Chapter 3

SEASONAL INTER-SITE CORRELATION AMONG AIR POLLUTION MONITORING SITES IN CAPE TOWN, SOUTH AFRICA

Background: Many pollutants show complex spatio-temporal profiles, which complicates measuring or modelling exposure patterns and obscures subsequent estimation of human exposure. Nevertheless, the majority of air pollution epidemiological studies are based on exposure data from a single central outdoor monitor. This may introduce information bias, which impairs the validity of epidemiological studies. The temporal correlation among outdoor concentrations of a particular air pollutant measured at different sites (inter-site correlation) may be investigated to control information bias. The higher the inter-site correlation, the lower the anticipated information bias when using data from one site for another with similar air pollution sources and the more valid the exposure assessment of the epidemiological study. The majority of the air pollution epidemiological and exposure assessment studies are carried out in developed countries. Very few quantitative exposure assessment studies have been conducted in South Africa. The aim of this study is not source apportionment, but to consider the suitability of information derived from the air pollution monitoring network in Cape Town, South Africa in epidemiological studies. Consequently this study investigated the seasonal inter-site correlation between 24-h average outdoor PM_{10} mass, NO_2, NO, SO_2, O_3 and CO in Cape Town.

Methods: Daily averages (24-h) were obtained from hourly averages measured during 1 August 1998 – 31 July 2003. All 24-h averages are based on at least 20 1-h samples in accordance with the ISO 17025 guidelines. If this requirement was not met, a 24-h average was set as a missing value. All the 24-h average concentrations did not have a normal distribution. Nonparametric Spearman's Rho correlation analysis was conducted. Statistical significance was assessed at 99% confidence level for the correlations. Seasons were defined as winter, spring, summer and autumn for the following periods 1 June – 31 August, 1 September – 30 November, 1 December – 28(29) February and 1 March – 31 May, respectively.

Results: The descriptive statistics of the different air pollutants measured at the sites under investigation are in accordance with the major air pollution sources present in each area. It was found that in general pollutant inter-site correlation coefficients are

not strong during all seasons. On average, the most homogeneously distributed pollutant is NO_2, followed by PM_{10} (including Khayelitsha data), PM_{10} (excluding Khayelitsha data), NO, CO, O_3 and finally SO_2 in the Cape Town air shed. Inter-site correlation coefficients for NO_2, NO, SO_2, CO and O_3 vary from 0.456 to 0.832; 0.212 to 0.791; -0.100 to 0.662; 0.302 to 0.676 and 0.123 and 0.557, respectively. PM_{10} measured at Bothasig, City Centre, Goodwood and Tableview presents correlations from 0.261 to 0.859. The PM_{10} inter-site correlation coefficients between Khayelitsha and the other sites (Bothasig, City Centre, Goodwood and Tableview) vary from 0.396 to 0.769.

Conclusions: The results highlight the importance of properly characterising relations among different outdoor pollution monitoring sites. Studies conducted in locations with strong inter-site correlation coefficients among outdoor pollutant concentrations should not assume that they necessarily persist across seasons. Given the resource stricken research environment in South Africa there is still merit in using NO, NO_2, SO_2, O_3 and CO data from one site for another. This approach will make outdoor air pollution exposure assessment easier during hospital time-series studies. This is however not the case for SO_2 measured at Bothasig and Tableview and for PM_{10} at all sites. Stemming from the preliminary results and associated limitations some thoughts are suggested to the City of Cape Town regarding its air quality monitoring network.

3.1 Introduction

The World Health Organisation reports that 25% of all preventable diseases are due to a poor physical environment.[1] No case in support of environmental action is deeper than that of the need to eradicate health risks. Various epidemiological and toxicological studies have linked air pollution to mortality and various morbidity outcomes. For reviews, refer to Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society, Vedal and Lighty et al.[2-5] However, cohort studies focusing on long-term health effects are still scarce.[6,7]

Once emitted into the environment, air pollutants typically undergo a process of dispersion. Exposure occurs when humans encounter the air pollutants. During dispersion pollutants may undergo many kinds of transformation. Dilution occurs due to the mixture with the transporting medium (e.g. air). Physical processes such as sedimentation and coagulation are the principal factors for causing primary suspended particulate matter to be heterogeneously distributed.[8] Chemical reactions occur, breaking down the original pollutants or converting them into new compounds, which may pose more harm than the original compound. Inert pollutants (e.g. CO) simply disperse after emission, resulting in a concentration gradient with increasing distance to the source.[9] Chemically reactive pollutants (e.g. NO) display a sharper concentration gradient than inert pollutants.[9] The formation of secondary pollutants (e.g. ammonium sulphate and O_3) is a large-scale occurrence and these pollutants are quite homogenously distributed in space.[10] Exceptions to this occur for reactive species in the environs of other reactive species (e.g. depletion of O_3 by NO along busy roads). Diffusion and transport of pollutants are influenced by atmospheric conditions such as wind speed, vertical temperature gradient and solar radiation.[9] As a result many pollutants show complex spatio-temporal profiles. This complexity means that measuring or modelling exposure patterns and subsequently clarifying levels of human exposure can be complicated.

Nevertheless, the majority of air pollution epidemiological studies are based on exposure data from a single central outdoor monitor. This may introduce information bias, which involves misclassification of the study participants with respect to exposure status. The validity of epidemiological studies is impaired by information bias. In order to control information bias the inter-site correlation between outdoor air pollution concentrations within a particular area may be

investigated. The higher the inter-site correlation, the lower the anticipated information bias when using data from one site for another with similar air pollution sources and the more valid the epidemiological study.

Most air pollution epidemiological and exposure assessment studies are carried out in developed countries. It is important to conduct more air pollution epidemiological and exposure assessment studies in South Africa as it is faced by pollution caused by industry (First World situation) and by domestic burning of coal and biofuels (Third World situation). Thus study results (e.g. exposure-response curves) - obtained from developed countries – cannot merely be extrapolated with total conviction to developing countries. The three global factors that directly or indirectly impact on health - the community and social environment, the physical environment and the family and individual environment – are different for developed and developing countries.[11]

Very few quantitative exposure assessment studies have been conducted in South Africa.[12-16] Exposure is usually based on a proxy measure, such as smoking status[17,18] or use of polluting fuels (wood, coal, animal dung, crop residues or paraffin) for cooking and space heating.[19,20]

Air pollution monitoring sites in Cape Town are located in different types of areas. It is therefore anticipated that the inter-site correlation coefficients for the different pollutants will differ. However, it is still necessary to quantify the inter-site correlation coefficients instead of describing the situation qualitatively. Consequently this study investigated the seasonal inter-site correlation between 24-h average outdoor PM_{10} mass, NO_2, NO, SO_2, O_3 and CO in Cape Town, South Africa. The aim of this study is not source apportionment, but to consider the suitability of information derived from the air pollution monitoring network in Cape Town in epidemiological studies.

