotspot areas are in the spring and summer (as seen in Figure 4.6) and are around the parking area, drop-off zone, apron on the north end of the airport, the fire station, and paint shop area.

The drop-off zone and car park areas are areas dominated by vehicle activity. Because vehicles are a known source of BTEX emissions, they are most likely the primary source in this area (Han and Naeher, 2006). Location 16 is at the end of the runway – the area where

aircraft start to taxi after landing – and engine thrusting is conducted near the area. Aircraft hangers dominate the paint shop area and the hanger area in the southeast area of the airport. As such, aircrafts taxi in and out of this area and start their engines in these areas. Besides the paint shop, the constant idling and movement of aircraft in this area may be the primary source of emissions in the area.

5.3 Comparing BTEX Ambient Air Passive Samples at different airports.

Selected air quality assessments have been conducted at numerous airports across the world, focusing on the evaluation of local airport emissions (Airports Council International, 2010; Barrett *et al*., 2012; Kim *et al*., 2012; Press-Kristensen and Økologiske Råd, 2012; Loader, 2013; Ratliff *et al*., 2009; Rissman *et al*., 2013; Schürmann *et al*., 2006; Zhu *et al*., 2011). Jung *et al*., 2010 and Loader conducted their studies at the airport's apron area and measured BTEX emissions using passive sampling, a technique that has been utilised for this study. Table 5.2 details the emission results of these studies. The variation of BTEX emissions across these airports is an indication of the difference in the sources of emissions at each airport, including the type of aircraft, the landing and takeoff time, time spent by aeroplanes idling, and the areas where samples are collected (FAO, 2003). The airport is a complex environment with multiple sources of BTEX emissions, as outlined in chapter 2 (ICAO, 2011; Kim *et al*., 2012). The composition and infrastructure of each airport vary and therefore, each will have varied compositions and BTEX concentrations. This study made a point of sampling at representative locations around the airport environment, from the apron and runway to parking lots and taxiways.

Table 5.2: A comparison of BTEX ambient air emissions from studies of different airports which used passive sampling

Author	**Airport detail**	**Benzene (ug/m-3)**	**Toluene (ug/m-3)**	**Ethylbenzene (ug/m-3)**	**Xylene (ug/m-3)**
Loader	Heathrow International	0.42	1.25	0.31	0.95

	Airport (apron)				
Jung *et al.*	Runway (Apron)	0.84	3.21	0.30	1.33
Current Study	Average	2.69	7.43	1.53	5.36
	(apron gate 3)	3.73	8.23	1.68	7.05

5.4 BTEX Occupational and Residential Exposure Comparative Analysis

5.3.1 Occupational exposure and Human Health Risk Assessment

The outdoor ambient air concentration for benzene in this study is outlined in Table 5.3. A study by Moolla *et al*. (2015 b) showed that concentrations for benzene were higher for indoor locations, the result of which was contrary to a study by Badjabo (2010). Another study conducted by Jung *et al*. (2010 also found that indoor concentrations are higher than outdoor levels. The occupational exposure of the current research was lower than that reported by Moolla *et al*. (2015 a), whose cancer risk assessment exceeded the US EPA guideline. Findings in this study suggest that cancer risk assessment will surpass the US EPA guideline.

In comparing the occupational health risks of the current study with other studies, occupational health risk assessments conducted in different types of micro-environments, from a refuelling station to a paint shop and those studies conducted at the Los Angeles International Airport (LAX) as seen in Table 5.4 were assessed. The 2004 study by the Los Angeles World Airports found that there was no significant cancer risk exposure with the expected risk of only 6.3 $x10^{-7}$ for all carcinogenic compounds found at the airport. A study by Badjagbo *et al*. (2010), on the other hand, found that all the locations in their research were above acceptable cancer risk levels, but below acceptable risk for general health defects with an HQ below 1. Another study by Tunsaringkarn *et al*., (2012) found that occupational exposure for gas station workers was above the acceptable risk while HQ was below acceptable risk. The average occupational cancer risk for this study is above acceptable risk

with 2.66 x 10^{-6}, while HQ is below acceptable risk for occupational exposure. Across all the studies, benzene's cancer risk is above acceptable risk.

Table 5.3: Occupational exposure emission comparison between the current study and studies by Moolla et al. (2015 a) and Badjagbo et al. (2010)

Study	Study area	Benzene	Toluene	Ethylbenzene	Xylene
Current study	International Airport	2.99	7.73	1.52	5.68
Raeesa *et al.* (2015)	Bus station	1.41	3.22	0.64	3.97
Badjagbo *et al*. (2010)	Automatic paint shop	9.2–23 μg/m^3	127–1101 μg/m^3	11–65 μg/m^3	50–323 μg/m^3

5.3.2 Residential BTEX emission exposure and Human Health Risk Assessment

When comparing the average concentrations of various land types (residential, industrial, agricultural, and roadside) in a study conducted by Masih *et al*. (2016), xylene is an average concentration that is higher than the rest of the BTEX contractions. Ho *et al*. (2004), in their study, found that residential BTEX concentrations in Hong Kong are the highest compared to the current study. Findings of the present study showed that the average concentration of residents is lower than the average concentrations for occupational exposure.

