AIR QUALITY IMPACTS AND HEALTH EFFECTS DUE TO LARGE STATIONARY SOURCE EMISSIONS IN AND AROUND SOUTH AFRICA'S MPUMALANGA HIGHVELD PRIORITY AREA (HPA)

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SUMMARY

I have been commissioned by the Centre for Environmental Rights to conduct an air-pollution dispersion model and health risk assessment for 14 industrial facilities (12 Eskom coal-fired power stations, the Sasol Synfuels chemical facility and the NatRef refinery), located in and around the Mpumalanga Highveld Priority Area (HPA) of South Africa.

Important results from the modeling and health risk assessment include:

1. Ambient $PM_{2.5}$ pollution from the 14 facilities **caused between 305 and 650 early deaths** in the area in 2016. The three worst offenders were Lethabo power station (57 to 122 early deaths), Kendal power station (46 to 99 early deaths), and Kriel power station (34 to 76 early deaths). If the 14 facilities were required to comply with the minimum emissions standards that will go into effect in 2020 (2020 MES), this would reduce early deaths by 60%, **preventing between 182 and 388 early deaths** in and around the HPA every year. (Tables 3 and 4)
2. Cumulative emissions from the 14 facilities created acute exposures in 2016 that **exceeded the World Health Organization's guidelines for daily or hourly averages for all pollutants**. The highest 24-hour average exposure of $PM_{2.5}$ was 45 $\mu g/m^3$, nearly twice the WHO guideline of 25 $\mu g/m^3$. (Table 2) These conditions occurred around Kendal, Kriel, and Duvha power stations. (Figure 5) The highest 24-hour average exposure of SO_2 was 241.4 $\mu g/m^3$, over 1200% of the World Health Organization standard of 20 $\mu g/m^3$. The highest NO_2 one-hour average was 2020 $\mu g/m^3$, over 1000% of the one-hour average standard of 200 $\mu g/m^3$. Implementing the 2020 MES would completely eliminate the WHO guideline exceedances for 24-hour average PM_{10} and 24-hour average $PM_{2.5}$, and would significantly reduce the number of exceedances for 24-hour average SO_2 and one-hour average NO_2 throughout the modeled area. (Table 2)
3. ***All* of the 120 sensitive sites** (primarily schools and hospitals) analyzed in the model exceeded the World Health Organization's 24-hour average SO_2 guideline (20 $\mu g/m^3$) in 2016 due to emissions from the 14 facilities. The modeled average peak 24-hour SO_2 concentration across all 120 sensitive sites was 66.4 $\mu g/m^3$ in 2016, with a maximum of 178 $\mu g/m^3$ at Duvha Primary School. Under the 2020 MES, the average concentration at the sensitive sites would be reduced to 13.6

µg/m^3. Implementing the 2020 MES at the facilities would bring SO_2 exposures at 93% of the sensitive sites (all but nine) to within the WHO guideline. (Appendix D)

4. Unhealthy, **acute exposures to NO_2 occurred at 28 of the 120 sensitive sites** in 2016, exceeding the WHO one-hour NO_2 guideline concentration of 200 µg/m^3. The worst acute exposure was at Camden Combined School, at 1079 µg/m^3. Under the 2020 MES, there would still be 14 sites in which the 200 µg/m^3 would be exceeded (led by Camden Combined School (588 µg/m^3). The average peak one-hour average NO_2 concentration across all 120 sites was 191 µg/m^3 in 2016. Under the 2020 MES, the average of all 120 sites would be reduced to 115 µg/m^3. (Appendix D)

5. The 14 facilities are responsible for the lion's share of air pollution allowed by national air quality limits. In 2016, emissions from the 14 facilities accounted for:

    - **92%** of the daily ambient SO_2 limit
    - **85%** of the hourly ambient SO_2 limit
    - **82%** of the hourly ambient NO_2 limit.
    - **68%** of the daily ambient $PM_{2.5}$ limit

    These levels of contribution indicate that ambient air quality standards cannot be achieved without reducing pollution from these sources. Given the hundreds of other sources of air pollution in and around the HPA, particularly PM and NO_2, these 14 facilities contribute alarmingly high — and relatively easily reducible — percentages of national limits.

    If these sources were to comply with the 2020 MES, their contribution to ambient air pollution would substantially decrease, accounting for:

    - **20%** of the daily ambient SO_2 limit (79% reduction from 2016)
    - **21%** of the hourly ambient SO_2 limit (75% reduction from 2016)
    - **53%** of the hourly ambient NO_2 limit (35% reduction from 2016)
    - **28%** of the daily ambient $PM_{2.5}$ limit (59% reduction from 2016)

    (Table 2)

6. **Major reductions of SO_2 emissions from the 14 sources are necessary to reduce the high levels of secondary $PM_{2.5}$** (from sulfate particles) contributing to $PM_{2.5}$ NAAQS exceedances in and around the HPA. Compliance with the 2020 MES would result in SO_2 emissions from the facilities being reduced by **78%** relative to 2016 emissions. NO_2 emissions from the facilities would be reduced by **43%**. PM_{10} emissions from the facilities would be reduced by **51%**. (Table 1)

7. The 14 modeled sources are responsible for substantial $PM_{2.5}$ exposures across at least 30% of the entire modeled area. If the sources complied with the 2020 MES, the area exposed to relatively high concentrations of $PM_{2.5}$ would be

completely eliminated, resulting in healthier air for the large populations in Johannesburg and Pretoria. (Figures 4 and 7)

INTRODUCTION

The HPA has experienced non-compliant and dangerous ambient air pollutant concentrations for decades. The Department of Environmental Affairs estimates that power generation contributes 82% of SO_2, 73% of NO_x, and 12% of PM_{10} in the HPA, while petrochemical facilities contribute 12% of SO_2, 15% of NO_x, and 3% of PM_{10}.[1] In 2007, the Ministry of Environment designated the area as a "Priority Area".[2] Despite this, ambient air quality has remained poor and non-compliant with national air quality standards.[3]

There are adverse health effects associated with both short-term and chronic exposures to air pollutants. Though there is no threshold of safety below which no harm is caused,[4] ambient air pollution guidelines have been established in South Africa for various time frames for SO_2, NO_2, ozone, PM_{10} and $PM_{2.5}$. South Africa's National Ambient Air Quality Standards (SA NAAQS) are significantly weaker than those recommended by the United States or the World Health Organization (WHO).[5]

Short term exposures (i.e., on the order of one-hour) to elevated SO_2 and NO_2 levels have been associated with serious health consequences, including inflammation, irritation, and

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[1] Department of Environmental Affairs, *Highveld Priority Area Air Quality Management Plan* (2011) at xi.

[2] Department of Environmental Affairs and Tourism, *The National Framework for Air Quality Management in the Republic of South Africa*, Government Gazette: 30284, 3-101, 2007.

[3] *See*, Department of Environmental Affairs, 2018 State of the Air Report (2 Oct. 2018), http://www.airqualitylekgotla.co.za/assets/2018_1.3_2018_state_of_air_report.pdf.

[4] United States Environmental Protection Agency, *Quantitative Health Risk Assessment for Particulate Matter,* Final Report, EPA-452/R-10-005 (Jun. 2010), https://www3.epa.gov/ttn/naaqs/standards/pm/data/PM_RA_FINAL_June_2010.pdf. The US EPA's quantitative human health risk assessment (RA) for particulate matter clearly demonstrates that there are significant health effects associated with air quality below the levels of the NAAQS. For example, the RA pointed out that there are actually greater overall health impacts to an urban area due to days with 24-hour average $PM_{2.5}$ levels nearer to the annual average value rather than days with relatively higher $PM_{2.5}$ levels falling in the tail of the annual 24-hour $PM_{2.5}$ distribution. As explained by EPA (RA, page 3-11): "This finding reflects the fact that the number of deaths associated with short-term exposure to $PM_{2.5}$ depends both on the number of days at a given concentration and on the concentration itself. Because the urban areas considered . . . had 24-hour $PM_{2.5}$ distributions that were closer to normal or log-normal in form (i.e., not uniform), overall incidence of short-term exposure-related mortality was driven by the relatively large number of days near the center of the distribution, rather than the small number of days out at the tail." EPA makes it very clear that there are measurable health impacts, including the increased risk of mortality, associated with exposure to $PM_{2.5}$ even at average daily $PM_{2.5}$ concentration levels.

[5] World Health Organization, *Ambient (outdoor) air quality and health*, (2 May 2018). Because the standards are configured as averages over different time periods or as specific highest occurring values, the standards are not directly comparable.

infection of the respiratory system, destruction of lung tissue (especially in children), and increased asthma attacks and heart disease in sensitive groups.[6]

DISPERSION MODELING

A. Methodology

In order to quantify the health impacts of the air pollution from the largest stationary sources of air pollution in and around the HPA, I analyzed contributions to ambient air quality from 12 Eskom coal-fired power plants, the Sasol Synfuels facility and the Natref Refinery located within 50 km of the HPA boundaries (Figure 1).[7] The air pollution modeling area covers a total area of 147,312 square kilometers, including the highly populated metropolitan areas of Pretoria and Johannesburg. The total population within the modeled area was 20.62 million in 2016. Figure 1 illustrates the area, including the 14 facilities and the nearby major cities.