3.2 Meteorology and Topography

The City of Cape Town was established in December 2000 by the merging of the previous Cape Metropolitan Council and six Metropolitan Local Councils: Tygerberg, Oostenberg, Blaauwberg, South Peninsula, Helderberg and Cape Town. It is the southern most metropolitan area on the African continent and covers an

area of 2487 km^2. The area is encircled by mountains and the Atlantic Ocean. Table Mountain is 1 086 metres above sea level (ASL). It is flanked by Devil's Peak (1000 m ASL), Lion's Head (669 m ASL) and Signal Hill, which precedes the Twelve Apostles (Noordhoek Peak 756 m ASL and Chapman's Peak 592 m ASL) in the mountain chain.

The Peninsula has a Mediterranean climate. Summer is from December to February with temperatures averaging at around 28°C. The prevailing wind during October to March (spring to autumn) is from SSE to SSW. It brings very little rain with it. Occasionally during summer the Cape will experience northerly "berg winds" with associated increase in temperatures. The Southeaster subsides slightly during February and March. The prevailing wind between May and August (autumn and winter) blows from N to NW. This wind is not as strong as the South Easter and occurs less frequently. It precedes a cold front and is therefore followed by much needed rain. The rainy season peaks during June and July. During March to August the area have calm atmospheric conditions and low level inversions.

3.3 Air Pollution Monitoring Network

Monitoring of air quality in Cape Town commenced in 1958 with the introduction of the first monitoring stationing measuring SO_2 and smoke.[21]

Bailie et al pointed out the deficiencies in the Cape Town monitoring equipment and lack of information on trends in photochemical smog levels.[22] They called for an upgrading of monitoring of air pollution in the city and for appropriate steps to prevent its further increase. Progress was made in the mean time.

The City of Cape Town adopted an Integrated Metropolitan Environmental Policy (IMEP) and its implementation strategy on 31 October 2001. The City of Cape Town now, for the first time, has a bold and clear environmental policy. The IMEP addresses key environmental issues and sets out the City's commitment to improving Cape Town's environment. The IMEP has six priority strategies: air pollution, biodiversity, coastal zone, litter and illegal dumping, quality open spaces and noise pollution. During 2002 two additional strategies were initiated: environmental education and energy.

Currently the Cape Town ambient air quality monitoring network comprises 9 continuous monitoring stations operating across the 500km² city area (Figure 1). [21] Two mobile stations are located at Killarney and Plattekloof.

Figure 1 Location of air pollution monitoring sites in Cape Town, South Africa[21]

The two sites at the City Hall and the Drill Hall are close to each other and were grouped together as the City Centre site during this investigation. The City Centre site is located in an urban area next to busy roads (Figure 2). Tableview is located in a residential area, but still relatively close to a busy highway and an oil refinery (Figure 3). Bothasig is located in a residential area, but closer to the highway and oil refinery than Tableview (Figure 3). Goodwood is also located in a residential area, but further from the highways and closer to a light industrial area (Figure 4). Molteno is located in a residential area, quite far from busy roads (Figure 2). Khayelitsha is located the furthest away from

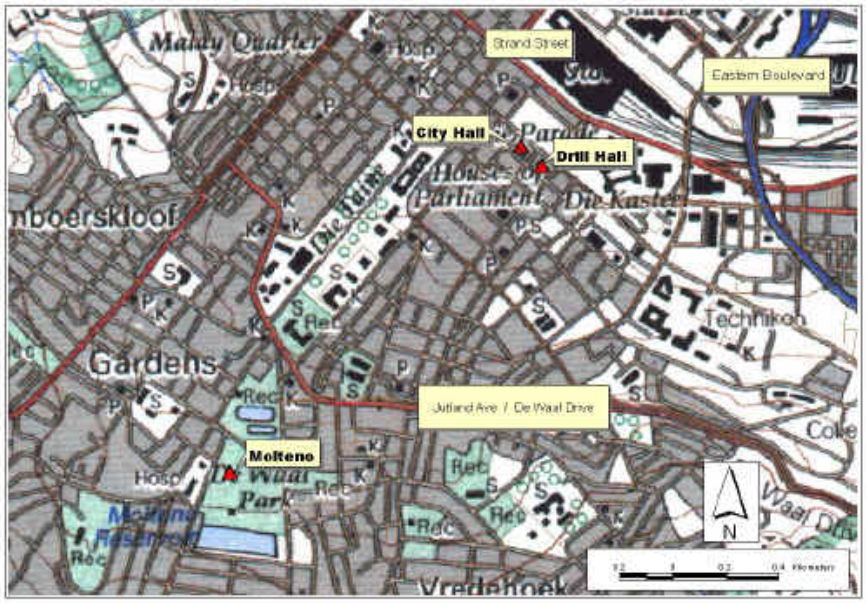


Figure 2 Location of air quality monitoring site in the City Centre and Molteno, City of Cape Town[21]

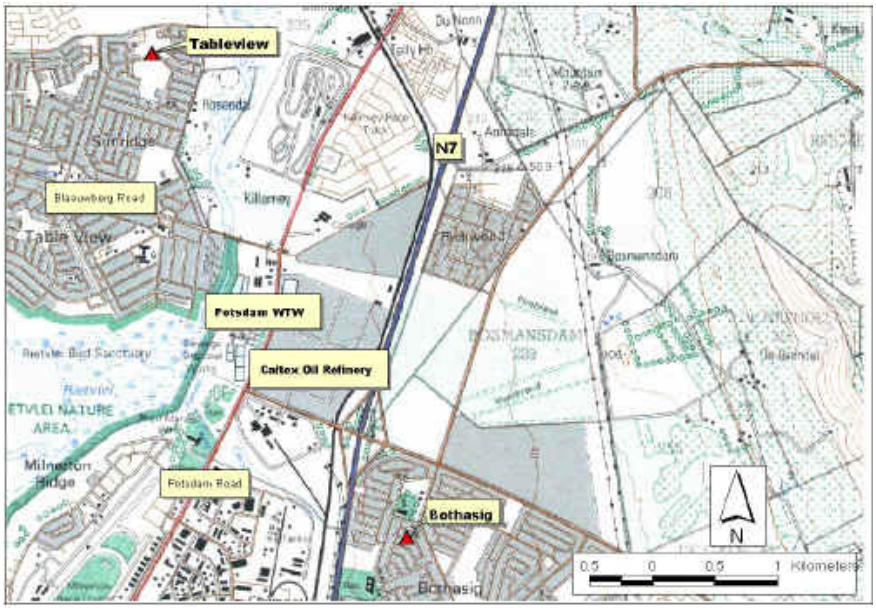


Figure 3 Location of air quality monitoring site in Tableview and Bothasig, City of Cape Town[21]

