Assessment of ambient air pollution in the Waterberg Priority Area 2012-2015

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Abstract
The Waterberg Priority Area ambient air quality monitoring network was established in 2012 to monitor the ambient air quality in the Waterberg Air Quality Priority Area. Three monitoring stations were established in Lephalale, Thabazimbi and Mokopane. The monitoring stations measure the concentrations of PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, O_3, BTEX and meteorological parameters. Hourly data for a 31 month period (October 2012-April 2015) was obtained from the South African Air Quality Information System (SAAQIS) and analysed to assess patterns in atmospheric concentrations, including seasonal and diurnal patterns of the ambient concentrations and to assess the impacts that such reported pollution concentration may have. Local source regions for SO_2, PM_{10}, $PM_{2.5}$ and O_3 were identified and trends in the recorded concentrations are discussed.

Keywords
Waterberg Priority Area, Air Pollution, PM_{10}, $PM_{2.5}$, SO_2, O_3

Introduction
The Waterberg coal fields extend across the border between South Africa and Botswana. These coal fields are estimated to hold a reserve of approximately 6Gt (6×10^9 Mg). This coal reserve is regarded as the last remaining large coal resource in the country (Hartnady 2010). As such, in the National Development Plan (National Planning Commission 2010), the Waterberg coal fields have been earmarked for further industrial development, related to exploitation of the coal resource for *inter-alia* power generation.

Due to the expected development within the Waterberg Area and the existing mining and metallurgical activities in the western arm of the bushveld igneous complex (Venter et al. 2012), there is concern regarding the future and current air quality in these regions. As a result the Waterberg District Municipality (Limpopo Province) and the Bojanala Platinum District Municipality (North West Province) were declared as the Waterberg Priority Area in 2012 since the Minister of Environmental Affairs expected the levels of pollutants in the Waterberg District to exceed the National Ambient Air Quality Standards (NAAQS) (DEA 2009) in the near future and that a significant trans-boundary situation exists between the Waterberg District Municipality in Limpopo Province and the Bojanala Platinum District Municipality in the North-West Province (Department of Environmental Affairs 2012) (Figure 1). A draft air quality management plan has been developed which details the major pollutant sources and receptors (Department of Environmental Affairs 2014).

A number of studies in ambient air pollution have been conducted in the past. A passive sampling network was operated over the northern parts of South Africa between 2005 and 2007 (Josipovic et al. 2010). This study reported occasional high concentrations of SO_2 at Thabazimbi and Mokopane, The source of the SO_2 at Thabazimbi was attributed to the Thabazimbi iron ore mine and smelter, the Matimba power station and the Grootgeluk coal mine in Lephalale. The elevated levels of SO_2 at Mokopane were attributed to the Mokopane platinum mine and the Matimba power station.

A long term air quality measurement campaign was conducted in the Bojanala District of the Waterberg Priority area (Venter et al. 2012). This campaign took place at Marikana from February 2008 to May 2010. In the Venter et al. 2012 study it was reported that the concentrations of NO_x , SO_2 and CO were within the NAAQS but there were significant exceedances of the standards for ozone and particulate matter. It was also within this region that Hirsikko et al. 2012 reported a high frequency of new particle formation events and an average particle number concentration of $10^4/cm^3$. They further postulated that SO_2 was the likely feed material for the new particle formation.

Due to the known and expected future exceedances of the NAAQS in the Waterberg Priority Area, it was necessary to establish an ambient air quality monitoring network, to monitor the ambient concentrations of criteria pollutants in the area. This study examines the first two and a half years of the monitoring results for the three ambient air quality stations in the Waterberg Priority area. This study intends to characterise the spatial and temporal patterns in criteria pollutant concentrations, and to identify potential pollutant sources.