Table 5.4: BTEX exposure concentrations for residents in the current study and other studies

Study	Study area	Benzene	Toluene	Ethylbenzene	Xylene
Current	Boundary concentratio	1.91	5.62	1.13	3.98

study	n				
Jung *et al*. (2010) (neighbourhood)	Neighbourhoods near an airport	0.84	3.76	0.39	1.61
Derwent *et al*. (2000)	UK	3.7	8.1	2.3	10.0
Durmusoglu *et al*. (2010)	Residential area near a landfill site	140.3	239.9	127.7	341.3
Masih *et al.* (2016)	Residential, industrial, agricultural, and roadside	15.91	28.21	3.88	2.84
Colon *et al*. (2001)	Brazil	4.6	44.8	13.3	16.5
Marc *et al*., 2014	Poland	0.9	1.11	0.38	0.5
Gulcin Demirel *et al*., 2014	Turkey	1.7	26.2	0.7	6.0
Ho *et al*.,	Hong Kong	30.5	200.8	15.1	45.6

2004					

For this study, the HHRA for the residential area was stratified according to age groups with the highest risk associated with the subpopulation group 0-6 months. The fact that the 0 to 6-months subpopulation group has the highest associated risk when compared to the other subpopulation groups supports the notion that young children and babies are at higher risk than other age groups (Demirel *et al*., 2014; Naidoo *et al*., 2015). When looking at the general average for cancer risk estimates for all locations, the study found that in general cancer risk is above the 1 x 10-6 guideline similarly found in the Intrinsik (2015) study where predicted cancer risk exposure due to emissions for the year 2022 is above the US EPA guideline. The results of the study carried out at the Los Angeles World Airport found that the general cancer risk was below significant levels. However, regardless of the risk being above or below an acceptable level, there are health risks associated with any exposure to BTEX compounds, from the potential of receptors developing leukaemia to experiencing headaches, dizziness, or a weakening immune and nervous system. The information derived from this type of study can go a long way in helping to manage or mitigate emission exposure challenges or catching a problem before it becomes unmanageable. Information from this research will be beneficial in alleviating the employee's unnecessary exposure to emissions at the study site.

5.5 General BTEX Exposure and Cancer Risk

Figure 5.1 shows the average benzene emissions and the relative sampled and extracted locations. The locations in pink and blue are for occupational exposure and residential exposure respectively. Annexe 4 illustrates the ranking of the locations by potential risk. The highest risk is around sampled locations 1, 15, 3, and extracted location for occupational exposure (blue dot)25. These are the areas where benzene emissions are highest and characterised by constant vehicle and aircraft movement. Location (sampled)15 and (occupational location)25 are along the apron area, and sampled location 3 is along the parking area. It seems that aircraft and vehicles may be the primary source of BTEX

emissions and pose the highest risk to on-site employees. Locations 12 (sampled) and 13 (sampled), which run along the airport approach area, pose the lowest risk.

Similarly, for residential exposure, the lowest concentration is along the south-west boundary, with residents located in the (residential or extracted locations) locations 2 and 21 having the least likelihood of cancer risk. However, the highest cancer risk for the residential subpopulation group is along the north boundary at the (residential or extracted) location 7 near the car park area along the fence line. On average, 1 in every 10 000 children aged 6 months or younger living near the area is likely to developed cancer.

However, when considering the conservative nature of the current study, the risk assessment results for residents are likely to be exaggerations of the real numbers. In comparison to the Toronto Person International Airport and the Los Angles World Airport, the results of this proved to be extreme. When we consider the locations of the more established settlements in and around the area, the influence of airport emissions on their health is likely to decrease as we move further away from the boundary.

However, when comparing the measured emissions of BTEX at two other airports, the results of the current study proved to be 6 times greater than Loader 2011 and 3 times greater than Jungle et al., 2011, which is concerning when considering the size of Heathrow as compared to the current study site. The residents of the Malatjie informal settlement will likely carry the most substantial burden as they are nearest to the airport and along with the highest estimated emissions along the fence line where the highest risk is estimated. However, the actual risk will be far less than estimated. The settlement on the southeast Savanna is the southwest side of the airport, which is an area dominated with the lowest emissions. These residents of the settlement are less likely to be adverse to the estimated risk along the Southwest boundary.

However, the more concerning of the risk estimates are those of the employees. Where in average about 2 in 1000 000 are likely to develop cancer-related to benzene exposure, furthermore employees that are likely at the highest risk are the ones working in the parking bay and the drop off zone where the cancer risk estimate is double for the average, where 4 in 1000 000 people are likely to develop cancer. However, in the drop-off zone, most employees do not stay there for long periods. If the environments that they are moving into have reduced emission, it will minimise their risk. They are security guards that drive golf carts and security guards that work in the carpark and these employees are the most concerning. The

employee risk assessment is calculated on the assumption that employees work 12 hours within the specific locations; however the schedule varies based on the function of the employees; therefore the estimates can be slightly exaggerated or underestimated.

readings for benzene exposure, this warrants further investigation.