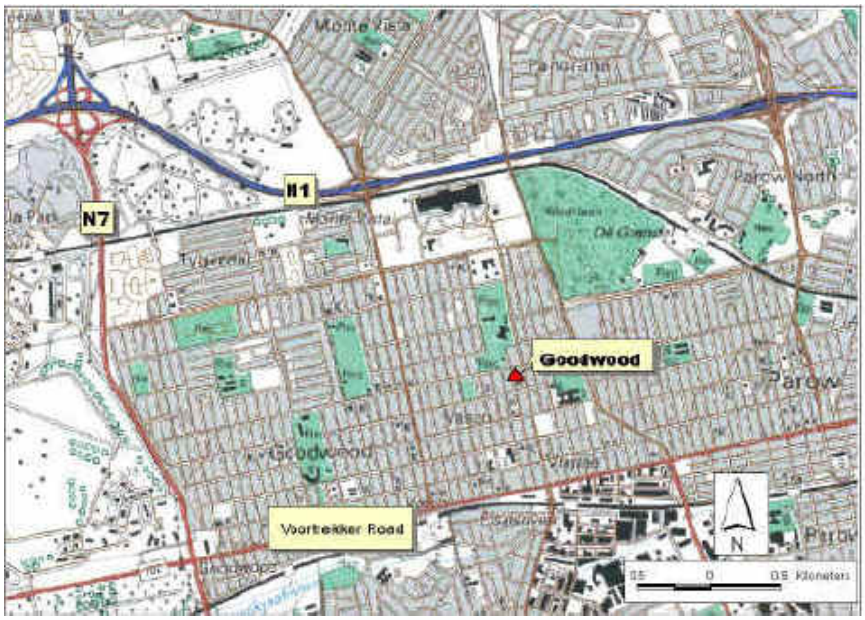


Figure 4 Location of air quality monitoring site in Goodwood, City of Cape Town[21]

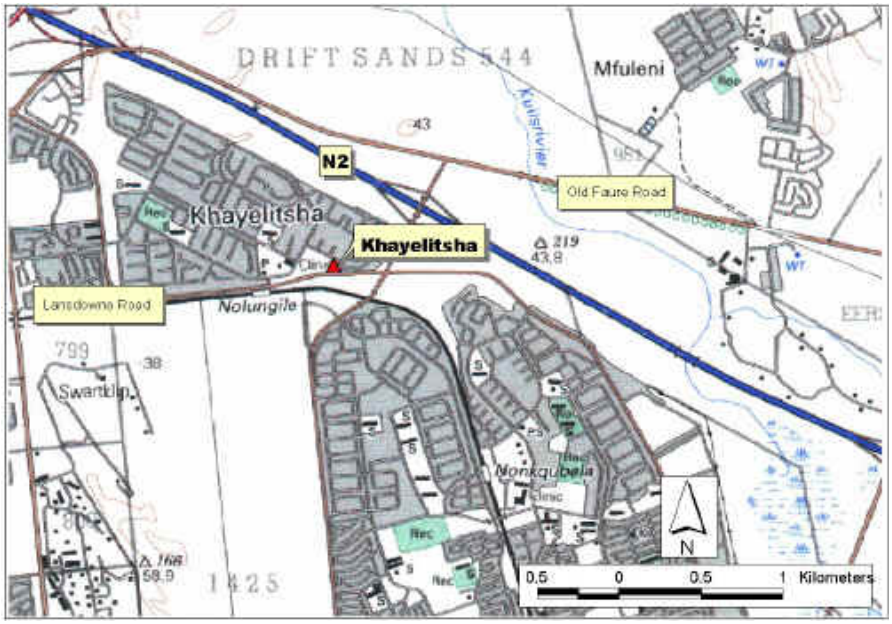


Figure 5 Location of air quality monitoring site in the Khayelitsha sub-district, City of Cape Town[21]

all the other sites (Figure 5) in a poor residential area, but closer to a highway and industries. The City Centre and Molteno sites are separated from the other sites as both are located in the city bowl, which is flanked on three sides by mountains. The location of City Centre and Molteno therefore provides favourable topographical conditions for the accumulation of pollutants over all seasons. All the sites are either downwind or upwind from the local sources as the wind direction changes during seasons (Section 3.2).

Thirty eight analysers, located at these 9 sites, continuously assess real-time concentrations of critical pollutants in the atmosphere using US-EPA equivalent methods in accordance with ISO 17025 guidelines. These instruments measure the concentration of ambient air pollutants in 20 second scans and values can be expressed in short term (10 min), one hour, twenty four hour, monthly or annual averages.

Minimum data completeness requirements for the calculation of period averages issued by the US-EPA in accordance with ISO 17025 guidelines for continuous monitoring are stipulated as follows: 24-h average - requires at least 20 1-h samples; monthly average requires at least 80% of data days of ≥ 20 h; quarterly average requires 80% data capture and no more than 10 consecutive incomplete days and annual average - requires 4 complete quarters.

Pollutants measured include PM_{10} (with TEOM 1400A), SO_2 (with fluorescence analysers), NO_x (with chemiluminescent analysers), O_3 (with UV analysers) and CO (with infrared analysers). The results are posted on the City's web site as soon as the data has been analysed statistically. The site can be visited at www.capetown.gov.za/airqual.