I compiled data from the United States National Climatic Data Center's Integrated Surface Database, the Global 30-Second Elevation Data Set, and the Africa Land Cover Characteristics Data Base (Version 2.0).[8] I used the US EPA-recommended CALPUFF dispersion model to assess two emissions scenarios: (1) the *actual* emissions released during 2016 by the 14 facilities, using data obtained through monthly reports to regulators; and (2) the *projected* emissions that would be released if these sources complied with the minimum emission standards that will go into effect in April 2020 (2020 MES). It should be noted that many of these sources, including the Eskom power plants, have sought postponements for compliance with the 2020 MES. If these postponements are granted, the emissions reductions achievable through compliance with the 2020 MES will not be achieved.

I also modeled exposure to the emissions from the 14 sources over various timeframes (hourly, daily, and annually) at 120 sensitive locations (primarily schools and hospitals) with particularly vulnerable populations.

Using the health impacts assessment from the World Health Organization's Global Burden of Disease, I modeled early deaths caused by exposure to primary and secondary

[6] World Health Organization, *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment* (2006).

[7] The Lethabo power station and the Natref refinery are located within 50 km of the HPA, and were also included in the current modeling analysis. Population centers of Johannesburg and Pretoria were also included.

[8] https://www.usgs.gov/media/images/africa-land-cover-characteristics-data-base-version-20; https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30.

$PM_{2.5}$[9] from the 14 facilities on the population of the region, both from each facility and cumulatively. Finally, I calculated early deaths due to the 2016 emissions as well as under the 2020 MES scenario.

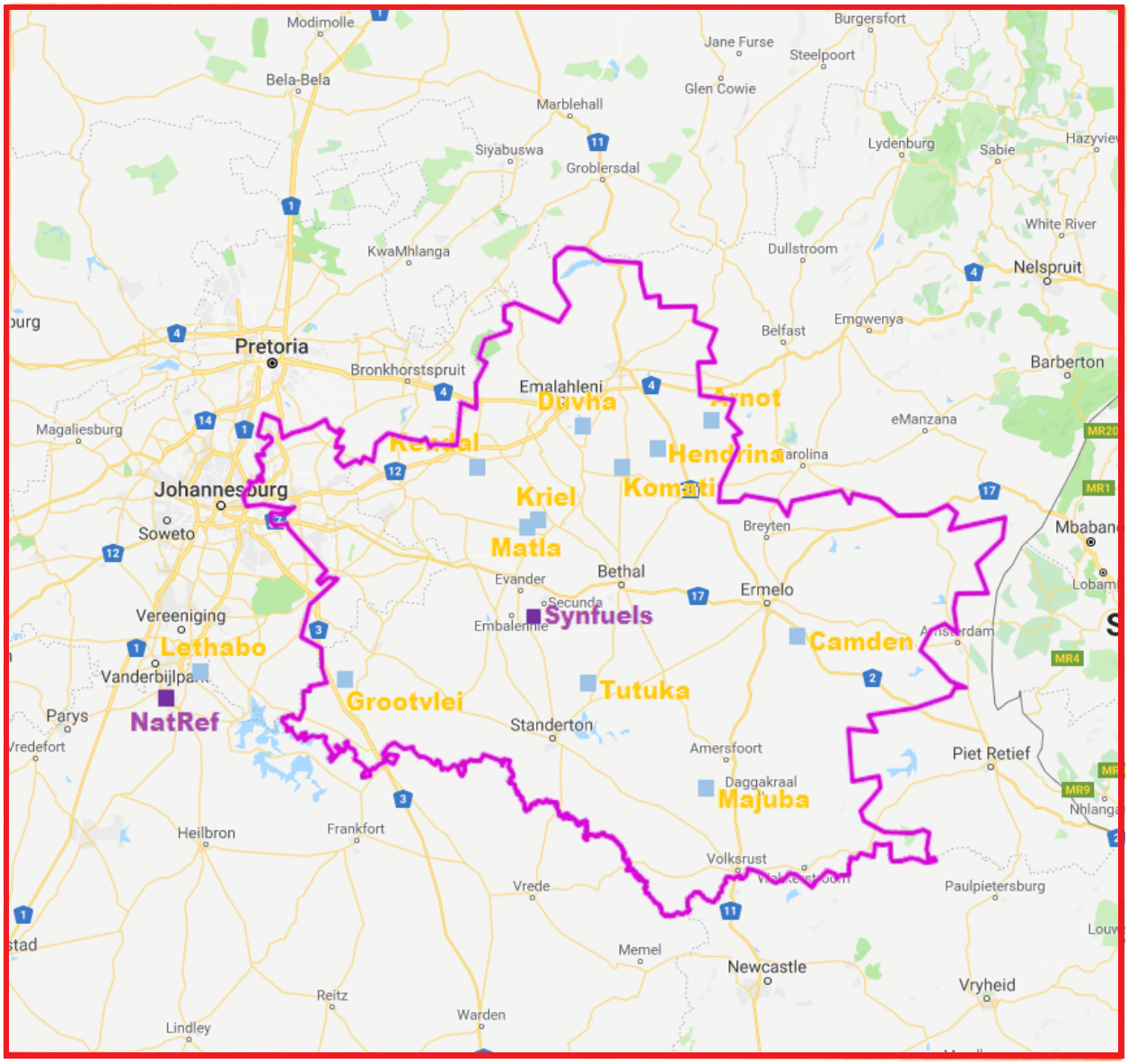

Figure 1. Modeling Domain (HPA area boundary in pink; modeling domain boundary in red)

[9] Ambient $PM_{2.5}$ forms in two ways: (1) through direct, or "primary" emissions of $PM_{2.5}$; and (2) through emissions of SO_2 and NO_x, which react in the air to form sulfate and nitrate particles known as "secondary" $PM_{2.5}$.

I used the CALPUFF dispersion modeling system (version 6.262, 25 Jul. 2008),[10, 11] to simulate the emissions and regional transport of sulfur dioxide (SO_2), oxides of nitrogen (NO_X), particulate matter smaller than 10 microns (micrometers) in diameter (PM_{10}), and particulate matter smaller than 2.5 microns in diameter ($PM_{2.5}$) originating from the Eskom coal-fired power plant stacks, the Synfuels chemical facility, and the Natref Refinery located in and near the HPA region.

The CALPUFF model is a state-of-the-art air quality dispersion model that simulates the atmospheric transport of pollutants within a defined modeling domain by representing a source's plume as a continuous series of spreading plume segments or "puffs" which are tracked forward in time. The model considers the formation of "secondary" $PM_{2.5}$ caused by reactions of SO_2 and NO_X emissions in the atmosphere, which accounts for the majority of the $PM_{2.5}$ attributable to the power stations. The CALPUFF model can be used to estimate the air pollutant concentration impacts that occur throughout the modeling domain due to each individual modeled source, as well as the combined (cumulative) impact of all the modeled sources.

The CALPUFF model was used to determine pollution concentrations due to emissions from 14 facilities during the calendar year 2016 (January to December). Meteorological data for every hour of 2016, including 3-dimensional wind fields, temperatures, and other atmospheric parameters, were combined with hourly surface data collected at 32 weather stations (typically located at regional airports) in and near the HPA. In addition to meteorological data, geophysical data were obtained in order to characterize the modeling domain, including terrain (elevation data), and other parameters related to the land surface. Further details regarding the meteorological and geophysical data that were used in the modeling can be found in Appendix A of this report.

The CALPUFF model is designed to estimate pollutant concentrations at a specified set of locations within the modeling domain, which are referred to as the modeled "receptors". For the current CALPUFF application, a large set of gridded receptors were defined, as well as a second smaller set of "sensitive" receptor locations. The gridded modeled receptors were defined to cover the entire modeling domain shown in Figure 1, using 4 km grid spacing, accounting for 9,207 virtual receptors (99 E/W x 93 N/S).

The modeled concentrations at the set of gridded receptors were used to: (1) determine the locations of maximum pollution concentrations from the modeled sources across the entire HPA; (2) compare those maximum concentrations against acceptable ambient air quality standard threshold levels; (3) develop spatial contour plots of pollutant

[10] Scire, J.S., Strimaitis, D.G., Yamartino, R.J., *A User's Guide for the CALPUFF Dispersion Model (Version 5)*, Earth Tech, Inc., Concord, MA, 2000, http://src.com/calpuff/download/CALPUFF_UsersGuide.pdf.

[11] Scire, et al., *CALPUFF Modeling System, Version 6 User Instructions*, April 2011, http://www.src.com/calpuff/download/CALPUFF_Version6_UserInstructions.pdf.

concentrations; and (4) establish pollutant exposure levels across the modeling domain for the health effects analysis.

In addition to the gridded receptors, a set of 120 sensitive receptor locations were identified, which includes a number of schools, hospitals and other locations where children, the elderly, and other sensitive segments of the population may be exposed. The locations of the sensitive receptors are shown on a map of the modeling domain (and HPA area) in Figure 2, below. The list of modeled sensitive receptors appears in Appendix A (Table A-2). Dispersion model results for the sensitive receptors are presented in Appendices C and D.

