The Minimum Emission Standard (MES) Health Benefit Cost Analysis (BCA) Study at Medupi Power Station

DRAFT
APPENDIX TO REPORT
FOR STAKEHOLDER COMMENT

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PRIME AFRICA
CONSULT

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Appendix of Report Draft: For Stakeholder Comment

This document forms an integral part of the full report and should be read in conjunction with the main report

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Prepared for:

Eskom Holdings SOC Ltd

Eskom Holdings SOC Ltd

Megawatt Park

Sunninghill, 2157

Johannesburg, South Africa

Prepared by:

The Factory, 274 Brander Street,
Jan Niemand Park
0186 Pretoria, South Africa
+27 (0)12 348 0317

www.primeafrica.net

Project Manager Contact: Dr Jackie Crafford

j.crafford@primeafrica.net

Authors: Dr Karen Eatwell, Dr Jackie Crafford, Christian Griffiths, Ntlale Mohumutji, Sean Bennett, Valmak Mathebula, Isabella Selzer, Atham Raghunandan*, Dr Mark Zunckel*, Dr Magretha Pierce**

* uMoya-NILU Consulting (Pty) Ltd responsible for CALPUFF modelling and air quality analyses

** BioSwitch Africa provided health evidence advisory and exposure-response functions technical memoranda

1 APPENDIX TO REPORT

1.1 Appendix A: Discreet and Sensitive Receptors

Discrete and Sensitive receptors and AQMS within the modelled domain:

Description	ID_Receptor	X co-ordinate (m)	Y co-ordinate (m)
Eskom Marapong AQMS - Monitoring Station	R_1	564043.96	7383714.82
Eskom Medupi AQMS - Monitoring Station	R_2	554985.15	7374551.69
SAWS Lephalale-NAQI AQMS - Monitoring Station	R_3	573617.23	7380785.92
Mokopane AQMS - Monitoring Station	R_4	701598.05	7327078.46
Thabazimbi AQMS - Monitoring Station	R_5	539646.74	7280276.20
Modimolle AQMS - Monitoring Station	R_6	643847.29	7265609.61
Mobile-Norplats AQMS - Monitoring Station	R_7	541542.32	7258123.21
Smashblock AQMS - Monitoring Station	R_8	529300.47	7258797.68
Bierspruit AQMS - Monitoring Station	R_9	514800.45	7244966.61
ES_Mantserre AQMS - Monitoring Station	R_10	509479.21	7240518.95
Fridge Plant AQMS - Monitoring Station	R_11	516713.06	7237831.41
Hostel AQMS - Monitoring Station	R_12	514190.59	7237432.32
4B Decline AQMS - Monitoring Station	R_13	512648.64	7238763.45
1-Phegelelo Senior Secondary	R_14	563060.27	7384176.92
2-Contractors Village	R_15	561293.06	7383583.06
3-Ditheku Primary School	R_16	562975.84	7384275.27
4-Ditheko primary School	R_17	564690.88	7383857.99
5-Marapong Training Centre	R_18	563086.96	7383464.90
6-Marapong Clinic	R_19	564192.87	7383463.50
7-Tielelo Secondary School	R_20	562969.19	7384034.60
8-Grootegeluk Medical Centre - Community centre	R_21	563209.97	7383420.19
9-Lephalale College	R_22	569911.07	7380729.80
10-Nelsonskop Primary School	R_23	563913.17	7383542.34
11-Hansie En Grietjie Pre-Primary School	R_24	569673.28	7380665.51
12-Sedibeng Special School for the Deaf and Disabilities	R_25	570930.07	7379737.60
13-Kings College	R_26	568333.03	7379207.08
14-Bosveld Primary School	R_27	569400.16	7379307.54
15-Lephalale Medical Hospital	R_28	562937.47	7383633.06
16-Ellisras Hospital	R_29	571712.64	7381272.63
17-Laerskool Ellisras Primary School	R_30	576066.50	7382618.99
18-Hoerskool Ellisras Secondary School	R_31	575189.24	7382497.00
19-Marlothii Learning Academy	R_32	575454.69	7382358.78
20-Hardekool Akademie vir C.V.O	R_33	577372.18	7382410.93
21-Lephalale Clinic	R_34	576043.80	7382373.65
22-Ons Hoop	R_35	573074.97	7392407.88
23-Woudend	R_36	573770.56	7422152.34
24-Ramabara's	R_37	584098.22	7373113.67
25-Ga-Shongoane	R_38	608321.44	7391281.64
26-Bulge River	R_39	570570.94	7332997.73
27-Kaingo Mountain Lodge	R_40	582064.36	7338855.39