The ambient network is run by the city's Air Quality Monitoring Laboratory, located in Athlone. Here a central 'audit' monitoring station is used to certify transfer standards for calibration purposes. Both locally and internationally certified standards and a complete range of analysers are housed here. The City has two movable monitoring stations. One of these stations, operated by the city in agreement with the local refinery, is positioned downwind from the refinery to determine "hotspots". The stationing is determined in consultation with the local

community. This station is moved every 6 months to a year. A second movable monitor, owned by the council, is used to determine "hotspots" within the City of Cape Town as well as to assess future expansion and location of monitoring stations.

It is important to point out that this study was done independently from the City of Cape Town. The City of Cape Town is responsible for developing an air quality management plan which should be incorporated into its integrated development plan according to the National Environment Management: Air Quality Act (Act 39 of 2004).[23] However, human resources capacity to investigate fundamental issues pertaining to air pollution exposure assessment in detail is not available at local government level.

3.4 Air Pollution Sources

Various environmental challenges confront the area. These are primarily the consequence of the growing population of over 3.15 million people and their concurrent need for infrastructure, housing, employment and education.[21]

Rapid urbanisation and urban growth have resulted in a larger population in Cape Town and this in turn leads to a larger number of people making use of public and especially private transport to commute to work. Due to urban sprawl the distances between work and residences have also greatly increased. During peak periods the capacity of some road networks is exceeded and other road networks are reaching their capacity. One of the reasons for the lack of capacity in the road system is the lack of investment in both road and public transport systems. Currently there are 825 000 registered vehicles in all classes. Vehicle ownership has increased by 45% in the ten-year period 1990-2000. The number of cars has increased to approximately 570 000, doubling in the last 25 years. There are now approximately 178 cars per I 000 people in the City.

During Census 2001 it was established that 80%, 2% and 16% of the nearly 760 000 households in Cape Town use electricity, gas and paraffin for cooking.[24] The corresponding fuel use for heating is 75%, 1% and 19%, with 2% of households using wood. The majority of households use electricity for lighting (89%), followed by paraffin (9%) and candles (2%). However, it is noteworthy to highlight the

different fuel mix used in Khayelithsa. Paraffin, electricity and candles are used for lighting by 22%, 76% and 2% of the nearly 86 000 households in Khayelithsa, respectively.[25] Statistics on the energy use for cooking and heating are not available on a sub-district level. As nearly 100% of people living in Khayelithsa are Black, the energy use profiles for cooking and heating in Black households in the entire City of Cape Town will be quoted here.[25] Race is still presently very much linked to past access to resources, socio-economic status and educational status. The energy use profiles for cooking in Black households in the entire City of Cape Town are as follows: 45%, 4%, 49%, 1% and 1% for electricity, gas, paraffin, coal and animal dung, respectively.[24] The figures for heating are 33%, 1%, 57%, 4% and 4% respectively for electricity, gas, paraffin, wood and other unspecified fuels.[24] The households using wood, coal and animal dung for space heating and cooking contribute to PM_{10} emissions.

Outdoor air quality remains a key issue in Cape Town, largely because of the visible air pollution, particularly during March to August - known as the 'brown haze'. The brown haze is associated with calm atmospheric conditions and low level inversions. It occurs over most of the City and is typically most severe in the morning. Air pollutants (such as SO_2, NO_2, particulate matter and heavy metals) result from combustion processes in industry, services, agriculture, transport and homes.

A few years ago the National Association for Clean Air (NACA) commenced a pilot study executed by the Energy Research Institute (ERI) of the University of Cape Town.[26] The key objective of the study was the source apportionment of the brown haze. Conclusions were that small particles are the single largest cause of the visible brown haze; vehicular emissions are accountable for 65% of visible degradation, of which 49% is caused by diesel driven vehicle emissions; industry is a notable source, in particular low level emitting industries, the industrial contribution estimated to be 22%; wood burning and natural sources, such as wind-blown dust and sea salt, contribute very little towards the brown haze and assuming a laissez faire approach, air pollution is projected to escalate by 48% from 1997 to 2007.

3.5 Statistical Analyses

SAS version 8 was used in the statistical analyses. The data comprised of concentrations averaged at hourly intervals. Table 1 reflects the hourly data

availability during 1 August 1998 - 31 July 2003 for Bothasig, City Centre, Goodwood and Tableview. PM_{10} data availability at Khayelitsha was 26.4% (1998/1999), 73.4% (1999/2000), 56.7% (2000/2001), 16.6% (2001/2002) and 97.1% (2002/2003).

Table 1 Percentage of air quality data availability during 1 August 1998 - 31 July 2003

Station	SO_2	NO_x	PM_{10}	O_3	CO
Bothasig					
1998 – 1999	97.7	84.7	81.3	NR	NR
1999 – 2000	58.6	20.9	13.5	NR	NR
2000 – 2001	93.0	97.2	54.1	NR	NR
2001 – 2002	89.5	97.0	88.4	NR	NR
2002 – 2003	90.8	90.7	82.7	NR	NR
City Centre					
1998 – 1999	89.3	99.4	99.3	NR	10.0
1999 – 2000	97.1	96.8	99.7	NR	66.3
2000 – 2001	96.8	96.7[1]	99.4	NR	96.3
2001 – 2002	97.4	96.3[2]	99.5	NR	96.7
2002 – 2003	99.6	99.8[3]	100	NR	99.1
Goodwood					
1998 – 1999	69.5	70.8	96.2	44.0	10.3
1999 – 2000	82.2	92.7	99.3	98.6	86.1
2000 – 2001	98.9	98.9[4]	99.7	98.7	99.7
2001 – 2002	99.8	99.9[5]	98.0	99.9	99.9
2002 – 2003	98.0	97.7[6]	97.8	96.9	94.0
Tableview					
1998 – 1999	97.4	88.9	96.8	NR	NR
1999 – 2000	86.4	69.9[7]	88.4	NR	NR
2000 – 2001	93.3	74.5	93.6	NR	NR
2001 – 2002	98.3	98.0[8]	97.2	NR	NR
2002 – 2003	98.4	98.6[9]	99.1	NR	NR

Notes: NR: Not recorded, IDS: Incomplete data set, 1: NO_2: 95.9%, NO: 96.6%, 2: NO_2: 96.1%, NO: 96.0%, 3: NO: 99.7%, 4: NO: 99.0%, 5: NO: 99.6%, 6: NO: 98.0%, 7: NO_2: 67.9%, NO: 70.3%, 8: NO2: 95.3%, NO: 97.4%, 9: NO: 97.0%

The corresponding availability for O_3 measured at Molteno was 76.6%, 96.7%, 94.4%, 96.4% and 97.7%. Data from Killarney and Plattekloof were excluded in the analysis. These were mobile stations with responses below 50%. All 24-h averages are based on at least 20 1-h samples in accordance with the ISO 17025 guidelines. If this requirement was not met, a 24-h average was set as a missing value.