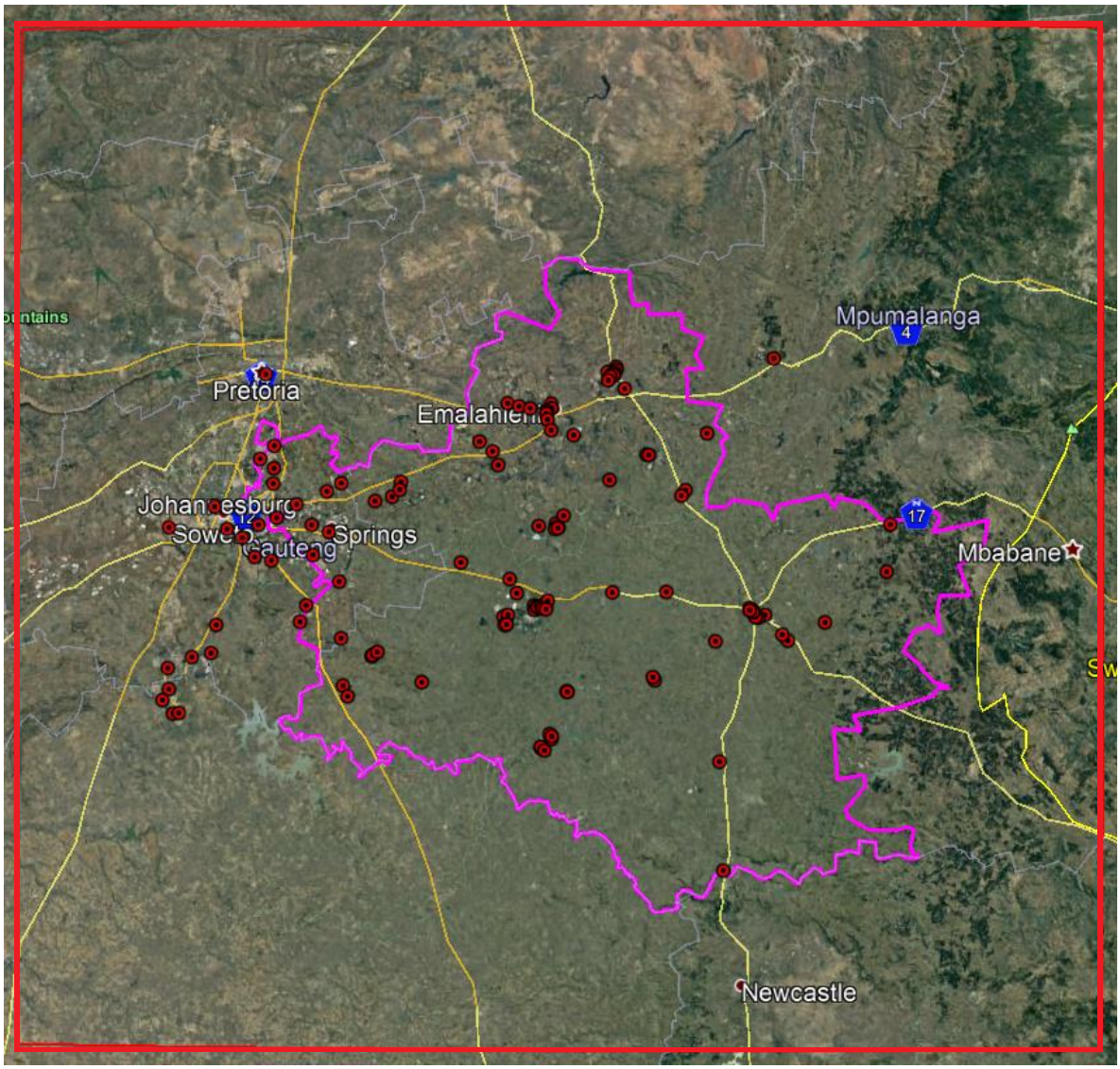

Figure 2. Sensitive Receptor Locations, with vulnerable populations in schools and hospitals. (HPA area boundary in pink; modeling domain boundary in red.)

Two emission scenarios were modeled using the CALPUFF model: (1) Baseline: The Baseline scenario represents actual emissions rates (in grams of pollution per second) from each facility in 2016. Pollutant emission rates were obtained from monthly and annual reports to regulators for each facility. (2) 2020 MES: The 2020 MES scenario represents the projected emissions from the 14 sources if these sources were to comply with 2020 MES, and assuming that the plants were operating at the same annual average capacity (load) as in 2016.[12]

The modeled pollutant emissions rates for each modeled facility are summarized in Table 1, below, for the Baseline (2016 actual emissions) and the 2020 MES scenarios.[13]

[12] The annual average capacity (load) ranged from 40 to 82 percent (of maximum) for the 12 Eskom power plants during 2016. Synfuels and Natref were assumed to be operating in 2016 at the same production rates as in 2014.

[13] The CALPUFF model was used to estimate impacts due to direct emissions of both PM_{10} and $PM_{2.5}$. It was assumed (conservatively) that 50% of the emitted PM_{10} from all modeled sources was in the fine ($PM_{2.5}$) fraction.

Table 1. Emission Rates (g/s)

	BASELINE			2020 MES		
SOURCE	SO2	NOx	PM10	SO2	NOx	PM10
Arnot	2,447.14	1,305.45	46.03	661.84	992.76	66.18
Camden	2,327.62	1,304.03	37.64	507.37	761.06	50.74
Duvha	4,154.37	2,129.10	112.33	685.20	1,027.79	68.52
Grootvlei	1,323.01	683.84	104.01	283.75	425.62	28.37
Hendrina	1,795.77	1,099.00	23.74	523.43	785.15	52.34
Kendal	5,953.07	2,349.79	346.27	1,319.07	1,978.60	131.91
Komati	1,004.81	794.07	35.89	246.91	370.37	24.69
Kriel	4,114.25	3,034.94	301.65	862.13	1,293.20	86.21
Lethabo	5,477.43	3,171.11	269.70	1,804.89	2,707.34	180.49
Majuba	4,601.49	3,698.54	80.35	1,218.40	1,827.60	121.84
Matla Stack 1	2,778.16	992.14	68.05	250.79	376.19	25.08
Matla Stack 2	2,891.73	992.14	75.20	250.79	376.19	25.08
Tutuka	4,568.82	2,845.18	531.14	1,029.00	1,543.50	102.90
Synfuels-ME	2,899.19	1,939.08	70.06	500.44	750.65	50.05
Synfuels-MWE	2,578.74	1,725.55	62.32	445.18	667.69	44.51
NatRef MS	286.11	46.39	30.56	10.30	20.83	5.95
NatRef B14001	0.13	0.28	0.04	1.05	0.65	0.11
NatRef B14002	0.13	0.05	0.03	0.48	0.30	0.02
NatRef B14005	2.08	0.70	0.24	3.14	1.96	0.41
NatRef B14006	0.58	0.27	0.09	0.90	0.56	0.10
NatRef B17004	0.53	0.14	0.05	0.51	0.32	0.06
NatRefB25001	5.60	3.19	0.57	8.08	5.05	0.82
NatRef-CCU	55.00	10.08	2.20	16.50	3.30	1.10
ALL	49,265.8	28,125.1	2,198.1	10,630.2	15,916.7	1,067.5

The 14 sources accounted for an average of 4,257 tonnes per day of SO_2 during 2016.[14] The sources also combined to emit 2,430 tonnes of NO_X and 190 tonnes of PM_{10} into the air each day, on average, in 2016.

B. 2020 MES Projections

Compliance with the 2020 MES would result in significant reductions in pollutant emissions of all three pollutants at all facilities, especially for SO_2; the total SO_2 emissions from all sources would be less than 920 tonnes per day, which represents a **78%** reduction relative to 2016 actual emissions. The 14 sources combined would emit 1,375

[14] The average modeled SO_2 emission rate from all sources during 2016 was 49,266 grams per second (as shown in Table 1), which is equivalent to 4,257 metric tonnes per day.

tonnes/per day of NO_X and 92 tonnes per day of PM_{10}, reductions of **43%** and **51%**, respectively, relative to 2016 actual emission rates.

The largest overall emitters in 2016 were Lethabo, Kendal, Majuba, Tutuka, Kriel, and Duvha. SO_2 emission reductions for the 2020 MES scenario range from 67% to 91% across the 14 facilities. Reductions in NO_X emissions would range from 15% to 62%, and PM_{10} emissions would be reduced by between 33% and 81% for the larger emitters of PM_{10}.[15] (Table 1)

C. Dispersion Model Results

The CALPUFF model was used to estimate the concentrations of SO_2, PM_{10}, $PM_{2.5}$ and NO_2 at every receptor location for each hour of 2016. The predicted concentrations were compared to the SA NAAQS[16, 17] to determine the percentage of each standard that is "taken up" by the 14 sources.