Description	ID_Receptor	X co-ordinate (m)	Y co-ordinate (m)
28-Community	R_41	557517.78	7338134.27
29-Kiesel	R_42	517255.71	7348639.09
30-Kremetartpan	R_43	537357.10	7361299.51
31-Mbala Private Camp	R_44	549971.72	7352418.06
32-Steenbokpan	R_45	541767.06	7375229.05
33-Receptor	R_46	535000.63	7391410.32
34-Sandbult	R_47	528615.79	7377834.21
35-Hardekraaltjie	R_48	526176.47	7399998.52
36-Receptor	R_49	560399.30	7395004.97
37-Receptor	R_50	545208.51	7400387.73
38-Receptor	R_51	559689.84	7413300.41
39-Receptor	R_52	583381.64	7409353.03
40-Receptor	R_53	587467.86	7399237.20
41-Ditaung	R_54	605601.90	7401959.87
42-Letlora	R_55	592779.39	7416528.43
43-Receptor	R_56	526898.56	7365393.83
44-Glenover	R_57	516499.93	7360781.12
45-Oxford Safaris	R_58	510472.00	7376086.60
46-Receptor	R_59	518190.18	7387977.95
47-Tholo Bush Estate	R_60	586072.95	7355406.24
48-Receptor	R_61	568867.89	7354020.76
49-Receptor	R_62	599331.14	7360082.91
50-Cheetah Safaris	R_63	537952.03	7340196.11
51-Rhinoland Safaris	R_64	607227.84	7376566.59

1.2 Appendix B: Mortality Memorandum

Addendum: MEMORANDUM

Sulphur Dioxide Air Pollution and Associated Mortality Impacts

Dr Magretha Pierce

Executive Summary

This memorandum constitutes an addendum to the previously completed cost-benefit analysis (CBA and addresses mortality outcomes only associated with ambient air pollution exposure. It documents the exposure-response functions (ERFs) applied in the mortality component of the CBA and provides clarification of their scientific basis, scope, and interpretation. Morbidity outcomes are addressed in a separate addendum and are not duplicated here.

The mortality assessment focuses on short-term (acute) exposure-mortality relationships, consistent with the structure of the underlying CBA, the temporal resolution of available exposure data, and the epidemiological evidence base for Sulphur dioxide (SO_2). Short-term time-series studies capture the triggering or advancement of death among susceptible populations following day-to-day fluctuations in ambient pollutant concentrations. Long-term mortality effects, where robust and pollutant-specific evidence exists, are addressed elsewhere within the broader air pollution assessment framework.

For SO_2, the memo adopts a deliberately conservative approach. While positive associations between short-term SO_2 exposure and daily mortality have been reported in multi-city studies, long-term SO_2 mortality estimates remain less consistent and are subject to greater uncertainty and co-pollutant confounding. SO_2 is therefore treated primarily as an indicator of broader combustion-related pollution mixtures rather than as an isolated causal agent.

The memo also recognises the South African context, including high burdens of underlying disease such as tuberculosis and HIV, which may increase susceptibility to air pollution-related mortality. These vulnerabilities are considered implicitly within all-cause mortality estimates; cause-specific TB or HIV mortality is not modelled separately, in order to avoid double counting.

1. Introduction

This memo serves the purpose to provide information on the Exposure Response Functions (ERFs) which are used in the Cost-Benefit Analysis (CBA) models for the Waterberg power stations. The CBA serves as an update to the CBA undertaken in 2024. The updated CBA will include morbidity and mortality health outcomes. This memorandum addresses mortality outcomes only; morbidity outcomes and associated exposure-response functions are assessed in a separate addendum. The same principles and methodology developed in Naidoo *et al.*

(2018) study, which previously investigated the costs and benefits of mitigating air pollution emissions for 13 Eskom coal-fired plants in the Highveld, are being applied. The Health CBA Model follows the General Principles of the World Health Organisation (WHO, 2016) for performing air pollution health risk assessments (AP-HRA).

The following section provides the background on the exposure-response functions (ERF) methodology. It also provides how it has been updated for the current study on the Waterberg region. Although limitations, as noted in the following sections, exist, they are primarily due to limitations of available scientific knowledge and time constraints within the defined scope.