An exploratory data analysis was conducted in which the untransformed and log transformed data were tested for normality using the Kolmogorov-Smirnov test at the 95% confidence level. It was concluded that log transformations were ineffective in normalising the data. An alternative for normalising the data was attempted by the culling of extreme values. This is practical as the data remain in their original units. This procedure was also ineffective in normalising the data.

Hence a nonparametric Spearman's Rho correlation analysis was undertaken on the concentration levels of a particular pollutant measured at the same point in time at different stations. Statistical significance was assessed at 99% confidence level for the inter-site correlations due to the large sample sizes. The seasonal fluctuations of the inter-site correlation coefficients were investigated using seasons as a proxy for meteorological factors. Seasons were defined as winter, spring, summer and autumn for the following periods 1 June – 31 August, 1 September – 30 November, 1 December – 28(29) February and 1 March – 31 May, respectively.

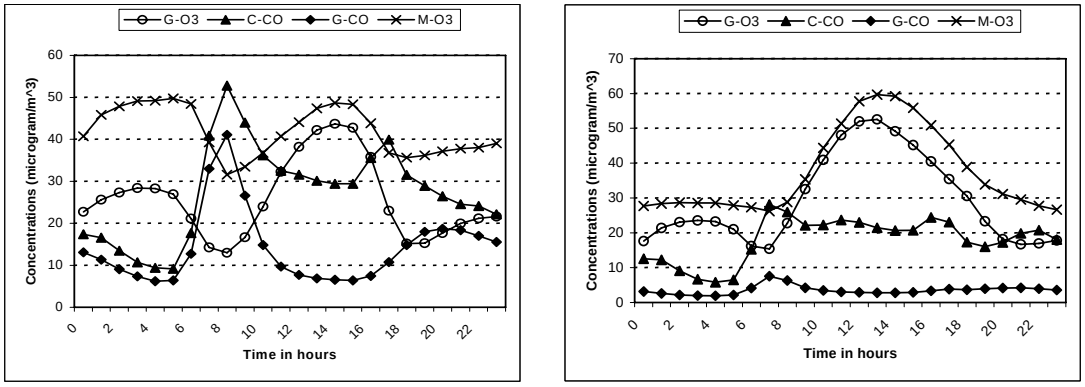
3.6 Results

3.6.1 General Seasonal and Diurnal Trends of Pollutant Concentrations

All the hourly pollutant concentrations were averaged over the five year period to derive Figure 6 and 7. These figures indicate the typical hourly variations of pollutant levels during winter and summer. The CO concentrations are reported as 1/100 of the original values in order to plot them on the same graph as those of O_3. In general the concentrations are highest in winter, decreasing in spring and summer and intensifying again in autumn, except for O_3 (diurnal trends not shown for spring and autumn). O_3 levels peak in spring and summer and were similar during winter and autumn.

Although the focus of this investigation is not source apportionment, it is still clear that the concentrations of NO, NO_2, SO_2, CO and PM_{10} closely follow the diurnal pattern of traffic with peak hour and off-peak hour differences, i.e. the higher levels are usually observed in the morning between 8:00 and 9:00 and the evening rush hours 16:00 to 19:00. However, the second peak for CO, SO_2 and PM_{10} vary between the sites during different seasons. NO_2 levels at City Centre appear to be constant between 8:00 and 18:00. Khayelitsha has a PM_{10} peak between 18:00 and 22:00 during winter, most probably due to the combustion of coal, animal dung and

paraffin for heating. The O_3 diurnal pattern is different from those of the other pollutants, it peaks during 13:00 to 14:00.



a) b)

Figure 6 Averaged 24-h O_3 and CO variations at City Centre (C), Goodwood (G) and Molteno (O) during a) winter and b) summer

Table 2 lists the descriptive statistics for valid 24-h averages of PM_{10}, SO_2, NO, NO_2, NO_x, CO and O_3 measured at Bothasig, City Centre, Goodwood, Khayelitsha and Tableview (24-h averages based on at least 20 1-hour values). PM_{10} concentrations appear to be higher at Khayelitsha compared to the other sites. SO_2 levels seem to be similar at all sites. NO, NO_2 and CO concentrations seem to be much higher at the City Centre site compared to the other sites. O_3 averages appear to be higher at Molteno compared to Goodwood.

3.6.2 Inter-site Correlations

Tables 3 to 5 list the inter-site correlation coefficients for pollutant concentrations between the sites. On average, the most homogeneously distributed pollutant is NO_2, followed by PM_{10} (including Khayelitsha data), PM_{10} (excluding Khayelitsha data), NO, CO, O_3 and finally SO_2 in the Cape Town air shed. A distinction is made between inter-site correlation coefficients for PM_{10} that include and exclude data from Khayelitsha due to poor data collection at Khayelitsha (Section 3.5 and Table 2). Inter-site correlation coefficients for NO_2, NO, SO_2, CO and O_3 vary from 0.456 to 0.832; 0.212 to 0.791; -0.100 to 0.662; 0.302 to 0.676 and 0.123 and 0.557, respectively. PM_{10} measured at Bothasig, City Centre, Goodwood and Tableview presents inter-site correlation coefficients from 0.261 to 0.859 (Table 3)