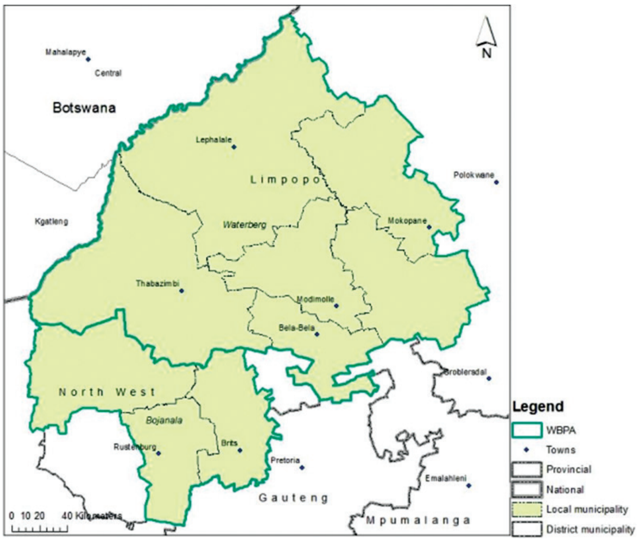

Figure 1: *Waterberg Priority Area (Department of Environmental Affairs 2014)*

Methods

Three ambient air quality monitoring stations were established in the Waterberg Priority Area in October 2012. The stations are located at Thabazimbi, Lephalale and Mokopane (Figure 1).

Each of the stations is fully equipped to monitor the following parameters at a temporal resolution of 1 minute:

- Sulphur Dioxide (SO_2)
- Particulate matter of aerodynamic diameter >10 um (PM_{10})
- Particulate matter of aerodynamic diameter > 2.5um ($PM_{2.5}$)
- Oxides of Nitrogen ($NO_x = NO + NO_2$)
- Ozone (O_3)
- Carbon Monoxide (CO)
- VOCs (Benzene, Toluene, Ethyl benzene, Xylene)
- Meteorological Parameters
  - Wind Speed
  - Wind direction
  - Pressure
  - Temperature
  - Relative Humidity
  - Solar Radiation
  - Rainfall

Data from the monitoring stations reports in real time to a server located at the South African Weather Service. On a monthly basis the data was assessed and validated to remove spikes and calibration data and to adjust drifts in the data.

Daily checks were performed on the stations by remotely accessing the data logging system, if problems with the station were identified non-routine maintenance was carried out. On a bi-weekly basis routine site visits were conducted to ensure that the instrumentation was functioning and to perform a zero and span (80% of instrument maximum) check using NMISA certified calibration gases to ensure that the drifts and deviations of the instrument were within the specified ranges, if the instrumentation was found not to respond within the data quality criteria the data was flagged and corrected or removed from the dataset. On a quarterly basis multipoint calibration verifications (zero, 80% of instrument range and three intermediate points) were conducted utilizing NMISA certified reference gases. A full calibration of all the instruments was conducted on an annual basis by a South African National Accreditation System (SANAS) accredited calibration laboratory.

Table 1*: Station location and monitoring purpose*

Latitude	Longitude	Data Recovery October 2012-April 2015	Monitoring purpose
Lephalale			
S23.681	E27.722	85.0%	Impact on human health in a low income residential community impacted by domestic combustion, vehicular emissions, biomass burning, the Grootgeluk coal mine and the Matimba power station. Future impacts from Medupi coal fired power station are expected.
Thabazimbi			
S24.591	E27.391	80.8%	Located in a low income residential community, domestic combustion, biomass burning, vehicular and road emissions and iron ore mining activity.
Mokopane			
S24.155	S24.155	85.9%	Human health impacts in a low income residential area, impacted by domestic combustion, vehicular and road emissions and small scale industry as well as biomass burning.

For this study hourly averaged data for SO_2, PM_{10}, $PM_{2.5}$ and O_3 were extracted from the South African Air Quality Information System (SAAQIS) and revalidated to remove negative concentrations and data spikes that were not removed during the original validation. A data completeness rule of 80% was used for data averaging to the hourly average that was utilised and any subsequent averaging. The data was assessed using the Open Air Package in R (Uria-Tellaetxe and Carslaw 2014; Carslaw 2014).

Results and Discussion

The monitoring data from the three monitoring stations were assessed to characterise the atmospheric dynamics of the site, including the diurnal and seasonal cycles and the potential pollutant sources. The results are presented for the four criteria pollutants of greatest concern in South Africa, namely sulphur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3) (Thompson et al. 2011; Lourens et al. 2011; Venter et al. 2012).

Sulphur Dioxide

The concentration of SO_2 at the monitoring stations is presented in Table 2. The ambient SO_2 concentrations over the period are low with mean values in the range of 1-1.5ppb. The 90 percentile at all the stations does not exceed 5ppb. In comparison the annual National standard is 19ppb. Compliance with the national standards is presented in the National State of the Air Report.