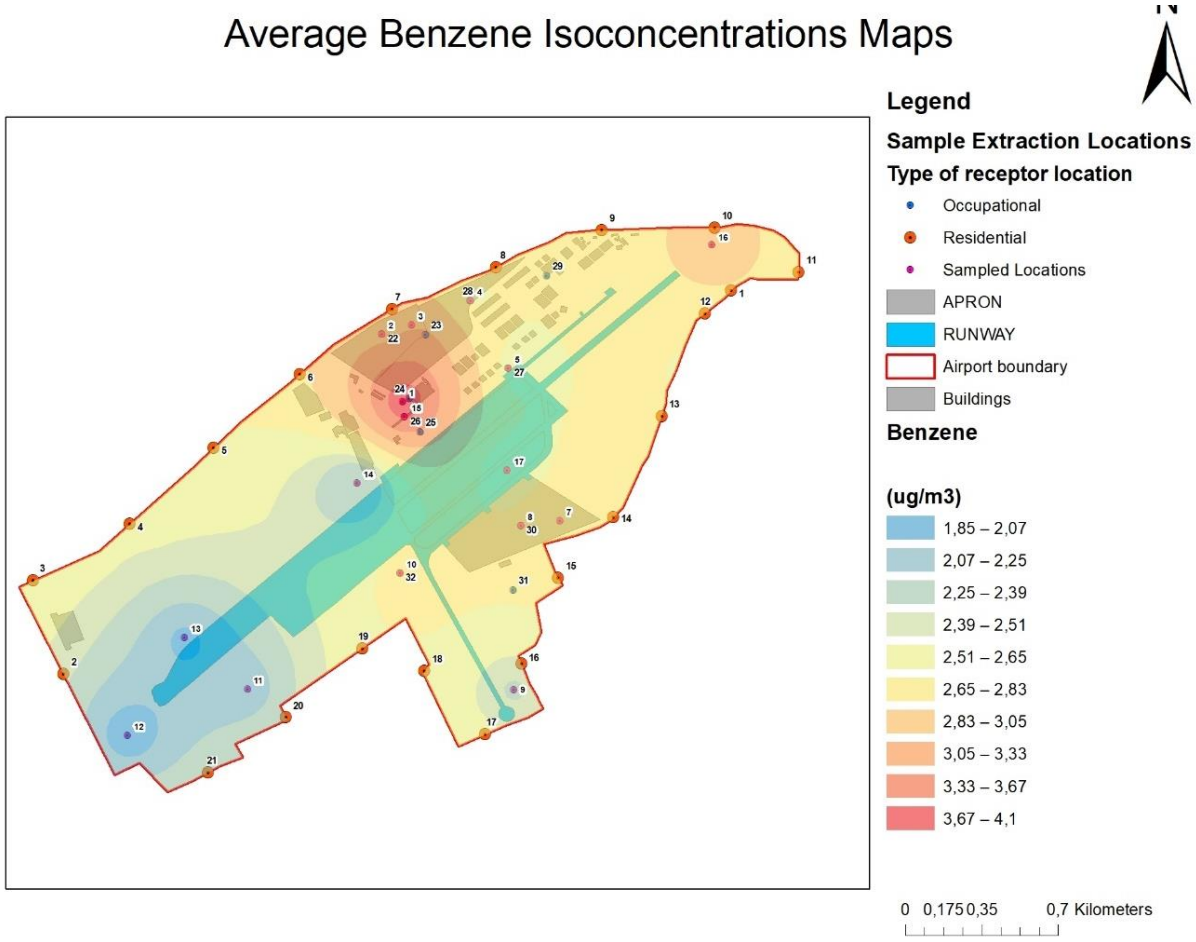


Figure 5.2: Average benzene exposure and the related location of receptors for on-site employees (sampled and occupational locations) and residential subpopulation groups (red)

5.5 Significance of the Study

The HHRA conducted in this study can help establish risk for population groups without the invasion of the receptors' privacy through an epidemiology study conducted by collecting personal health statistics and air quality measurement equipment in their homes. This non-invasive study allowed the researcher to conduct a type of baseline campaign to inform

researchers and airport managers about the general seasonal pattern and spatial distributions of emissions at the airport. The HHRA informs the airport management of the potential risks associated with exposure to BTEX emissions and the findings in this study can be used to inform air quality management's plans and to address areas of great concern in order to reduce emissions. Furthermore, this research has shed light on the health implications of BTEX emissions in an airport environment, and it can inform policymakers on health policies or the need to develop BTEX emission limits in South Africa. However, given the global increase in air travel and airport expansions, and the findings of the above acceptable risk

5.7 Conclusion

This chapter provided a comprehensive discussion on the findings regarding ambient emission measurements at the airport and HHRAs for employees and residential subpopulation groups. This chapter highlighted that the employees are at higher risk of exposure to potential health risks than the residential subpopulation groups are and of all the residential subpopulation groups the group aged younger than 6 months are at the highest risk. The highest risk area is along the northern fence line for the residential group and the car park and apron area for on-site employees.