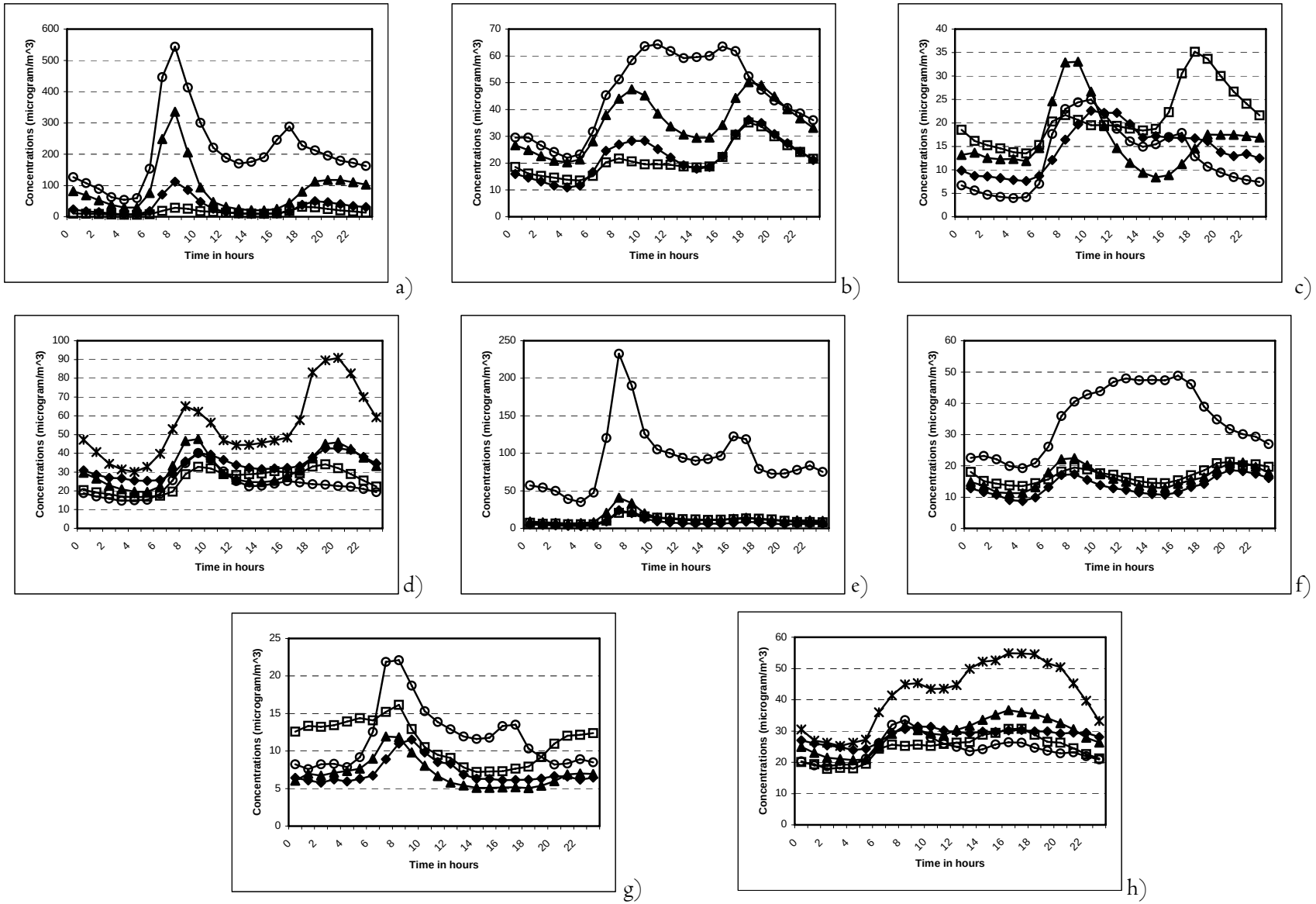


Figure 7 Averaged 24-h a) NO, b) NO_2, c) SO_2 and d) PM_{10} variations at Bothasig (◆), City Centre (○), Goodwood (▲), Khayelitsha (×) and Tableview (□) during winter and during summer e), f), g), h)

Table 2 Descriptive statistics for PM_{10}, SO_2, NO, NO_2, NO_x, CO and O_3 24-h average concentrations (in $\mu g.m^{-3}$) measured at Bothasig, City Centre, Goodwood, Khayelitsha and Tableview during 1 August 1998 – 31 July 2003

Pollutant	Site	N (valid obser-vations)	% valid obser-vations	Min	25th percent-tile	Median	Mean	75th percent-tile	Max	Std Dev
PM_{10}	Bothasig	1157	63.4	2.92	17.38	25.29	28.49	37.63	107.54	14.28
	City Centre	1811	99.2	3.79	15.08	20.92	23.29	28.75	95.58	11.49
	Goodwood	1782	97.6	3.29	19.58	26.69	29.48	35.42	110.42	13.90
	Khayelitsha	965	52.8	4.63	30.92	40.92	46.39	56.75	164.75	23.31
	Tableview	1720	94.2	4.67	16.60	22.35	25.19	30.94	108.13	12.69
SO_2	Bothasig	1559	85.4	0.17	4.79	8.04	10.35	13.00	87.63	8.80
	City Centre	1740	95.3	0.04	5.90	10.31	12.79	17.13	61.50	9.60
	Goodwood	1623	88.9	0.67	5.54	9.08	12.27	15.83	71.92	10.00
	Tableview	1718	94.1	0.46	4.96	8.75	12.47	16.17	94.42	11.34
NO	Bothasig	1415	77.5	1.17	4.88	8.63	17.61	18.13	203.08	24.96
	City Centre	1767	96.8	4.54	80.13	118.38	149.50	179.63	924.17	112.99
	Goodwood	1664	91.1	1.29	10.56	20.75	45.83	52.85	569.42	61.05
	Tableview	1547	84.7	0.38	4.75	8.71	12.79	15.88	125.88	13.10
NO_2	Bothasig	1416	77.5	1.38	10.13	16.27	18.04	23.10	104.96	10.77
	City Centre	1766	96.7	3.38	28.83	38.54	42.12	52.00	132.21	19.26
	Goodwood	1664	91.1	2.83	14.96	22.42	25.96	33.00	130.00	15.38
	Tableview	1539	84.3	0.29	11.04	18.83	20.82	27.71	78.67	12.74
CO	City Centre	1357	74.3	58.54	1528.08	2059.92	2254.33	2755.71	9273.71	1150.17
	Goodwood	1433	78.5	14.04	321.42	563.63	849.49	1080.25	5098.63	765.89
O_3	Goodwood	1613	88.3	0.04	20.00	27.54	28.48	35.71	86.63	11.76
	Molteno	1727	94.6	0.71	28.33	38.13	39.27	49.04	88.29	15.10

The PM_{10} correlation coefficients for the Bothasig, City Centre, Goodwood and Tableview sites with Khayelitsha are presented in Table 4. The inter-site correlation coefficients vary from 0.396 to 0.769. The majority of inter-site correlation coefficients for all the pollutants were positive, which means that if a particular air pollutant's levels are increasing at one site they are also increasing at another site. The inter-site correlation coefficient for SO_2 between Bothasig and Tableview was negative during spring, which means that if SO_2 levels were increasing at Bothasig they were decreasing at Tableview and vice versa. However, all SO_2 inter-site correlation coefficients between Bothasig and Tableview were not significant during all seasons.