Each ambient pollutant standard includes: (1) a specified *averaging time* (such as one-hour average, 24-hour average, or annual average), (2) a concentration *level*, and (3) a *form*, which defines the requirements for attainment/compliance. For example, the one-hour SO_2 SA NAAQS requires that the one-hour average (the *averaging time*) SO_2 concentration not exceed 350 µg/m^3 (the *level*), with 88 allowed exceedances per year at each location (the *form*). The form and averaging time for each standard can be combined to determine the *design value* metric (or statistic) that must be compared to the acceptable level to assess whether the region is in compliance with the standard. If the 89th highest one-hour average SO_2 concentration exceeds the standard level (350 µg/m^3), then the area would not be in compliance with the one-hour SO_2 standard. Therefore, the design value (DV) for the one-hour SO_2 standard is the 89th highest one-hour average SO_2 concentration.

The design values for each emission scenario were extracted from the set of modeled hourly concentration data (for all sources combined) and compared to the acceptable standard level for each of the SA NAAQS, as shown in Table 2, below. As a comparison to the SA NAAQS, the modeled design values corresponding to US NAAQS levels were also measured against allowable levels for a few of the US standards.[18] For example, the US NAAQS requires that the 4th highest daily peak one-hour average SO_2 concentration is below 196 µg/m^3, which is a much more stringent standard than the one-hour SO_2 NAAQS for SA, which requires that the 89th highest one-hour average

[15] Four of the smaller PM_{10} emitters would have *increased* PM_{10} emissions under the 2020 MES scenario, relative to the 2016 actual emission rates (as shown in Table 1).
[16] South Africa Department of Environmental Affairs, National Environment Management: Air Quality Act, 2004 (Act No. 39 of 2004): National Ambient Air Quality Standards. Staatskoerant No. 32816. 24 Dec. 2009, https://www.gov.za/sites/default/files/gcis_document/201409/328161210.pdf.
[17] South Africa Department of Environmental Affairs, National Environment Management: Air Quality Act, 2004 (Act No. 39 of 2004): National Ambient Air Quality Standard for Particulate Matter with Aerodynamic Diameter Less Than $_{2.5}$ Micron Metres ($PM_{2.5}$). Staatskoerant No. 35463. 29 Jun. 2012.
[18] https://www.epa.gov/criteria-air-pollutants/naaqs-table

concentration is below 350 µg/m^3. According to the model results shown in Table 2, the maximum 4th highest daily peak one-hour average SO_2 concentration during 2016 (1,886 µg/m^3) was almost **ten times** the acceptable US one-hour NAAQS level of 196 µg/m^3. Even if the 2020 MES were met, the model indicates that the 14 sources would contribute enough SO_2 to reach **twice** the acceptable levels of the US one-hour SO_2 standard.

Emissions from these sources are substantially responsible for the ambient concentrations to exceed acceptable standards, because there is only a small percentage of the standard left for *all other sources*.

If the modeled sources were compliant with South Africa's 2020 MES, their contributions to ambient air pollution would substantially decrease.

Table 2. Modeled Design Value Concentrations.

Pollutant / Design Value	Standard Level (µg/m^3)	Modeled DV (µg/m^3) Baseline (2016)	Percent of Standard	Modeled DV (µg/m^3) 2020 MES	Percent of Standard	Percent Reduction
SO_2						
SA NAAQS						
SO_2 1-hr average, 89th high	*350*	296.8	85%	73.6	21%	**75%**
SO_2 24-hr average, 5th high	*125*	115.4	92%	24.7	20%	**79%**
SO_2 annual average	*50*	19.0	38%	4.0	8%	**79%**
US NAAQS						
SO_2 1-hr average, 4th high daily peak	*196*	1,885.9	962%	429.9	743%	**77%**
WHO Guidelines						
SO_2 24-hr average, maximum	*20*	241.4	1,207%	58.6	486%	**76%**
PM_{10}						
SA NAAQS						
PM_{10} 24-hr average, 5th high	*75*	29.7	40%	11.9	16%	**60%**
PM_{10} annual average	*40*	3.7	9%	1.4	4%	**62%**
US NAAQS						
PM_{10} 24-hr average, 2nd high	*150*	44.5	30%	14.6	10%	**67%**
WHO Guidelines						
PM_{10} 24-hr average, maximum	*50*	51.9	104%	16.1	32%	**69%**
PM_{10} annual average	*20*	3.7	19%	1.4	7%	**62%**
$PM_{2.5}$						
SA NAAQS						
$PM_{2.5}$ 24-hr average, 5th high	*40*	27.0	68%	11.0	28%	**59%**
$PM_{2.5}$ annual average	*20*	3.2	16%	1.2	6%	**63%**
US NAAQS						
$PM_{2.5}$ 24-hr average, 8th high	*35*	23.1	66%	9.2	26%	**60%**
WHO Guidelines						
$PM_{2.5}$ 24-hr average, maximum	*25*	45.0	180%	14.0	56%	**69%**
$PM_{2.5}$ annual average	*10*	3.2	32%	1.2	12%	**63%**
NO_2						
SA NAAQS						
NO_2 1-hr average, 89th high	*200*	164.0	82%	106.5	53%	**35%**
NO_2 annual average	*40*	8.76	22%	4.7	12%	**46%**
US NAAQS						
NO_2 1-hr average, 8th high daily peak	*188*	633.6	337%	395.8	211%	**38%**
WHO Guidelines						
NO_2 1-hr average, maximum	*200*	2,020.6	1,010%	1,563.2	782%	**23%**
NO_2 annual average	*40*	8.76	22%	4.7	12%	**46%**

Mapping Pollution Concentrations

The modeled gridded concentrations were used to develop contour plots (maps) showing pollutant concentrations from the 14 sources at each grid location.

Appendix A includes additional 3-D contour plots illustrating the spatial variability of modeled peak concentrations for one-hour (SO_2 and NO_2) and 24-hour (PM_{10}) averaging times.

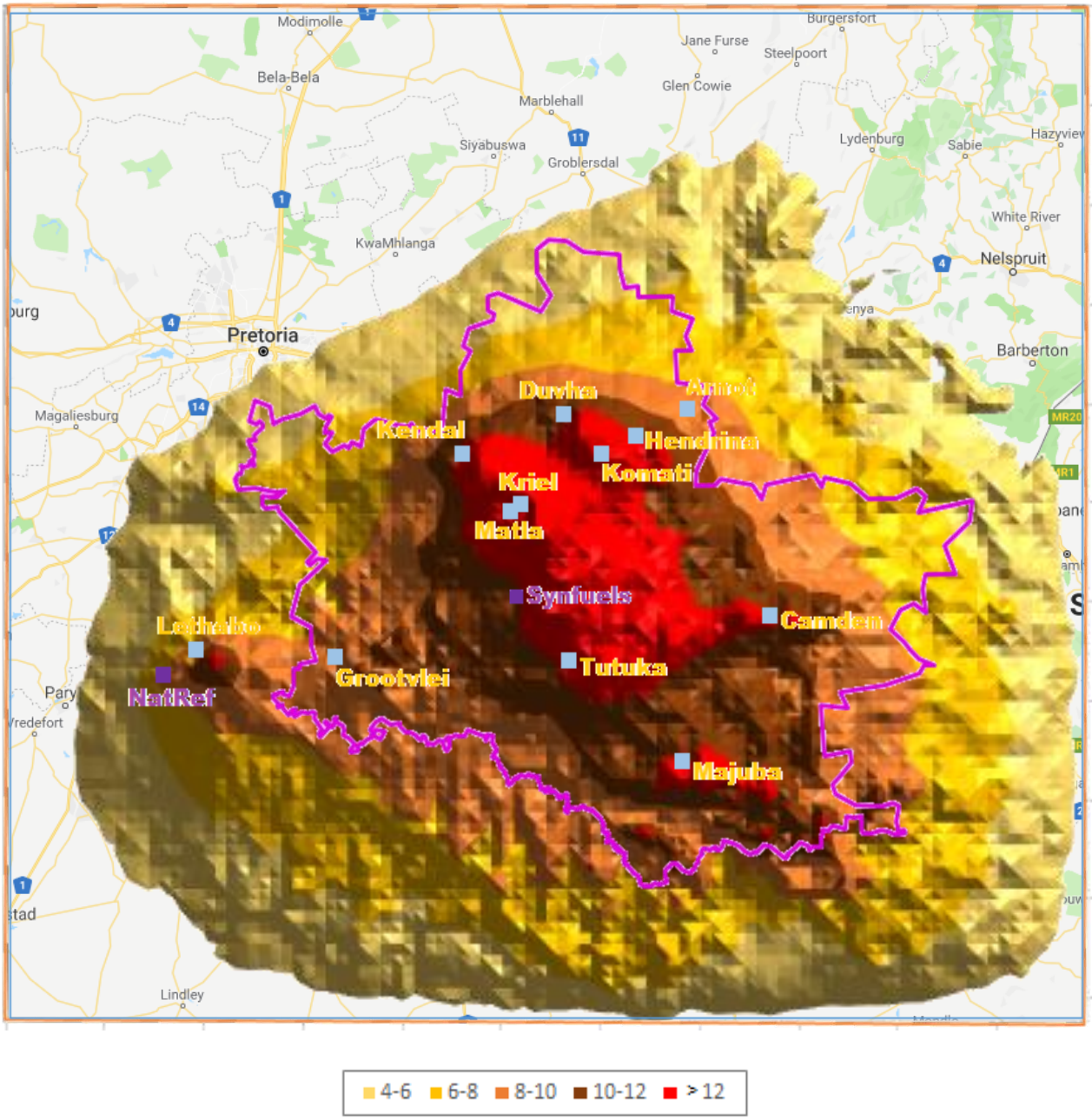

Figure 3. Modeled Annual Average SO_2 Concentration (µg/m^3): All Sources, 2016 Actual Emissions