2. Exposure

Exposure to air pollution is the intersection in time and space between a concentration of air pollution and the presence of a human being. For benefits analyses, exposure is typically assessed at the population level by geographically linking estimates of outdoor pollution concentrations with projected population numbers; these together represent the necessary input to population concentration-response functions for calculating health impacts. The use of ambient air concentrations to represent population exposures is justifiable when the health findings underlying the benefits analysis are similarly based on ambient concentration data and when the outdoor concentrations are correlated with personal exposures. Prospective cohort studies examine differences between cities in mortality among individuals followed over an extended period and the variations in annual (or longer) mean outdoor pollutant concentrations. These studies are believed to address the relationship between chronic exposure and mortality. Epidemiological cohort studies consistently find associations between long-term exposure to outdoor air pollution and a range of morbidity and mortality endpoints (Brunekreef *et al.*, 2021). More recent evaluations by the WHO and the Global Burden of Disease study have suggested that these associations may be nonlinear and may persist at very low concentrations (Burnett *et al*. 2014; Cohen *et al.* 2017; WHO 2013). Systematic reviews of long-term effects of $PM_{2.5}$, PM_{10} continue to support the findings of effects of long-term exposure at low to very low concentrations on mortality. Consistent associations between air pollution and all-cause mortality (Beelen *et al.* 2014a; Cesaroni *et al.* 2014; Raaschou-Nielsen *et al*. 2013; Stafoggia *et al.* 2014) have been reported.

3. All-cause mortality

This provides a measure of all deaths within the population from natural causes. It includes natural deaths from all causes of death as provided in the WHO (2016b) International statistical classification of diseases and related health problems (IDC-10). In South Africa, all-cause mortality makes up 87% of total deaths (StatsSA, 2025). All-cause mortality associated with $PM_{2.5}$ and PM_{10} has high certainty of evidence. Sulphur dioxide (SO_2) is a common atmospheric pollutant generated by geothermal activities. Robust positive associations have been demonstrated between short- and long-term exposure to ambient SO_2 and all-cause mortality, noting that SO_2 often functions as an indicator of broader combustion-related pollution mixtures and that co-pollutant confounding is recognised in the epidemiological literature. All-cause mortality will be obtained from the National Health Research Databases for Health subdistricts within the Waterberg District. This will ensure accurate representation of population health baselines and vulnerabilities.

4. Exposure Response Functions

The World Health Organisation (WHO, 2016) recommends that the health risk in a population associated with air pollution be estimated using exposure-response functions (ERFs). ERFs are based on Relative Risk (RR) estimates derived from primary epidemiological studies. Updates to the WHO (2024) guidelines demonstrated the bulk of studies encompassed European, American and Western Pacific regions, with no studies stemming from Southern Africa (Orellano *et al.,* 2024). The ERF is specific to the joint distribution of covariates in the population from which it was derived and may not apply to populations with different demographics. Individual susceptibility/covariates such as age, sex, pre-existing health conditions (co-morbidities), genetics, lifestyle (smoking status, diet) and socioeconomic status (income, education) can modify the individual response to a given exposure level. An individual's activities (sedentary, exercising) affect physiological factors like breathing rate, which in turn influence the delivered dose of inhaled pollutants. These RR functions estimate the likelihood of health outcomes in a population exposed to a higher level of air pollution compared with a population with a lower exposure level (WHO, 2016). RR is usually expressed as the proportional increase in the assessed health outcome associated with a given increase in pollutant concentrations, measured in $\mu g/m^3$. Ideally, ERF studies and their RRs should be determined from primary epidemiological studies within the exposed population. In the absence of such studies, as in South Africa, the WHO (2016) recommends using ERFs from other countries.

Direct epidemiological evidence for an association between long-term pollutants is mostly based on studies from high-income countries. Compared with low-income and middle-income countries (LMICs), exposure to air pollution is substantially lower in high-income countries and the distribution of co-morbidities and risk factors also differ, limiting direct extrapolation of relative and absolute risks from high-income countries to LMICs. Africa currently has the highest (HIV) and second highest (TB) burden of Human immunodeficiency virus (HIV) and Tuberculosis globally. Significant associations between exposure to air pollution mixtures and HIV/AIDS incidence and mortality rates, with $PM_{2.5}$ and PM_{10} being the primary drivers are evident. The relationship between Pulmonary TB risk and environmental factors, including air pollutants and meteorological conditions, is well-established (You et al., 2016, Popovic et al., 2019, Huangfu et al., 2020). Despite notable progress in the last decades, tuberculosis is still a public health concern in most of the countries within the WHO European Region (WHO, 2025). HIV infection is the most important risk factor for developing tuberculosis in patients already infected with Mycobacterium tuberculosis and tuberculosis is the most common acquired immunodeficiency syndrome (AIDS)-defining condition worldwide. Given the influence of HIV and TB on the susceptibility of individuals to exposures, choosing ERFs that consider the greater vulnerability evident in South African populations is vital. While TB and

HIV increase susceptibility to air pollution-related mortality, cause-specific TB or HIV mortality is not modelled separately, as these vulnerabilities are implicitly captured within all-cause mortality estimates.