***Table 2**: SO_2 measurement summary*

	Lephalale	Makopane	Thabazimbi
N	21280	20053	21250
% recovery	95.1%	86.8%	95.0%
Mean	2.19	1.68	2.14
Median	0.82	0.97	1.11
10 percentile	0.278	0.45	0.38
25 percentile	0.48	0.64	0.63
75 percentile	1.7	1.82	2.25
90 percentile	3.30	3.56	4.52

The relation between the concentration of SO_2 and wind speed and direction is presented in Figure 3. The Lephalale plot shows a hotspot of SO_2 associated with low to medium speed winds from the westerly and north westerly sectors. This corresponds to the location of the Matimba power station and the Grootgeluk coal mine which are likely the source of the SO_2.

The monthly trend of the SO_2 concentrations at the monitoring stations is presented in Figure 4. Of the three stations only Mokopane showed a statistically significant trend in the SO_2 concentrations. At Mokopane the SO_2 concentration decreased at a rate of 0.3ppb per year (P> 0.001). The decrease at the Mokopane station appears to have occurred from late 2013 or early 2014. The SO_2 concentrations at Lephalale and Thabazimbi did not show any statistically significant trends.

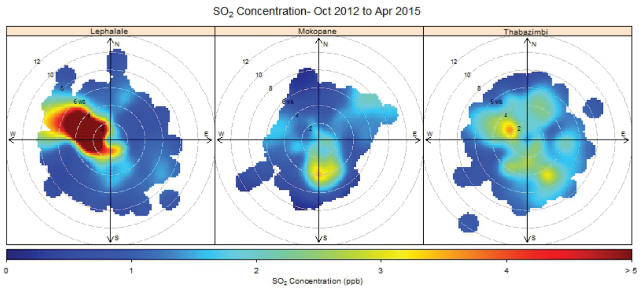

***Figure 2:** Polar Plot of the SO_2 concentration at the Waterberg monitoring stations*

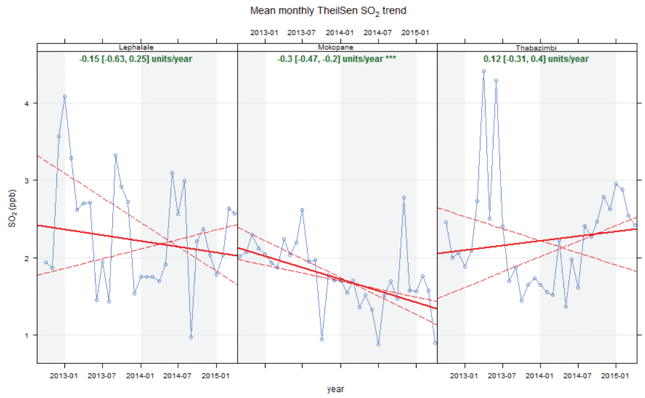

***Figure 3:** Monthly Mean Deseasonalised SO_2 Trend, for the period Oct 2012-April 2015. The solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

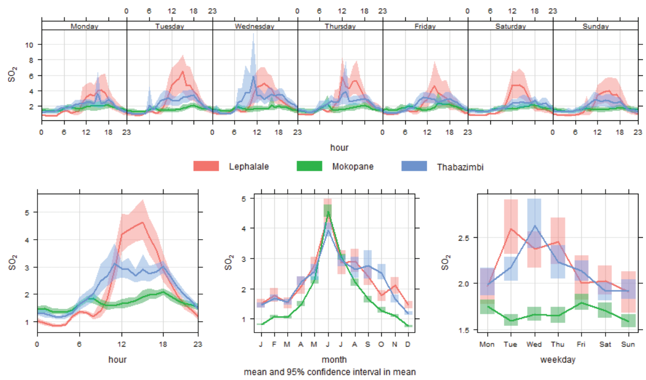

***Figure 4:** SO_2 Time variation plot for the period October 2012 to April 2015*

The time variation in the hourly SO_2 concentrations is presented in Figure 5. It is shown that there is a strong diurnal profile in Lephalale and Thabazimbi, where there is a peak in the SO_2 concentrations during the day; this is typical of sites influenced by pollution from industrial stack emissions, which is brought to the surface during periods of high convection (Venter et al. 2012; Zhou et al. 2012) For the Lephalale site, the mid-day peak occurs throughout the week, which would correspond to a high level source that is emitting continuously. For the Thabazimbi site the largest SO_2 peak occurs on the Wednesday morning and may indicate a specific process that occurs on a weekly basis at one of the facilities in the area. All three sites show a strong seasonal profile in the SO_2 concentrations, where the highest values are recorded during the winter months.