Chapter 6: Summary, Conclusion, and Recommendations

6.1 Introduction

This chapter presents a summary of the study's significant findings. The conclusions based on the details of the significant results of this study are described, and the final recommendations emerging from the findings of this study are proposed.

6.2 Summary of Findings

6.2.1 Overview of study

The purpose of this study was to conduct an HHRA at a South African airport on a subset of pollutants, namely BTEX compounds, which have been identified to cause a variety of health defects in humans. BTEX has been the subject of many HHRA within a variety of environments, from homes to refuelling stations, and paint shops. The results of many of these studies have shown that the expected risk of exposure to benzene is above the US EPA guideline of 1 x10-6. While the general non-cancer risk for all BTEX compounds is not consistently above or below the Hazard Quotient limit of 1. In an airport environment, there are several BTEX sources, from the car park areas, waste sorting sites, paint workshops, and aircraft. The car park area is characterised by long-term parking and short-term. The drop-off area is used by taxi services that drop-off and pick up clients. At the waste sorting site, all the waste generated at the airport is taken hear and sorted and collected by an external waste management company. The paint shop is where aircraft are painted. They are several aircraft hangars where aircraft are kept. The amount of BTEX sources within the airport raises concerns on the actual concentrations of BTEX which are maybe found in the airport environment as well as the overall associated non-cancer and cancer risk. Several studies have been conducted for airports in Europe and the United States which have evaluated the overall health impact of airport emissions on surrounding communities, and these studies took one of three methodological approaches namely, an HIA, Epistemology study or HHRA. Several airports have taken the HHRA approach; however, in their emissions estimations, they used modelling and focused on a number of emissions. The current study attempts to provide a snapshot of the potential health effects of exposure to airport-related BTEX emissions. Further exploring the associated spatial and temporal distributions of emissions at the airport.

In conducting the study, the US EPA guidelines in conducting an HHRA assessment where utilised and are largely sublimated by the Toronto Pearson International airport methodological approach. In the Exposure assessment, a scenario-based approach was used where emissions were measured separately from the actual exposure time weight average. The time weight average of all the hypothetical group was assumed to be 24 hours a day 7 days a week for residents and 12 hours per day 7 days a week. To measure emissions diffusive passive samplers where utilities and the sampling locations were distributed throughout the entire airport and some near BTEX source. To further estimated the emissions, that residents might be exposed to, estimates were taken from the kriging surfaces produced using the kriging method in ArcMap. These emissions were extracted from the kriging surface, and when comparing some of the actual passive sampled results and the extract emission where passive samples were taken. The extracted and actual passive sampled location have a strong correlation; therefore, the extracted surface is a good representation of the likely measured emissions at the extracted locations. The overall method worked well in yielding results for the full HHRA.