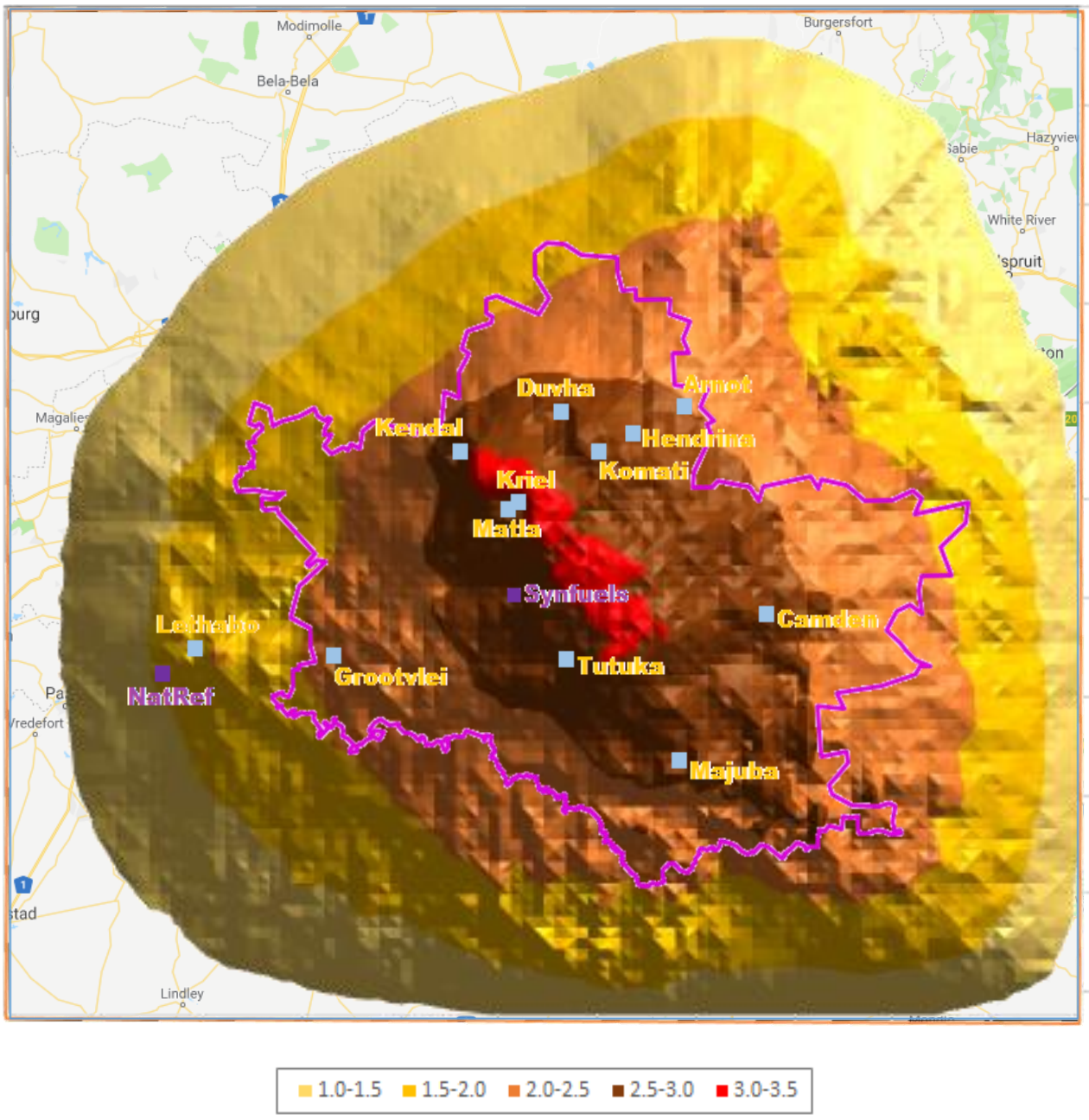

Figure 4. Modeled Annual Average $PM_{2.5}$ Concentration (µg/m³): All Sources, 2016 Actual Emissions

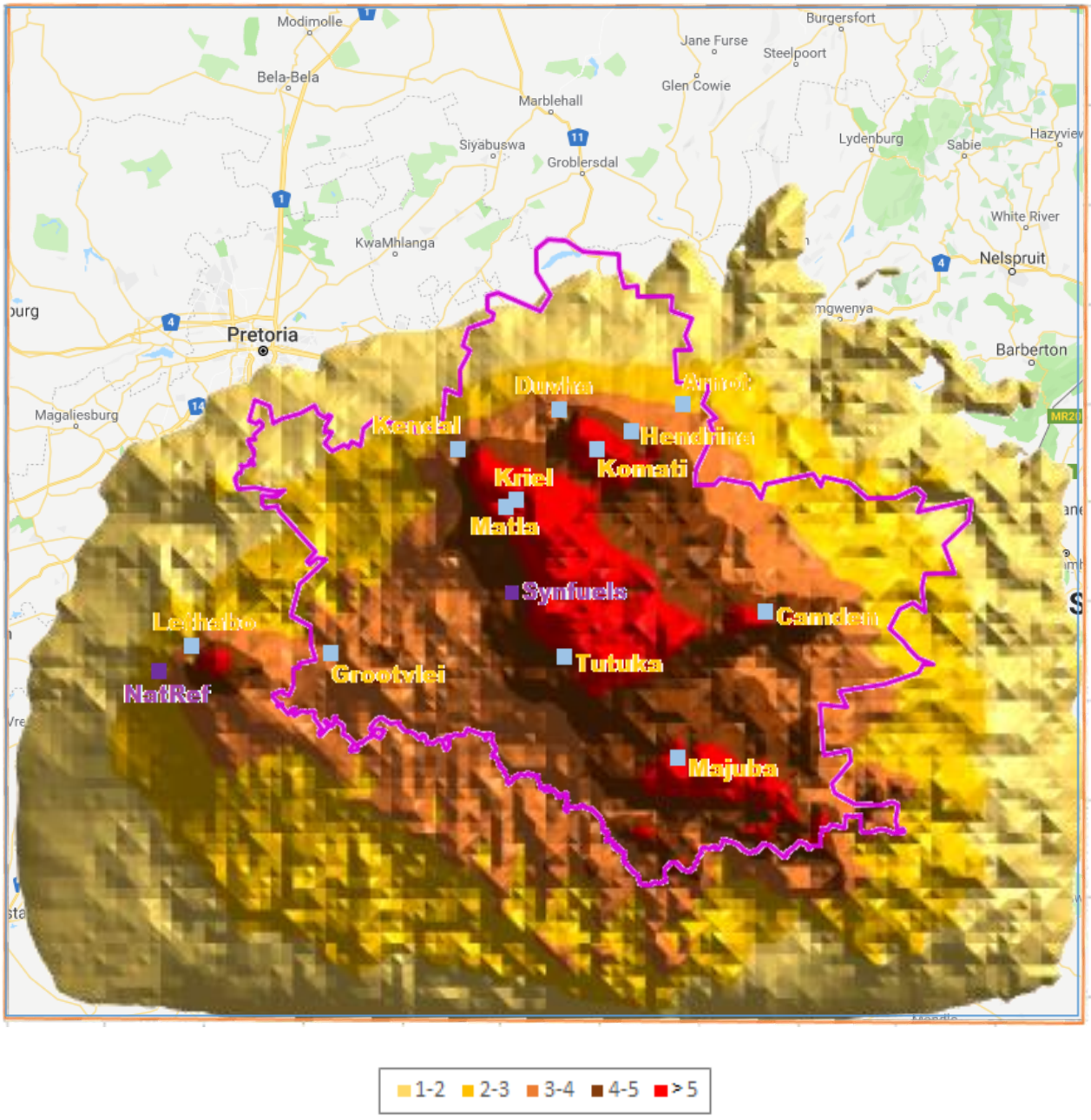

Figure 5. Modeled Annual Average NO_2 Concentration (µg/m³): All Sources, 2016 Actual Emissions