The seasonal fluctuations of the inter-site correlation coefficients were investigated using seasons as a proxy for meteorological factors. The results suggest that the inter-site correlation coefficients of NO, CO and SO_2 display seasonal fluctuations: generally strongest in winter/autumn and weakest in summer (Tables 3 and 5). NO_2 appears to be homogenously distributed over all four seasons. This is also the case for the PM_{10} inter-site correlation coefficients between Bothasig-City Centre (BC), City Centre-Goodwood (CG). The inter-site correlation coefficients of PM_{10} between Bothasig-Goodwood (BG) and Bothasig-Tableview (BT) appear to be stronger during autumn and those between City Centre-Tableview (CT) and Goodwood-Tableview (GT) during spring. The inter-site correlation coefficients of PM_{10} between Khayelitsha and Bothasig, City Centre, Goodwood and Tableview seem to be independent of seasonal influences. O_3 presents the strongest inter-site correlation coefficients in summer and weakest during spring.

3.7 Discussion

As the air pollution monitoring sites in Cape Town are located in different types of areas it was anticipated that the inter-site correlation coefficients for the different pollutants would differ. However, it is still necessary to quantify the inter-site correlation coefficients instead of describing the situation qualitatively. This study therefore investigated the seasonal inter-site correlation between 24-h average outdoor PM_{10} mass, NO_2, NO, SO_2, O_3 and CO in Cape Town, South Africa. The aim of this study was not source apportionment, but to consider the suitability of information

Table 3 Sample sizes and p-values for NO_2, NO, SO_2 and PM_{10} inter-site correlation coefficients between Bothasig, City Centre, Goodwood and Tableview

Pollutant	Season	B-C			B-G			B-T			C-G			C-T			G-T		
		Corr	n	p	Corr	n	p	Corr	n	p	Corr	n	p	Corr	n	p	Corr	n	p
NO_2	Winter	0.504	355	<.0001	0.706	352	<.0001	0.786	289	<.0001	0.612	443	<.0001	0.613	388	<.0001	0.553	375	<.0001
	Spring	0.671	373	<.0001	0.733	306	<.0001	0.781	339	<.0001	0.591	357	<.0001	0.617	384	<.0001	0.606	305	<.0001
	Summer	0.456	338	<.0001	0.596	310	<.0001	0.832	281	<.0001	0.490	393	<.0001	0.597	335	<.0001	0.672	317	<.0001
	Autumn	0.607	310	<.0001	0.561	324	<.0001	0.703	312	<.0001	0.572	411	<.0001	0.681	385	<.0001	0.552	396	<.0001
NO	Winter	0.722	354	<.0001	0.791	352	<.0001	0.738	292	<.0001	0.656	442	<.0001	0.626	392	<.0001	0.487	380	<.0001
	Spring	0.613	372	<.0001	0.451	306	<.0001	0.363	339	<.0001	0.462	356	<.0001	0.350	383	<.0001	0.244	305	<.0001
	Summer	0.562	338	<.0001	0.360	310	<.0001	0.464	276	<.0001	0.392	393	<.0001	0.444	337	<.0001	0.212	317	<.0001
	Autumn	0.742	312	<.0001	0.713	323	<.0001	0.702	310	<.0001	0.628	414	<.0001	0.682	390	<.0001	0.532	398	<.0001
SO_2	Winter	0.148	373	0.004	0.395	393	<.0001	**0.048**	390	0.342	0.662	414	<.0001	0.388	411	<.0001	0.330	429	<.0001
	Spring	0.155	374	<0.010	0.206	302	0.000	**-0.100**	384	0.051	0.379	323	<.0001	0.387	434	<.0001	0.249	330	<.0001
	Summer	0.147	365	0.005	0.478	336	<.0001	**0.112**	356	0.034	0.294	385	<.0001	0.485	407	<.0001	0.170	373	0.001
	Autumn	0.360	380	<.0001	0.609	383	<.0001	**0.004**	357	0.938	0.536	424	<.0001	0.374	387	<.0001	0.287	398	<.0001
PM_{10}	Winter	0.564	290	<.0001	0.615	278	<.0001	0.272	277	<.0001	0.714	439	<.0001	0.564	443	<.0001	0.694	428	<.0001
	Spring	0.464	288	<.0001	0.490	272	<.0001	0.261	285	<.0001	0.678	436	<.0001	0.636	429	<.0001	0.750	415	<.0001
	Summer	0.398	281	<.0001	0.717	277	<.0001	0.414	276	<.0001	0.665	440	<.0001	0.609	430	<.0001	0.747	425	<.0001
	Autumn	0.601	290	<.0001	0.859	294	<.0001	0.487	275	<.0001	0.678	452	<.0001	0.544	405	<.0001	0.588	411	<.0001

Bold correlation coefficients are insignificant at 99% level

Table 4 Sample sizes and p-values for PM_{10} inter-site correlation coefficients between Khayalitsha and the other sites

Season	KH-B			KH-C			KH-G			KH-T		
	Corr	n	p	Corr	n	p	Corr	n	p	Corr	n	p
Winter	0.496	138	<.0001	0.529	270	<.0001	0.769	257	<.0001	0.676	267	<.0001
Spring	0.673	89	<.0001	0.396	225	<.0001	0.612	226	<.0001	0.678	205	<.0001
Summer	0.616	97	<.0001	0.406	217	<.0001	0.641	216	<.0001	0.756	206	<.0001
Autumn	0.548	116	<.0001	0.508	248	<.0001	0.655	249	<.0001	0.616	224	<.0001

Table 5 Sample sizes and p-values for O_3 and CO inter-site correlation coefficients between City Centre, Goodwood and Molteno.

Season	C-G (CO)			G-M (O_3)		
	Corr	n	p	Corr	n	p
Winter	0.676	404	<.0001	0.521	415	<.0001
Spring	0.517	297	<.0001	0.123	355	<.0001
Summer	0.302	268	<.0001	0.557	363	<.0001
Autumn	0.546	352	<.0001	0.237	440	<.0001

derived from the air pollution monitoring network in Cape Town in epidemiological studies.