6.2.2 Overall Findings

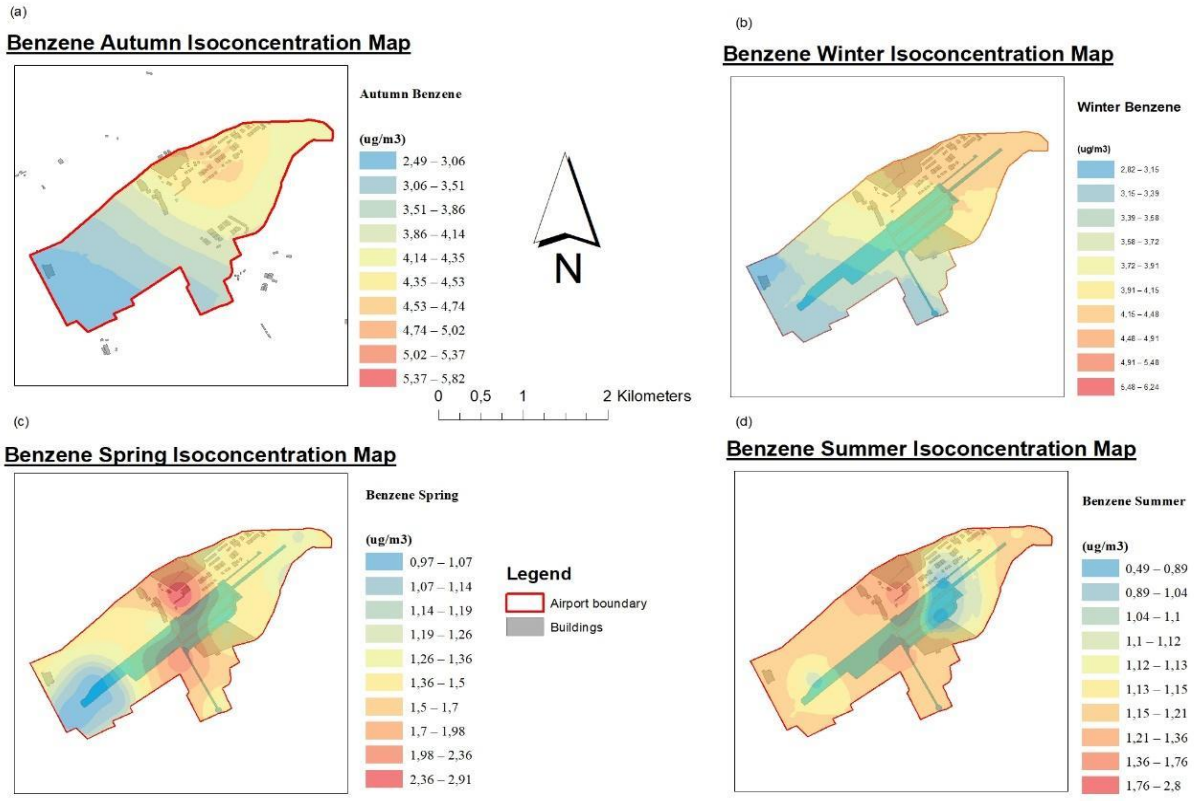


Figure 6.1: Isoconcentration maps for benzene

In the results, we found that the car park and apron areas are a significant source of benzene emissions with concentrations of benzene highest in those areas. The highest toluene concentrations were found in the sampling location 7 near the paint shop, which was identified as an anomaly. From the samples collected, it was evident that activities like the painting of aircraft can be associated with high levels of toluene. The highest concentrations of benzene levels are near mobile sources throughout all seasons, in summer and spring, as seen in Figure 6.1, where spring and summer have hotspots over the car-park area and the fire station. However, wind patterns influenced the dispersion of benzene toward the northeastern area of the airport for both autumn and winter. The air pollution results displayed in the isoconcentration map gives an illustration of the changes in impact from season to season. As seen in Figure 4.1 to Figure 4.6 in chapter 4, the concentrations of emissions are higher during the autumn and winter campaigns.

The results of both the air quality study and the final HHRA can help airport managers decide on their emission control strategies. Knowing the distribution of emission sources and the overall probable impact thereof can have an effect on the long-term decision of changing the location and composition of airport activities. When the results of emissions recorded in the current study were compared with those of previous studies, it was found that emissions in this study are higher.

This study revealed that cancer risk is higher than the US EPA standard, with on-site employees and children younger than six months, most at risk of developing cancer. On-site employees near the carpark and the apron areas are at highest risk, with a reported 4 in 1 000 000 likely to develop cancer as compared to the employee average of 2 in 1 000 000. When looking at the general health implications, the HQ for most sites is below the acceptable risk level of 1. However, for children younger than six months, the health implications are above the acceptable measurements for all the BTEX compounds. Benzene poses the highest risk out of the BTEX compounds for children younger than 6 months old.

The risk assessment comes with many assumptions and when using the results, these assumptions should be considered, although the cancer risk estimates are above the US EPA guidelines. The conservative nature of our approach for estimating residential emissions exposure in which we utilised the emission estimates along the boundary of the airport, may

have caused a slight exaggeration of risk estimates, but one must take note that they are small informal settlements around the north fence line and the south-east fence line, where the estimates may be reflective for residents who stay in the area for 24 hours and not necessarily actual for residents who work outside the settlement. When considering employees risk results, the assumption was made that the employee works for a total of 12 hours in a day in the sampled or extracted location. However, the work schedule for airport employees will vary according to their function and therefore, the results made is some cases be an underestimation or an overestimation of actual risk.

The results of this study have, like many other HHRAs, helped identify the associated risk of exposure to emissions for different age groups. This study widens the understanding of the potential health risks posed by BTEX emissions on the residents near airports, delving deeper into the knowledge of BTEX concentrations across spatial, temporal, and seasonal variation at an airport.

6.3 Study Limits

This study has limitations as the results are only applicable to a hypothetical population with assumed behaviour. A detailed behavioural analysis could give a better view of associated health risks, meaning personal sampling would be ideal. However, there were limitations to what could be done in this study, and no personal sampling was allowed. Besides results from this research spark other possible research questions within the study site to be carried out as additional research.

6.4 Further Research

- Furthermore, an HIA could be conducted using the results of this study as well as health information gathered from surrounding communities to establish the real health impact on residents like a research carried out by Visser *et al*. (2005). This could be done through a longitudinal study, which will look at the overall health conditions of sampled communities near an airport.
- Analyse how an airports aircraft schedule and mix of aircraft sizes, influence BTEX concentrations.
- A follow-up study should be conducted to establish the real health impact in the areas near the airport.