PM_{10}

The average PM_{10} concentration at the three Waterberg stations for the period October 2012- April 2015 was 52μg/m^3 for Thabazimbi, 40.6μg/m^3 for Mokopane and 26μg/m^3 for Lephalale (Table 3). The 90th percentile for the Thabazimbi and Mokopane stations is higher than 100μg/m^3. The average PM_{10} concentration over the 2.5 year measurement period (October 2012 to April 2015) is greater than the annual PM_{10} standard (40μg/m^3).

***Table 3**: PM_{10} measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measure-ments	20739	19608	15027
% recovery	92.68%	84.8%	67.2%
Mean	26.04	40.64	52.31
Median	19.11	26.93	30.93
10 percentile	5.94	8.60	8.01
25 percentile	11.03	14.88	16.52
75 percentile	32.95	50.64	59.46
90 percentile	53.37	87.48	115.62

When the relation between the PM_{10} concentrations and the wind speed and wind direction are considered (Figure 7) the periods of highest PM_{10} concentration correspond to periods of high wind speed, typically greater than 6m/s. These are periods when the high PM_{10} concentrations are likely to be attributable to the generation of windblown dust. Marticorena & Bergametti (1995) modelled the generation of aeolian dust based on threshold friction velocities, or the point at which the wind speed is high enough to entrain soil particles from the surface. This approach has successfully been used to model dust generation in other regions (Kocha et al. 2011; Schmechtig et al. 2011).

The trend in the PM_{10} concentrations seems to be decreasing in all three sites (Figure 8) where there is a decrease in the PM_{10} concentration of between 4.5 and 6.5 μg/m^3/year. This, however, is only statistically significant at the Lephalale site ($p<0.01$).

The seasonal, diurnal and day of week time variation plots for PM_{10} are presented in Figure 9. The PM_{10} concentrations show a distinct diurnal pattern at all stations, with peaks occurring in the morning (06:00) and in the evening (18:00). The evening peak is greater than the morning peak. This pattern holds for all the stations and is likely linked to domestic combustion or traffic sources. The seasonal cycle shows a strong peak during the winter months from April to October, which corresponds to the periods where there is increased atmospheric stability over the interior of the country (Preston-Whyte et al. 1976; Scott & Diab 2000; Lourens et al. 2011) increased biomass burning (Korontzi 2005) and domestic combustion for space heating (Wernecke et al. 2015) .

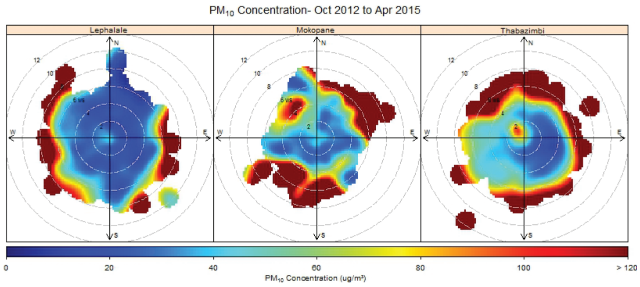

***Figure 5:** Polar Plot of the PM_{10} concentration at the Waterberg monitoring stations*

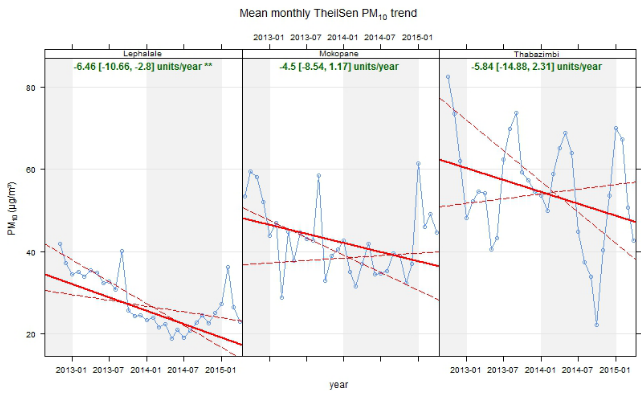

***Figure 6:** Monthly Mean Deseasonalised PM_{10} Trend for the period Oct 2012-April 2015 the solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