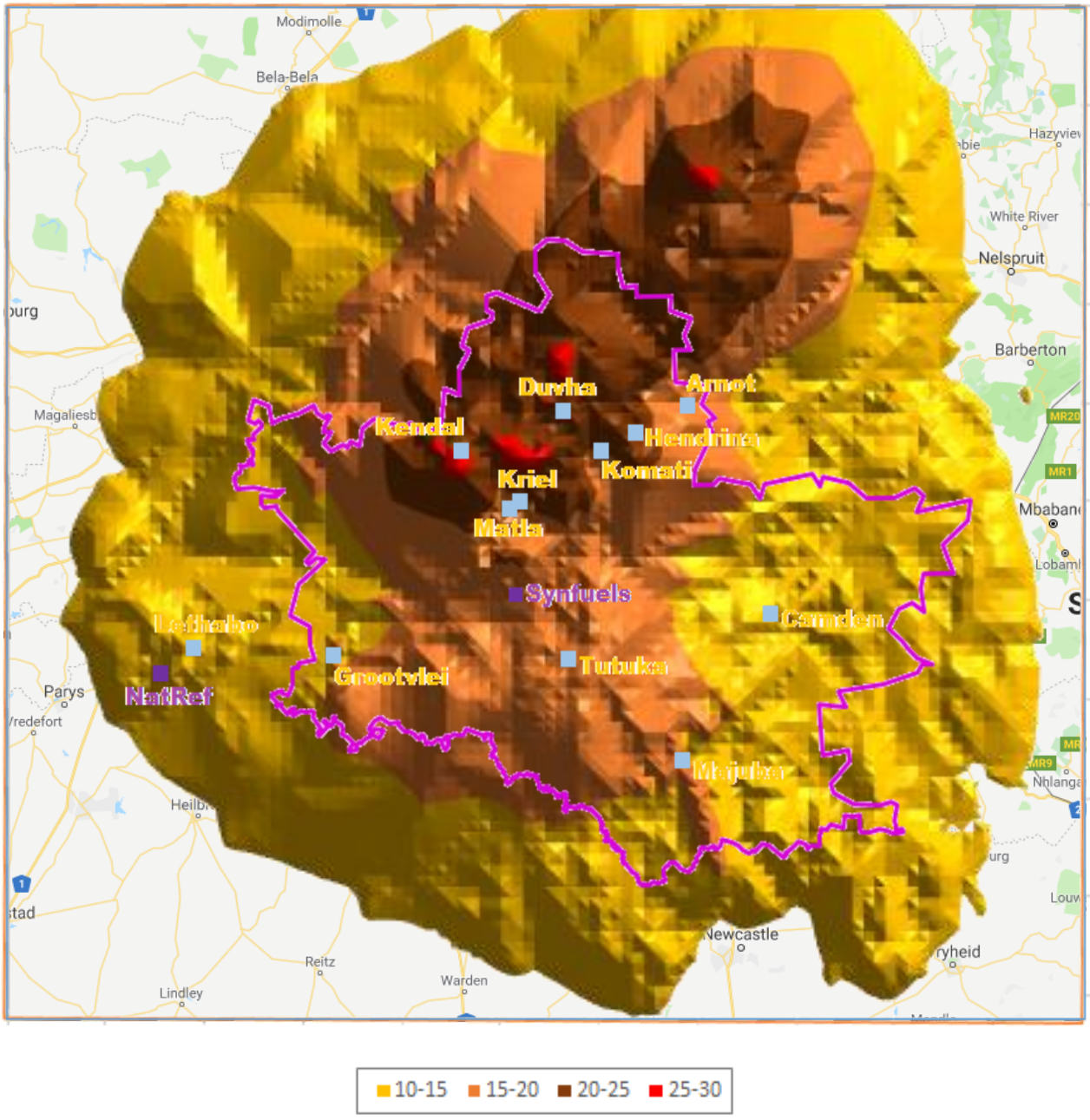

Figure 6. Modeled 5th Highest 24-hour Average $PM_{2.5}$ Concentration (µg/m³): All Sources, 2016 Actual Emissions

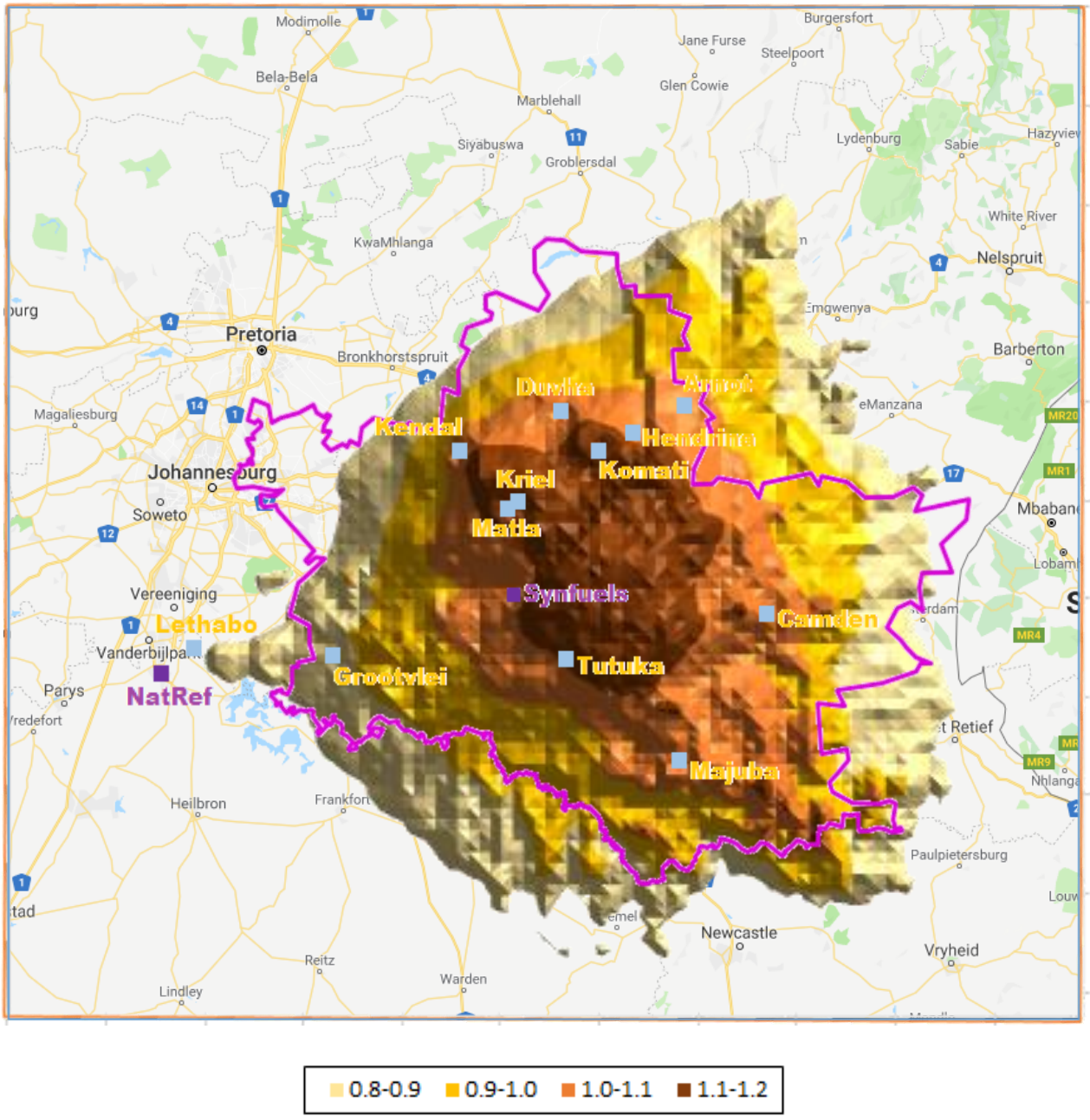

Figure 7. Modeled Annual Average $PM_{2.5}$ Concentration (µg/m³): All Sources, 2020 MES

The contour plots demonstrate that pollution from the 14 facilities occurs over a large area of the HPA. For example, the model results indicate that the annual average SO_2 concentration from the 14 facilities during 2016 exceeded 8 µg/m^3 over an area of 33,632 square kilometers (corresponding to the area within the orange contour band in Figure 3). This is almost one quarter of the entire modeling domain area. If the modeled sources were compliant with the 2020 MES, this area of relatively high pollution concentrations from the 14 sources would be completely eliminated (the highest annual average SO_2 concentration would only be 4.0 µg/m^3 under the 2020 MES scenario; see Table 2).

Similarly, the modeled annual average $PM_{2.5}$ concentration during 2016 due to emissions from the 14 sources was at least 2 µg/m^3 over an area of 44,368 square kilometers (30% of the full modeling domain area; the area within the orange contour band in Figure 4). The 5th highest modeled 24-hour average $PM_{2.5}$ concentration from the 14 sources exceeded 15 µg/m^3 over an area of 38,304 square km (the area within the orange contour band in Figure 6). If the 2020 MES were met, the model results indicate that these areas of greater $PM_{2.5}$ concentrations from the 14 sources would be completely removed. Under the 2020 MES scenario, the annual average $PM_{2.5}$ concentrations would exceed 1.0 µg/m^3 over an area of 16,576 km^2 (the area within the orange contour band in Figure 7), which is less than 15 percent of the area impacted at that concentration level during 2016 (within the outer contour band in Figure 4).[19]

Sensitive Locations: Schools and Hospitals

In addition to the gridded receptors, the CALPUFF model was also used to predict concentration impacts at each of the 120 sensitive receptor locations shown in Figure 2, consisting mostly of schools, hospitals, and other locations where children, the elderly, and the infirm might reside (the list of sensitive receptor locations appears in Table A-1 of Appendix A). The modeled concentrations from each individual source (facility) at each sensitive receptor location, corresponding to each of the pollutant design value metrics in Table 2, are shown in Appendices C and D.