Epidemiological assessments of air pollution and mortality distinguish between short-term (acute) exposure effects, typically examined using time-series or case-crossover study designs, and long-term (chronic) exposure effects, most often evaluated using cohort studies (WHO, 2013; Atkinson et al., 2014). Short-term exposure analyses estimate the triggering or advancement of deaths among susceptible individuals following day-to-day fluctuations in ambient pollutant concentrations, whereas long-term exposure analyses reflect the cumulative effects of sustained exposure over extended periods.

This memorandum focuses on short-term exposure-mortality relationships. This approach is consistent with the structure of the underlying cost-benefit analysis, the temporal resolution of the available exposure data, and the current epidemiological evidence base for sulphur dioxide (SO_2). For SO_2, long-term mortality estimates remain less consistent across studies and are subject to greater uncertainty and co-pollutant confounding, whereas short-term associations with daily mortality have been more consistently reported in multi-city analyses (WHO, 2021).

Accordingly, short-term exposure-response functions are applied to estimate mortality impacts associated with acute increases in ambient SO_2 concentrations. These estimates primarily reflect the advancement of death among vulnerable populations, including individuals with pre-existing cardiopulmonary disease, rather than the induction of new disease (WHO, 2013; Atkinson et al., 2014). Long-term mortality impacts, where robust and pollutant-specific evidence exists, are addressed elsewhere (morbidity) within the broader air pollution assessment framework.

Updated ERFs are recommended for all-cause mortality analysis (Table 1). Functions are internationally validated through systematic reviews and meta-analyses and have direct relevance to South African settings. Limpopo’s environmental context, with high levels of mining, biomass and coal burning, informal settlements, unpaved roads, health baseline and limited infrastructure, means both exposure and population sensitivity are elevated. The higher risk estimates for $PM_{2.5}$ and PM_{10} are justified by greater observed vulnerability in low-income and rural populations in South Africa. The SO_2 exposure-response function was retained unchanged from the original analysis, as recent reviews do not provide sufficiently consistent long-term estimates to justify revision, and to avoid potential over-attribution given recognised co-pollutant confounding.

Table 1 Indicator pollutants and relative risks of each for all-cause mortality for Waterberg CBA.

	2024		2025	
Indicator Pollutant	RR or HR per 10 µg/m^3	Ref	RR or HR per 10 µg/m^3	Ref
PM_1	-	-	1.136	Brunekreef et al., 2021
$PM_{2.5}$	1.08	Chen & Hoek, 2020	1.095**	Orellano et al., 2024
PM_{10}	1.04	Chen & Hoek, 2020	1.081**	Orellano et al., 2024
SO_2	1.0059	Orellano et al., 2021	1.0059	Orellano et al., 2021

**WHO updated guidelines

Several studies warn against potential double counting of pollutant effects (co-pollutant confounding effects) when estimating or quantifying health impacts. While health outcomes can be attributed to many different indicator pollutants, using all would result in double counting mixture effects in health impacts as these pollutants are associated with each other (WHO, 2013a, WHO2013b, WHO, 2016a, Malmqvist et al., 2018). In the AP-HRA, a health outcome must be attributed to an individual indicator pollutant.

5. References

Adebayo-Ojo, T.C., Wichmann, J., Arowosegbe, O.O., Probst-Hensch, N., Schindler, C., Künzli, N. (2022). Short-Term Joint Effects of PM_{10}, NO_2 and SO_2 on Cardio-Pulmonary Hospital Admissions in Cape Town, South Africa. International Journal of Environmental Research and Public Health, 19(1), 1326. doi:10.3390/ijerph19011326.

Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C. and Walton, H.A. (2014). Epidemiological time series studies of $PM_{2.5}$ and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax, 69(7), pp.660-665.

Brauer, M., Brook, J.R., Christidis, T., Chu, Y., Crouse, D.L., Erickson, A., Hystad, P., Li, C., Martin, R.V., Meng, J., Pappin, A.J., Pinault, L.L., Tjepkema, M., van Donkelaar, A., Weichenthal, S., Burnett, R.T. (2019). Mortality-Air Pollution Associations in Low-Exposure Environments (MAPLE): Phase 1. Research Report Health Effects Institute, 2019:203.