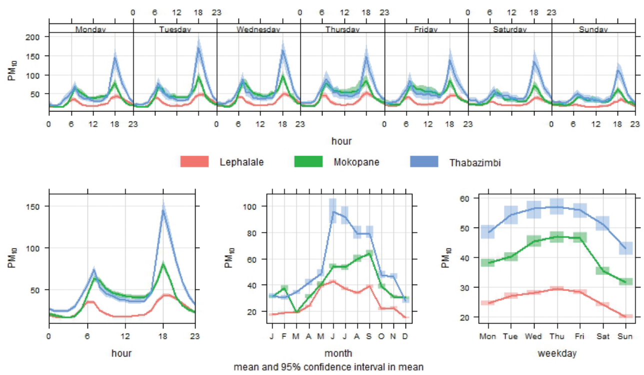

***Figure 7:** PM_{10} Time variation plot for the period October 2012 to April 2015*

A strong diurnal pattern in the PM_{10} concentrations was observed occurring in the early morning and in the evening. This is strongest at the Thabazimbi and Mokopane stations where the evening peak PM_{10} concentration is considerably greater than the morning peak. To further allude to the domestic combustion component of the PM_{10} source a day of week pattern was also observed at all the stations, with higher average PM_{10} concentrations being observed between Monday and Friday, followed by decreases on Saturday and Sunday, especially in the morning peak over the weekend. This could indicate that the behaviour patterns of the people in these areas changes over the weekends and there is less vehicular traffic and the timing of activities may be more staggered than during the work week. For all the sites there is a strong contrast in the temporal profiles of PM_{10} and SO_2, indicating that these pollutants are generated at different sources.

$PM_{2.5}$

The mean $PM_{2.5}$ concentration at the three Waterberg monitoring stations ranges from 12.3µg/m³ for Lephalale to 20 µg/m³ and 20.3µg/m³ for Thabazimbi and Makopane respectively (Table 4). Thabazimbi and Mokopane showed the highest $PM_{2.5}$ values. For the 2.5 year monitoring period considered here the average $PM_{2.5}$ concentration at all the sites is below the national standard for the period of the measurement (25µg/m³), however for Mokopane and Thabazimbi it exceeds the stricter standard (20µg/m³) that came into effect at the beginning of 2016.

***Table 4**: $PM_{2.5}$ measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measurements	20743	19633	14687
% recovery	92.70%	85.0%	65.6%
Mean	12.34	20.29	19.98
Median	9.49	12.88	10.74
10 percentile	2.50	3.90	1.92
25 percentile	4.93	7.29	5.35
75 percentile	16.54	22.86	20.85
90 percentile	25.79	43.95	43.56

The polar plot figures, which show the relationship between the wind speed, direction and the $PM_{2.5}$ concentration show that similarly to PM_{10} the periods of highest $PM_{2.5}$ concentration are associated with periods of high wind speed (> 6m/s). At the Mokopane station there is a hotspot of high $PM_{2.5}$ concentration associated with moderate wind speeds (4-6m/s) from the south-west and north-west. This wind direction corresponds to the location of the low income residential areas and associated agricultural areas of Sekgakgapeng and Masodi, respectively.

The trend analysis for $PM_{2.5}$ (Figure 12) shows no significant trends in the $PM_{2.5}$ concentrations at any of the sites. This is in contrast to the PM_{10} concentrations which show a mean decrease at all sites and which is statistically significant at the Lephalale site. This could indicate that the sources of PM_{10} and $PM_{2.5}$ at Waterberg sites are different and therefore different management interventions are needed to address them.

The time variation plots for $PM_{2.5}$ are similar to those of PM_{10}; there is a clear seasonal pattern, with the highest $PM_{2.5}$ concentrations recorded during the winter period. A strong diurnal pattern exists with morning and evening peaks and there is a weekly cycle where an increase in the $PM_{2.5}$ concentrations is observed between Monday and Friday followed by a large decrease over the weekend, with an especially large reduction in the morning peak over the weekends.