- There should be further research to look at another approach to adequately define the potential risk of BTEX emissions.

6.5 Conclusion

The chapter summarises the present study and presents the conclusions and recommendations drawn from the findings the study highlights the potential health risk for on-site employees and residents living in the vicinity of the airport as a result of airport-related emissions. In the study, we found that the cancer risk for exposure to benzene airport-related emissions, both on-site employees and residents, the results are above the acceptable risk of 1 in 1000 000 people. For onsite employees, the average cancer risk is that 2.66 in 1000, 000 employees are like to develop cancer. On the other hand of residents, the highest at-risk group are the 0 to 6-month residents. However, the results are riddled with assumptions and therefore may be a slight exaggeration of actual results, therefore follow up studies are encouraged to establish the real implication of airport-related BTEX emissions on employees and residents.

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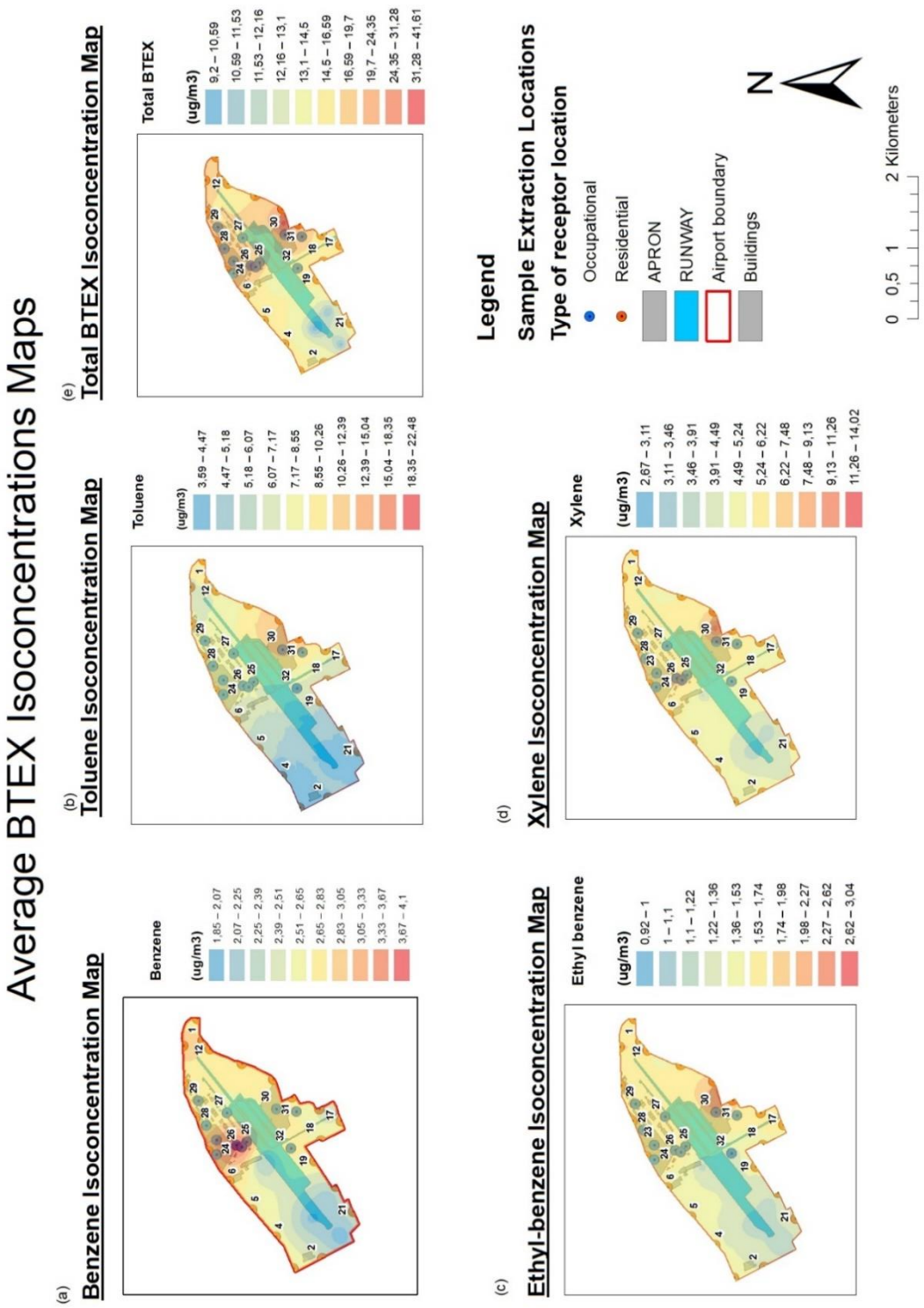
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Annexe 1: Average BTEX emission isoconcentration map with extraction locations



Annexe 2: Risk Assessment results for residential Subpopulation groups.