Daily average SO_2 exposure from the 14 facilities exceeded the World Health Organization's health-based guideline at *all* of the 120 sensitive sites in 2016. Implementing the 2020 MES at the facilities would bring SO_2 exposures at all except nine of the sensitive sites to within the WHO guideline.

One-hour average exposures of NO_2 due to cumulative emissions from the 14 facilities occurred at levels above the WHO guideline at 28 locations in 2018 and were highest at Elsie Ballot Hospital, Kwanala Primary School, Duvha Primary School, and Camden Combined School. If the 2020 MES were implemented, all but 14 locations would no longer be exposed to NO_2 levels that exceed the WHO one-hour average guideline.

[19] The 1.0 µg/m^3 contour in Figure 4 extends beyond the modeling domain.

D. Conclusions Regarding Dispersion Modeling Results

The CALPUFF results demonstrate that the 14 sources contributed large amounts of pollutants to the ambient air in the HPA region during 2016. The 14 sources *alone* significantly contributed to exceedances of the SA NAAQS, and the unhealthful air quality conditions in the region.

According to the model, emissions from the 14 sources alone come close to exceeding the one-hour SA NAAQS level for SO_2 in the HPA region. (The modeled sources were responsible for 85% of the one-hour SO_2 standard level and 92% of the 24-hour SO_2 standard level in 2016.) The 14 sources represent the majority of the SO_2 emissions in and around the HPA,[20] that if combined with peak short-term modeled SO_2 impacts from other (non-modeled) sources[21] would likely lead to exceedances of the one-hour standard.[22] The peak modeled one-hour NO_2 concentration due to the 14 sources also nearly exceeded the acceptable SA NAAQS level. (The 14 sources alone accounted for over 80% of the acceptable one-hour NO_2 SA NAAQS level.) The peak modeled one-hour SO_2 and NO_2 concentrations due to the 14 sources in 2016 far exceeded the more stringent US NAAQS and the World Health Organization guidelines.

There are measurable human health impacts even at pollutant concentrations below the NAAQS standard levels. The NAAQS levels do not represent a "threshold of safety", below which no harm occurs.[23] This is particularly true for NAAQS that are weaker than the World Health Organization guidelines.

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[20] South Africa Department of Environmental Affairs. *Highveld Priority Area Air Quality Management Plan (AQMP)*. 2011.

[21] Comparisons of modeled and observed monthly average SO_2 concentrations suggests that other sources likely contribute significant amounts of SO_2 at certain locations, especially during winter months when the monitored SO_2 levels are observed to be elevated (for example, at Witbank; see Appendix A).

[22] Examination of air quality monitoring data for the HPA region for 2015-2017 shows that the peak (99th percentile) observed one-hour average SO_2 concentration was 361 µg/m^3 at Witbank, which exceeds the acceptable SA NAAQS level. The peak observed one-hour average SO_2 concentration in the HPA region during 2016 was 285 µg/m^3 (also at Witbank) (which is very close to the modeled 89th high of 297 µg/m^3 due to the 14 modeled sources, although not at the same location). The peak observed one-hour average SO_2 concentration during 2016 at the other four HPA monitoring sites ranged from 144 to 188 µg/m^3. The peak observed daily (24-hour average) SO_2 concentration in 2016 at the five HPA monitors ranged from 71 µg/m^3 (at Secunda) to 190 µg/m^3 (at Witbank), which exceeded the acceptable SA NAAQS level of 125 µg/m^3. (The modeled peak daily average SO_2 concentration in 2016 due to the 14 sources was 115 µg/m^3).

[23] The US EPA's quantitative human health risk assessment (RA) for particulate matter (Quantitative Health Risk Assessment for Particulate Matter. Final Report. EPA-452/R-10-005. June 2010. https://www3.epa.gov/ttn/naaqs/standards/pm/data/PM_RA_FINAL_June_2010.pdf) clearly demonstrates that there are significant health effects associated with air quality below the levels of the NAAQS. For example, the RA pointed out that there are actually greater overall health impacts to an urban area due to days with 24-hour average $PM_{2.5}$ levels nearer to the annual average value rather than days with relatively higher $PM_{2.5}$ levels falling in the tail of the annual 24-hour $PM_{2.5}$ distribution. As explained by EPA (RA, page 3-11): "This finding reflects the fact that the number of deaths associated with short-term exposure to $PM_{2.5}$ depends both on the number of days at a given concentration and on the concentration itself. Because the urban areas considered… had 24-hour $PM_{2.5}$ distributions that were closer to normal or log-normal in form (i.e., not uniform), overall incidence of short-term exposure-related mortality was

Both the one-hour and 24-hour SA SO_2 standards and the one-hour NO_2 standard are close to being exceeded in the HPA due just to the 14 sources, which demonstrates that these sources contribute to unhealthful short-term exposures to SO_2 and NO_2. When measured against the US health-based NAAQS, there is clear evidence that the 14 sources were alone responsible for causing unhealthful short-term exposures to SO_2 and NO_2 during 2016.[24]

There are significant health consequences associated with both long-term (annual) and short-term (i.e., 24-hour) $PM_{2.5}$ exposures, including increased risk of mortality. Although the combined emissions from all 14 modeled sources were not predicted to have caused an exceedance of the recently adopted $PM_{2.5}$ 24-hour SA NAAQS (40 µg/m^3) under the 2016 baseline (actual emissions) scenario, the modeled sources alone accounted for almost 70% of the acceptable level, which represents a substantial contribution to short-term ambient $PM_{2.5}$ levels. The maximum modeled annual average $PM_{2.5}$ concentration also did not exceed either the SA or US NAAQS, however the combined impact of all modeled sources accounted for as much as 3.2 µg/m^3, which is more than 15 percent of the acceptable SA NAAQS level for $PM_{2.5}$ (20 µg/m^3), and more than 25 percent of the acceptable US annual average standard level (12 µg/m^3). Given the numerous sources of $PM_{2.5}$ in and around the HPA, the power stations are significant contributors.

The modeled power stations' $PM_{2.5}$ impacts, together with the other significant sources of $PM_{2.5}$ in the HPA region, including automobiles, trucks (especially diesels), buses, and off-road vehicles, mining, construction equipment, trains, residential heating and cooking, agricultural activity, and windblown dust, all combine in varying amounts, both in time and location, to create the (routinely) observed exceedances of the 24-hour $PM_{2.5}$ standard level in the HPA region.[25] The long-term (annual average) $PM_{2.5}$ impacts from the 14 modeled sources did not, on their own, exceed the annual $PM_{2.5}$ standard levels in 2016, but they substantially contributed to elevated ambient concentrations. The increased exposure to fine particulate matter was experienced over a large area with a sizeable population. Even a modest long-term increase in $PM_{2.5}$ exposure can have significant health consequences, as established by the World Health Organization[26], and as demonstrated in the next section of this report.

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driven by the relatively large number of days near the center of the distribution, rather than the small number of days out at the tail." EPA makes it very clear that there are measurable health impacts, including the increased risk of mortality, associated with exposure to $PM_{2.5}$ even at average daily $PM_{2.5}$ concentration levels.

[24] The model results indicate the potential for very high (intermittent) one-hour average SO_2 and NO_2 concentrations, which are not adequately controlled by the form of the SA one-hour SO_2 NAAQS (based on the 89th highest one-hour average).

[25] Examination of monitoring data shows that the peak (99th percentile) observed 24-hour average $PM_{2.5}$ concentration exceeded the (recently adopted) SA NAAQS level of 40 µg/m^3 at all ten HPA and VTPA sites during the 2015 to 2017 period, with peak concentrations ranging from 52 to 207 µg/m^3. (The modeled 5th highest 24-hour average $PM_{2.5}$ concentration (corresponding to the 99th percentile) from the 14 sources during 2016 was 27 µg/m^3).

[26] World Health Organization, *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment* (2006) at 10.

The $PM_{2.5}$ impacts from the modeled sources are caused by a combination of both directly emitted (primary) $PM_{2.5}$ and secondary particulate matter, which is formed in the atmosphere from the conversion of SO_2 and NO_X. In fact, the majority of the modeled $PM_{2.5}$ concentration impacts in the HPA from the 14 sources is due to secondary sulfate and nitrate (as a result of SO_2 and NOx emissions from the 14 sources). The significant modeled improvements in PM air quality if the 14 sources complied with the 2020 MES are largely due to reductions in SO_2 emissions (and to a lesser extent the emission reductions in $PM_{2.5}$ and NO_X emissions).

The CALPUFF model results demonstrate that emissions from the 14 sources during 2016 were responsible for large contributions to air pollution throughout the modeling domain, which caused considerable harm to the exposed population. If the 2020 MES were met, the model results confirm that there would be a significant reduction in exposures to both short-term and long-term pollutant concentrations in the HPA area (as shown in Table 2).