The descriptive statistics are in accordance with the major air pollution sources present in each area. The majority of the inter-site correlation coefficients of all the pollutants under investigation are significantly different from zero at the 99% level, exceptions include those for SO_2 between Bothasig and Tableview. The majority of the coefficients for the pollutants are lower than 0.7. These differences in inter-site correlation coefficients may not only be because the sites are located in different types of areas with different local air pollution sources, but also due to topographical and meteorological factors (temperature, relative humidity, wind speed, wind direction, rainfall). These factors also influence the diurnal variation differences. The influence of meteorological factors on the inter-site correlation coefficients could not be investigated due to the lack of their measurements at these sites.

Seasonal inter-site correlation has exposure assessment implications. If outdoor inter-site correlations are found to be higher in winter it has little use as most people then spend their time indoors, whilst the opposite might be true in summer when correlations are low. The results highlight the importance of properly characterising relations among different outdoor pollution monitoring sites. Studies conducted in locations with strong inter-site correlation coefficients among outdoor pollutant concentrations should not assume that they necessarily persist across seasons.

In South Africa detailed air pollution epidemiological studies are competing for limited funds against common diseases of pressing current importance (such as HIV/AIDS, malaria, TB) and approximately 5% of the research budget is spent on health-related research, compared with 30% in developed nations.[27] This means that under the current research circumstances, there is still merit in using NO, NO_2, SO_2, O_3 and CO data from one site for another. This approach will make outdoor air pollution exposure assessment easier during hospital time-series studies when relating health outcomes of patients living and moving around in different areas of the city to outdoor air pollution. This is however not the case for SO_2 measured at Bothasig and Tableview. Furthermore, the composition of PM_{10} is anticipated to be heterogeneous at the different sites due to different local air pollution sources. The air quality data from a site should ideally be used in conjunction with knowledge of the local demographical factors when conducting human exposure assessments, as older and sicker people spend more time indoors and/or outdoors in the one area.

Using outdoor air pollution exclusively in epidemiological studies are still prone to information bias as people move around during the day from one area to the next, with a small proportion of their time spent outdoors. Great variability occurs in the different micro-environments, in particular indoors, where pollutants may be far in excess of national guidelines, especially in South Africa and other developing countries where people are still using polluting fuels for household purposes, living in poorly ventilated informal dwellings in close proximity to the pollution sources. The variability is particularly important in townships and informal settlements.

Limitations of this investigation include poor data collection of PM_{10} at Khayelithsa; poor data collection of NO, NO_2, SO_2, O_3 and CO at the other sites during some periods of the investigation; lack of meteorological data collection (temperature, relative humidity, wind speed, wind direction, rainfall) at each monitoring site; lack of emission source data and dispersion modelling.

The vast majority of studies published in reputable scientific journals on inter-site correlations are from developed nations. It is not feasible to compare the results from

this study with those derived in developed nations due to the mix of air pollution sources in South Africa. Pollution sources include traffic, industry and households using polluting fuels for lighting, cooking and heating. The only other study conducted in developing countries was identified as the Central European Study on Air Pollution and Respiratory Health (CESAR).[28] CESAR was conducted in Bulgaria, Czech Republic, Hungary, Poland, Romania and Slovak Republic during November 1995 and October 1996. The study found that the median of the correlation coefficients for PM_{10} between study areas within the same country was 0.76 and that between study areas from different countries was 0.54. The median of the correlation coefficients for PM_{10} for Cape Town is 0.614 (lumping correlation coefficients of all seasons in Tables 3 and 4 together). It thus appears that air pollution is much more heterogeneously distributed on a small scale in Cape Town than between different cities, as was the case for the CESAR study.

Given the lack of resources for outdoor air pollution measurement and the dearth of air pollution epidemiological studies in South Africa, local cities should thus attempt to optimise and update their air quality monitoring networks in such a manner as to serve both compliance monitoring and epidemiological exposure assessment. Inter-site correlation analysis is only one of the evaluation criteria in the design of an air quality monitoring network. The local authorities are encouraged to consult the latest scientific literature with the assistance of research and academic institutions when updating or designing their air quality monitoring networks.[29,30]

Chang and Tseng discussed the optimal evaluation of expansion alternatives for existing air quality monitoring networks in a growing metropolitan region, which poses many uncertainties such as the changing population density and the changing emission sources in the urban environment.[29] They discussed the principles for siting air quality monitoring stations through a multi-objective analysis, which may include the following: monitoring stations should be located in areas of high population density; where pollution concentrations are expected to be highest; where the highest frequency of violation can be detected; where significant growth is expected to occur and near major downwind sources. The optimisation modelling addressed by Chang and Tseng

considered three objectives: the maximisation of protection capability of the highest population density; detection capability of the highest pollution concentrations and detection capability of the highest frequency of violation of health guidelines/standards, along with cost, effectiveness and efficiency factors.[29]

Kanaroglou et al discussed the establishment of an air pollution monitoring network for intra-urban population exposure assessment, which is quite relevant in epidemiological studies.[30] The impetus for their study was to address the limitation of locating monitors in an ad hoc fashion, which favours the placement of monitors in source "hot spots" or in areas deemed subjectively to be of interest. Their study addressed the development of a formal method of optimally locating a dense network of air pollution monitoring stations and the subsequent development of an exposure assessment model based on these monitoring data and related land use, population and biophysical information.

Stemming from the preliminary results of this investigation along with its associated limitations, the following thoughts are suggested to the City of Cape Town:

(1) not to reduce the number of sites in the city;
(2) add NO_x, SO_2, CO and O_3 monitors to the Khayelitsha site due to the proximity to a busy highway, the dense population of the area and relatively high use of polluting fuels for cooking and space heating;
(3) increase data response at the Khayelitsha site;
(4) collect meteorological data (temperature, relative humidity, wind speed, wind direction, rainfall) at each monitoring site;
(5) increase the number of O_3 monitors in background areas and
(6) place O_3 monitors downwind from precursor sources.

Although O_3 is not a primary pollutant, it is at the moment unclear whether it is generated in the Khayelitsha area. Furthermore, it is suggested not to reduce the number of measurements per day as hourly measurements are needed to indicate peaks and for acute health effects assessment. These suggested recommendations aim at increasing the accuracy and reliability of using the air quality network data in epidemiological studies. Future studies should investigate the current air pollution trends against health

guidelines and establish the surrogate or confounder relationship between air pollutants in a time-series analysis (that is inter-pollutant correlations at each monitoring site).

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