Table A2.1: Risk Assessment results for subpopulation group < 6 months

Extracted Locations	Benzene CR	Benzene HQ	HQ Toluene	HQ Ethylbenzene	HQ Xylene	Total HQ
1	**1.28E-04**	1.17	0.14	0.02	0.04	1.38
2	**9.73E-05**	0.89	0.08	0.02	0.03	1.03
3	**1.01E-04**	0.93	0.09	0.02	0.04	1.07
4	**1.09E-04**	1.00	0.10	0.02	0.04	1.15
5	**1.18E-04**	1.08	0.11	0.02	0.04	1.25
6	**1.30E-04**	1.19	0.14	0.02	0.04	1.40
7	**1.36E-04**	1.25	0.16	0.02	0.04	1.48
8	**1.32E-04**	1.21	0.16	0.02	0.05	1.44
9	**1.32E-04**	1.21	0.16	0.02	0.05	1.44
10	**1.29E-04**	1.18	0.15	0.02	0.05	1.40
11	**1.28E-04**	1.17	0.14	0.02	0.04	1.38
12	**1.28E-04**	1.17	0.14	0.02	0.04	1.38

13	**1.26E-04**	1.15	0.14	0.02	0.04	1.36
14	**1.25E-04**	1.14	0.14	0.02	0.04	1.35
15	**1.21E-04**	1.11	0.15	0.02	0.04	1.32
16	**1.14E-04**	1.05	0.13	0.02	0.04	1.23
17	**1.10E-04**	1.01	0.12	0.02	0.04	1.18
18	**1.11E-04**	1.02	0.12	0.02	0.04	1.19
19	**1.12E-04**	1.03	0.11	0.02	0.04	1.20
20	**1.01E-04**	0.92	0.09	0.02	0.03	1.07
21	**9.54E-05**	0.87	0.09	0.02	0.03	1.01

Table A2.2: Risk Assessment results for subpopulation group 6 months to 6 years

	Benzene CR	Benzene HQ	HQ Toluene	HQ Ethylbenzene	HQ Xylene	Total HQ
1	**5.84E-05**	0.53	0.06	0.01	0.02	0.63
2	**4.43E-05**	0.41	0.04	0.01	0.02	0.47
3	**4.61E-05**	0.42	0.04	0.01	0.02	0.49
4	**4.95E-05**	0.45	0.04	0.01	0.02	0.52
5	**5.36E-05**	0.49	0.05	0.01	0.02	0.57
6	**5.91E-05**	0.54	0.06	0.01	0.02	0.64
7	**6.20E-05**	0.57	0.07	0.01	0.02	0.67
8	**6.00E-05**	0.55	0.07	0.01	0.02	0.66
9	**6.01E-05**	0.55	0.07	0.01	0.02	0.65
10	**5.87E-05**	0.54	0.07	0.01	0.02	0.64
11	**5.83E-05**	0.53	0.06	0.01	0.02	0.63
12	**5.83E-05**	0.53	0.06	0.01	0.02	0.63
13	**5.71E-05**	0.52	0.07	0.01	0.02	0.62

14	**5.68E-05**	0.52	0.07	0.01	0.02	0.61
15	**5.51E-05**	0.50	0.07	0.01	0.02	0.60
16	**5.20E-05**	0.48	0.06	0.01	0.02	0.56
17	**5.00E-05**	0.46	0.05	0.01	0.02	0.54

Table A3.3: Risk Assessment results for subpopulation group 6 years to 16 years

	Benzene CR	Benzene HQ	HQ Toluene	HQ Ethylbenzene	HQ Xylene	Total HQ
1	**1.75E-05**	0.16	0.02	0.00	0.01	0.19
2	**1.32E-05**	0.12	0.01	0.00	0.00	0.14
3	**1.38E-05**	0.13	0.01	0.00	0.00	0.15
4	**1.48E-05**	0.14	0.01	0.00	0.00	0.16
5	**1.60E-05**	0.15	0.02	0.00	0.01	0.17
6	**1.77E-05**	0.16	0.02	0.00	0.01	0.19
7	**1.85E-05**	0.17	0.02	0.00	0.01	0.20
8	**1.80E-05**	0.16	0.02	0.00	0.01	0.20
9	**1.80E-05**	0.16	0.02	0.00	0.01	0.20
10	**1.76E-05**	0.16	0.02	0.00	0.01	0.19
11	**1.74E-05**	0.16	0.02	0.00	0.01	0.19
12	**1.74E-05**	0.16	0.02	0.00	0.01	0.19
13	**1.71E-05**	0.16	0.02	0.00	0.01	0.18

14	**1.70E-05**	0.16	0.02	0.00	0.01	0.18
15	**1.65E-05**	0.15	0.02	0.00	0.01	0.18
16	**1.56E-05**	0.14	0.02	0.00	0.01	0.17
17	**1.50E-05**	0.14	0.02	0.00	0.01	0.16
18	**1.52E-05**	0.14	0.02	0.00	0.01	0.16
19	**1.53E-05**	0.14	0.02	0.00	0.01	0.16
20	**1.37E-05**	0.13	0.01	0.00	0.00	0.15
21	**1.30E-05**	0.12	0.01	0.00	0.00	0.14