ANALYSIS OF EARLY DEATHS FROM $PM_{2.5}$

A. Methodology

The dispersion model results were used to estimate the health effects associated with exposure to primary and secondary $PM_{2.5}$ from the modeled sources.[27] Health impacts associated with $PM_{2.5}$ exposure were estimated using concentration-response functions that were originally adapted from the WHO Global Burden of Disease (GBD) 2010 project (Lim et al. 2012). The study was an authoritative examination of preliminary deaths caused by $PM_{2.5}$ globally, and developed a new risk model with emphasis on applicability at high average concentrations. The risk functions in the model level off at high concentrations, taking into account the findings showing that risk for the same concentration increase is higher at low concentrations. The risk functions have recently been extended to account for ambient $PM_{2.5}$ concentrations over the entire global exposure range (Burnett et al. 2014). These risk functions were used to relate $PM_{2.5}$ exposure to mortality in more recent GBD studies (2015 and 2016).

Burnett et al. (2014) developed an integrated exposure–response (IER) model to predict the relative risk (RR) associated with increased levels of exposure to $PM_{2.5}$ for four causes of mortality in adults: ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC). They also developed RR functions for the incidence of acute lower respiratory infection (ALRI) that can be used to estimate mortality in children under 5 years of age. Total mortality in the

[27] Other air pollutants from the power stations with potentially severe health impacts include SO_2, NO_X, dioxin, mercury, volatile organic compounds, mercury, lead, cadmium, and arsenic, however their health impacts have not been sufficiently studied for quantitative risk assessment modeling.

IER model is estimated as the sum of the four cause-specific mortality risks for the adult population and the ALRI risk for children.

The IER model was used to estimate the increase in the causes of adult mortality that are most closely associated with increases in fine particle exposure in and around the HPA. The four causes of adult mortality are responsible for about 40 percent of the total (non-AIDS) deaths in South Africa. The cause-specific approach provides better transferability from one country to another than earlier approaches that used all-cause mortality as the indicator, and provides a breakdown of the causes of the preliminary deaths attributable to $PM_{2.5}$ exposure from the modeled coal-fired power plants and other sources.[28]

The IER method used in the current analysis accounts for the increase in mortality risk for five cause-specific types of mortality. The results of a more recent study, conducted by the same researchers who developed the IER (GBD) model, in which $PM_{2.5}$ exposure was related to *all-cause* (non-accidental) mortality, "suggest that $PM_{2.5}$ exposure may be related to additional causes of death than the five considered by the GBD and that incorporation of risk information from other, non-outdoor, particle sources leads to underestimation of disease burden, especially at higher concentrations".[29] For this reason, the rates of increased mortality that were estimated in the current analysis using the five-cause IER model should be considered a conservative, lower bound, estimate of the mortality impacts due to the modeled sources.

Data that were used in the health analysis include: (1) population data for South Africa, by gender (male/female) and age group in each administrative unit (neighborhood) within the entire modeling domain, (2) baseline mortality rates for South Africa for each cause of death, by gender and age group, (3) concentration response function data, representing the IER model's risk functions (the relative increase in mortality due to an increase in $PM_{2.5}$ exposure concentration) for each cause of death, by gender and age, (4) baseline $PM_{2.5}$ exposures across the modeling domain , and (5) incremental $PM_{2.5}$ exposures due to the 14 modeled sources (model output) for each emissions scenario (2016 actual emissions, and 2020 MES). A detailed description of the health analysis methodology can be found in Appendix B of this report.

[28] RRs developed for all-cause mortality are not directly translatable to South Africa (where mortality rates are higher for a number of non-air pollution related causes). The World Health Organization (WHO) Health Risks of Air Pollution in Europe (HRAPIE) project (2013) experts recommend estimation of the impact of long-term (annual average) exposure to $PM_{2.5}$ on all-cause (natural) mortality in adult populations (age 30+ years) based on a linear concentration response function (CRF), with an RR of 1.062 (95% CI = 1.040, 1.083) per 10 $\mu g/m^3$ increase in exposure (at all levels of baseline $PM_{2.5}$ exposure). Using this all-cause RR (which was developed based on data from adult populations in North America and Europe) would over-estimate the mortality impact in South Africa. Nevertheless, I applied the simple all-cause all-age HRAPIE model to provide an (alternative) *upper-bound* estimate of the mortality impacts due to $PM_{2.5}$ concentration impacts from the 14 modeled sources

[29] Burnett, R.T., et al., *Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter*, Proceedings of the National Academy of Sciences, Sept. 2018, www.pnas.org/cgi/doi/10.1073/pnas.1803222115.

The dispersion model results were used to determine average $PM_{2.5}$ exposure levels for the population within the entire modeling domain (total 2016 population: 20.6 million) for each emission scenario. The population-weighted average incremental $PM_{2.5}$ exposure from all 14 sources combined under the 2016 baseline (actual emissions) scenario was estimated to be 1.45 µg/m^3. For the 2020 MES scenario, an average individual in the modeling domain would be exposed to 0.59 µg/m^3 of $PM_{2.5}$ from all modeled sources, a significant reduction relative to the baseline scenario.

B. Health Analysis Results

The estimated annual mortality for each cause attributable to the $PM_{2.5}$ from all modeled sources is shown in Table 3. Table 4 shows the estimated mortality impacts due to the increase in $PM_{2.5}$ exposure from each modeled source.[30] The results for the baseline (actual emissions) scenario indicate that the 14 sources were responsible for between 305 and 650 early deaths in and around the HPA region during 2016 (95 percent confidence interval.

The three worst offenders were Lethabo power station (57 to 122 early deaths), Kendal power station (46 to 99 early deaths), and Kriel power station (34 to 76 early deaths).

The modeled $PM_{2.5}$ concentration impacts for all sources under the 2020 MES scenario (123 to 263 early deaths) were significantly lower than for the baseline scenario. Implementing the 2020 MES would result in 60 percent fewer deaths per year, preventing early death for between 182 and 388 people in and around the HPA every year. [31]

[30] The $PM_{2.5}$ concentration impacts and associated health impacts due to all sources is less than the sum of the modeled sources. Combining all sources within the model slightly reduces the formation of particulate nitrate.

[31] As an alternative, I applied the HRAPIE experts' recommended method for estimating the impact of long-term (annual average) exposure to $PM_{2.5}$ on all-cause (natural) mortality in adult populations (age 30+ years). The results using the simple all-cause all-age HRAPIE model indicate that between 1,536 and 3,186 deaths (mean; 2,380) occurred in 2016 due to 14 sources. If the 2020 MES were met, the HRAPIE-recommended all-cause mortality model estimates that the 14 sources would be responsible for between 622 and 1,291 (mean: 965) annual deaths. The all-cause HRAPIE mortality model represents an (alternative) *upper-bound* estimate of mortality in the HPA region. However, although informative, as explained in footnote 29 (above), using the all-cause all-age HRAPIE model (which was developed based on data from adult populations in North America and Europe) would over-estimate the mortality impact in South Africa.

Table 3. Estimated Annual Mortality (Additional Deaths/Year), by Cause

	BASELINE			2020 MES		
	MEAN	CI LOW	CI HIGH	MEAN	CI LOW	CI HIGH
IHD	192.2	116.9	305.3	77.4	47.1	123.3
Lung Cancer	21.3	4.8	36.2	8.6	2.0	14.6
Stroke	183.3	56.2	340.1	74.1	22.7	137.5
COPD	29.2	11.4	50.5	11.8	4.6	20.4
Lower Respiratory Infections (children under 5)	28.6	17.6	41.0	11.6	7.2	16.6
Total	**454.7**	**304.5**	**650.2**	**183.6**	**122.9**	**262.6**

Table 4. Estimated Annual Mortality (Additional Deaths/Year), by Source

	BASELINE			2020 MES		
	MEAN	CI LOW	CI HIGH	MEAN	CI LOW	CI HIGH
Arnot	24.7	16.6	35.3	11.0	7.4	15.7
Camden	20.8	14.0	29.7	7.8	5.2	11.1
Duvha	41.3	27.7	59.0	11.7	7.9	16.8
Grootvlei	20.0	13.3	28.6	7.0	4.7	10.0
Hendrina	18.8	12.6	26.8	9.7	6.5	13.9
Kendal	69.2	46.3	99.0	27.7	18.6	39.7
Komati	12.0	8.0	17.1	4.3	2.9	6.2
Kriel	50.7	34.0	72.5	15.4	10.3	22.0
Lethabo	85.1	56.6	121.8	48.1	32.0	68.9
Majuba	37.4	25.1	53.4	14.3	9.6	20.5
Matla	49.4	33.1	70.7	8.4	5.6	12.0
Tutuka	41.8	28.0	59.7	14.2	9.5	20.3
Synfuels	50.3	33.7	72.0	13.7	9.2	19.6
NatRef	5.3	3.5	7.5	1.2	0.8	1.8
ALL SOURCES	**454.7**	**304.5**	**650.2**	**183.6**	**122.9**	**262.6**

Dr. H. Andrew Gray

3 June 2019

Date