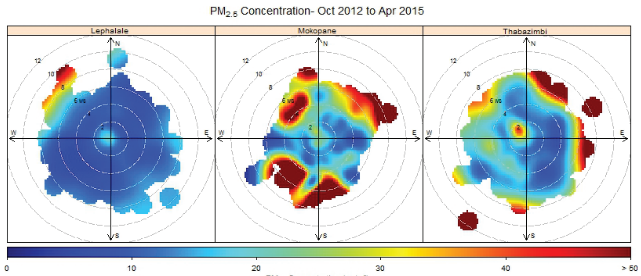

***Figure 8:** Polar Plot of the $PM_{2.5}$ concentration at the Waterberg monitoring stations*

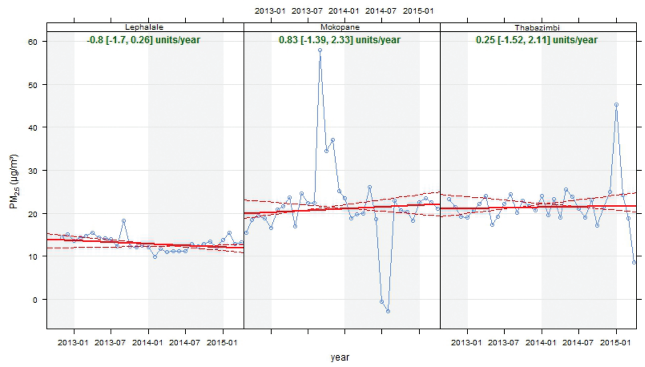

***Figure 9:** Monthly Mean Deseasonalised $PM_{2.5}$ Trend for the period Oct 2012-April 2015. The solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

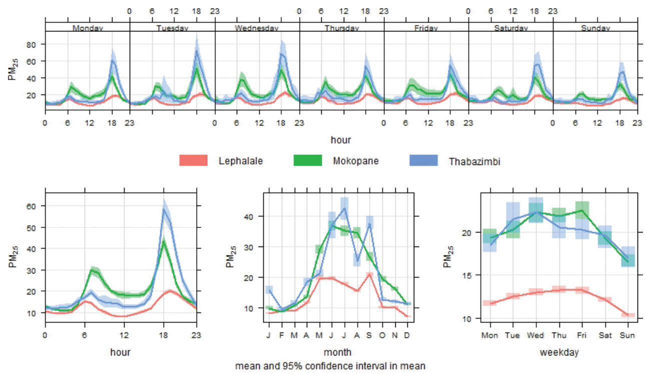

***Figure 10:** $PM_{2.5}$ Time variation plot for the period October 2012 to April 2015*

Ozone

The mean ozone concentrations recorded over the period ranges between 24.2 ppb (Lephalale) to 28.2 ppb (Mokopane and Thabazimbi) (Table 5).

The periods of high ozone concentration are typically associated with periods of relatively strong winds, specifically from the north westerly sectors for Lephalale and Mokopane. In a study of ambient air quality in the Vaal Triangle high ozone concentrations were observed under similar conditions during the approach of a cold front over the South African interior (Feig et al. 2014). For all the sites during periods of very low wind (as is typical of night time conditions) the ozone concentrations are very low The periods of high ozone concentration at the Thabazimbi site are associated with winds from the north east and easterly directions.

***Table 5**: Ozone measurement summary*

	Lephalale	Makopane	Thabazimbi
Number of measure-ments	21061	20708	20255
% recovery	94.12%	89.6%	90.5%
Mean	24.27	28.20	28.21
Median	23.52	27.23	27.88
10 percentile	4.81	11.88	7.44
25 percentile	12.65	18.62	16.18
75 percentile	34.07	36.65	38.52
90 percentile	43.57	45.41	48.78