Table A2.4: Risk Assessment results for subpopulation group adults

	Benzene CR	Benzene HQ	HQ Toluene	HQ Ethylbenzene	HQ Xylene	Total HQ
1	**1.11E-05**	0.10	0.01	0.00	0.00	0.12
2	**8.38E-06**	0.08	0.01	0.00	0.00	0.09
3	**8.73E-06**	0.08	0.01	0.00	0.00	0.09
4	**9.37E-06**	0.09	0.01	0.00	0.00	0.10
5	**1.01E-05**	0.09	0.01	0.00	0.00	0.11
6	**1.12E-05**	0.10	0.01	0.00	0.00	0.12
7	**1.17E-05**	0.11	0.01	0.00	0.00	0.13
8	**1.14E-05**	0.10	0.01	0.00	0.00	0.12
9	**1.14E-05**	0.10	0.01	0.00	0.00	0.12
10	**1.11E-05**	0.10	0.01	0.00	0.00	0.12
11	**1.10E-05**	0.10	0.01	0.00	0.00	0.12
12	**1.10E-05**	0.10	0.01	0.00	0.00	0.12
13	**1.08E-05**	0.10	0.01	0.00	0.00	0.12

14	**1.08E-05**	0.10	0.01	0.00	0.00	0.12
15	**1.04E-05**	0.10	0.01	0.00	0.00	0.11
16	**9.85E-06**	0.09	0.01	0.00	0.00	0.11
17	**9.47E-06**	0.09	0.01	0.00	0.00	0.10
18	**9.59E-06**	0.09	0.01	0.00	0.00	0.10
19	**9.68E-06**	0.09	0.01	0.00	0.00	0.10
20	**8.68E-06**	0.08	0.01	0.00	0.00	0.09
21	**8.22E-06**	0.08	0.01	0.00	0.00	0.09

Annexe 3: Pearson Correlation Test results

Table A3.1: Emissions for sampled and extracted location as well as the Pearson correlation between sampled and extracted emissions for, short-term parking, Long-term parking, drop-off zone, Gate 3 apron, Taxi-way, waste sorting site, NAC fence line, and fire station

	Extracted Locations/Sampled location	**Benzene (extracted)**	**Benzene (sampled)**	**Toluene (extracted)**	**Toluene (sampled)**	**Ethyl (extracted)**	**Ethyl (sampled)**	**Xylene (extracted)**	**Xylene (sampled)**
Short term	22 -2	2.93	2.97	7.47	6.34	1.35	1.43	5.00	4.91

parking									
Long term parking	23-3	2.95	3.06	7.54	8.72	1.36	1.77	5.44	6.00
Drop-off	24-1	3.20	4.10	7.29	8.48	1.39	1.77	6.37	7.71
Taxi way (security)	28-5	2.81	2.57	7.63	6.70	1.40	1.43	5.88	4.18
Waste sorting Area	29-4	2.84	2.63	7.51	8.81	1.43	1.64	5.41	5.95
NAC Fence	30-8	2.63	2.69	6.98	10.57	1.31	1.84	5.80	6.29
Fire Station	32-10	2.76	2.74	6.11	5.89	1.18	1.18	5.06	4.93
	Correlation	0.941185		0.859259		0.912837		0.920689	

	Coefficient				

Annexe 4: Occupational Risk Assessment Analysis

Table A4.2: Occupational Risk Assessment results ranked by benzene cancer risk descending

Rank	Sample number	Benzene CR	Benz HQ	HQ Toluene	HQ Ethylbenzene	HQ Xylene	Total HQ
1	1	3.90E-06	0.04	0.00	0.00	0.00	0.04
2	15	3.55E-06	0.03	0.00	0.00	0.00	0.04
3	3	2.91E-06	0.03	0.00	0.00	0.00	0.03
4	25	2.87E-06	0.03	0.00	0.00	0.00	0.03
5	2	2.82E-06	0.03	0.00	0.00	0.00	0.03
6	7	2.70E-06	0.02	0.01	0.00	0.00	0.04
7	27	2.64E-06	0.02	0.00	0.00	0.00	0.03
8	10	2.61E-06	0.02	0.00	0.00	0.00	0.03
9	8	2.56E-06	0.02	0.00	0.00	0.00	0.03
10	4	2.50E-06	0.02	0.00	0.00	0.00	0.03

11	31	2.47E-06	0.02	0.00	0.00	0.00	0.03
12	6	2.46E-06	0.02	0.00	0.00	0.00	0.03
13	5	2.45E-06	0.02	0.00	0.00	0.00	0.03
14	9	2.22E-06	0.02	0.00	0.00	0.00	0.02
15	14	1.98E-06	0.02	0.00	0.00	0.00	0.02
16	13	1.88E-06	0.02	0.00	0.00	0.00	0.02