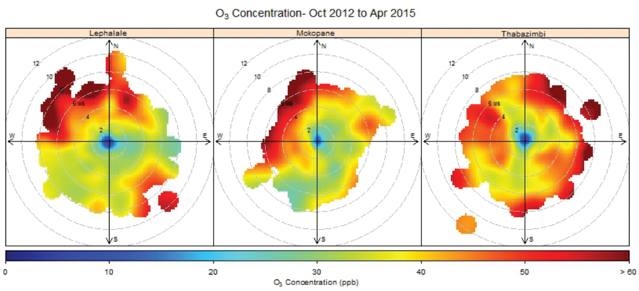

***Figure 11:** Polar Plot of the O_3 concentration at the Waterberg monitoring stations*

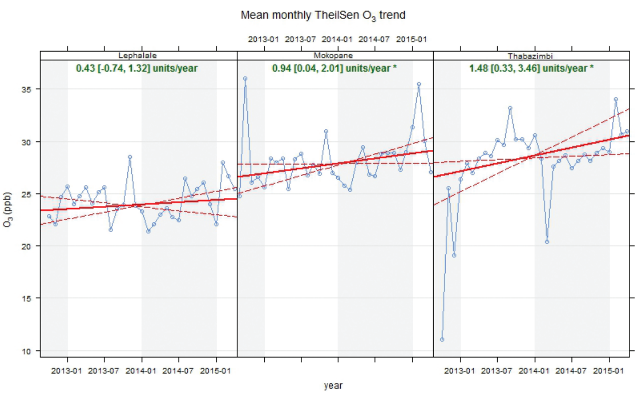

***Figure 12:** Monthly Mean Deseasonalised O_3 Trend for the period Oct 2012-April 2015 the solid trend line represents the mean slope of the trend, while the dashed trend lines represent the 95% confidence interval of the slope*

The trend analysis (Figure 16) indicates that over the monitoring time period there is a statistically significant increase in the monthly ozone concentration ($P<0.05$) at the Mokopane and Thabazimbi stations. This increase is 0.94ppb/year and 1.48ppb/year for the Mokopane and Thabazimbi station respectively.

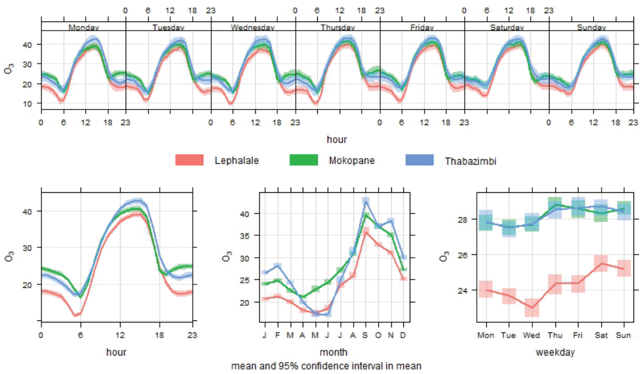

***Figure 13:** O_3 Time variation plot for the period October 2012 to April 2015*

There is strong seasonal trend in the ozone concentrations observed at all the stations, with peaks in the ozone concentrations being observed in the September/October periods, which has been frequently observed and reported (Thompson et al. 2003; Thompson et al. 2011; Thompson et al. 2014; Scholes & Scholes 1998; Zunckel et al. 2004)

Conclusion

This study aims to provide an assessment of the ambient air quality monitoring that has occurred in the Waterberg priority area between October 2012 and April 2015. Data recovery from the three monitoring stations has been good with a valid data capture percentage of greater than 80 % for all the stations.

The recorded SO_2 concentrations are generally low. At the Lephalale station there is a strong source of SO_2 located to the west and north-west of the station that is likely a high level industrial source. The Thabazimbi station shows a distinct peak in SO_2 concentrations on Wednesday mornings.

The PM_{10} and $PM_{2.5}$ concentrations show a strong seasonal pattern with the highest values occurring during the winter months. There has been a statistically significant decrease in the PM_{10} concentrations at Lephalale over the monitoring time period, which is not seen in the $PM_{2.5}$ concentrations. The periods of high PM_{10} concentration are associated with high wind speeds. In addition to the temporal patterns in the PM_{10} and $PM_{2.5}$ concentrations are indicative of local domestic combustion or traffic sources in that there are strong peaks in the early morning and evening, and a strong weekend effect is seen especially with regards to a reduction in the morning peak during on Saturdays and Sundays.

The concentrations of ozone are highest in the spring period, similarly to what has been found in the Vaal Triangle high ozone events may occur during the advance of a frontal system across the country (Feig et al. 2014).

The Waterberg priority area was declared in anticipation of the development of air quality problems associated with the development of the Waterberg coal fields. The initial analysis indicates that the area may already be facing air quality problems, prior to the initiation of the major planned developments in the area. The continued operation of these ambient air quality monitoring stations will be vital in assessing the pollutant concentrations in the area and monitoring how the pollutant levels change with the implementation of the planned developments. This paper also demonstrates the value of utilizing advanced data analysis methods in order to identify potential pollution sources and to track trends in the ambient air quality over the region.

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