CER (Centre for Environmental Rights) (2022). The health effects associated with ambient pollution arising from coal and mining in Limpopo. Johannesburg. Available at: https://cer.org.za/wp-content/uploads/2022/05/Health-effects-associated-with-ambient-pollution-2022.pdf.

Chen, J., Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. Environmental International, 143, 105974. doi:10.1016/j.envint.2020.105974.

Dirgawati, M., Hinwood, A., Nedkoff, L., Hankey, G.J., Yeap, B.B., Flicker, L. et al. (2019). Long-Term Exposure to Low Air Pollutant Concentrations and the Relationship with All-Cause

Mortality and Stroke in Older Men. Epidemiology, 30(Suppl. 1), S82-S89. doi:10.1097/EDE.0000000000001034.

Guo, C., Yu, T., Bo, Y., Lin, C., Chang, L.-Y., Wong, M.C.S. et al. (2022). Long-term Exposure to Fine Particulate Matter and Mortality: A Longitudinal Cohort Study of 400,459 Adults. Epidemiology, 33, 917. doi:10.1097/EDE.0000000000001464.

Hanigan, I.C., Rolfe, M.I., Knibbs, L.D., Salimi, F., Cowie, C.T., Heyworth, J. et al. (2019). All-Cause Mortality and Long-Term Exposure to Low Level Air Pollution in the 45 and Up Study Cohort, Sydney, Australia, 2006-2015. Environment International, 126, 762-770. doi:10.1016/j.envint.2019.02.044.

Hvidtfeldt, U.A., Sørensen, M., Geels, C., Ketzel, M., Khan, J., Tjønneland, A. et al. (2019). Long-term Residential Exposure to $PM_{2.5}$, PM_{10}, Black Carbon, NO_2 and Ozone and Mortality in a Danish Cohort. Environment International, 123, 265-272. doi:10.1016/j.envint.2018.12.010.

Huangfu, P., Atkinson, R.W. (2020). Long-term exposure to NO_2 and O_3 and all-cause and respiratory mortality: A systematic review and meta-analysis. Environmental International, 144, 105998. doi:10.1016/j.envint.2020.105998.

Kobayashi, Y., Santos, J.M., Mill, J.G., Griep, R.H., Laniado-Laborín, R., Loftus, C.J., Otmani, G., Provençal, N., Shamsher, P., Zhang, B., et al. (2020). Mortality risks due to long-term ambient sulphur dioxide exposure: large variability of relative risk in the literature. Environmental Science and Pollution Research, 27, 35908-35917. doi:10.1007/s11356-020-07867-5.

Li, Z., Mao, X., Liu, Q., Song, H., Ji, Y., Xu, D., Qiu, B., Tian, D., Wang, J. (2019). Long-Term Effect of Exposure to Ambient Air Pollution on the Risk of Active Tuberculosis. International Journal of Infectious Diseases, 87, 177-184. doi:10.1016/j.ijid.2019.07.027.

Naidoo, N., Crafford, J.G., Mulders, J., Mathebula, V. (2018). The provision of professional, independent consulting services to assist Eskom in compiling applications for renewed postponement of the Minimum Emission Standards: Component 4 Health impact focused cost benefit analyses.

Orellano, P., Kasdagli, M-I., Pérez Velasco, R., Samoli, E. (2024). Long-Term Exposure to Particulate Matter and Mortality: An Update of the WHO Global Air Quality Guidelines Systematic Review and Meta-Analysis. International Journal of Public Health, 69, 1607683. doi:10.3389/ijph.2024.1607683.

Orellano, P., Reynoso, J., Quaranta, N. (2021). Short-term exposure to sulphur dioxide (SO_2) and all-cause and respiratory mortality: A systematic review and meta-analysis. Environmental International, 150, 106434. doi:10.1016/j.envint.2021.106434.

Pope III, C.A., Turner, M.C., Burnett, R.T., Jerrett, M., Gapstur, S.M., Diver, W.R., Krewski, D., Brook, R.D. (2015). Relationships Between Fine Particulate Air Pollution, Cardiometabolic Disorders and Cardiovascular Mortality. Circulation Research, 116, 108-115. doi:10.1161/CIRCRESAHA.116.305060.

Popovic, I., Soares Magalhaes, R.J., Ge, E., Marks, G.B., Dong, G.H., Wei, X., Knibbs, L.D., (2019). A systematic literature review and critical appraisal of epidemiological studies on outdoor air pollution and tuberculosis outcomes. Environ Res. Mar;170:33-45. doi: 10.1016/j.envres.2018.12.011. Epub 2018 Dec 7. PMID: 30557690.

Sawada, N., Nakaya, T., Kashima, S., Yorifuji, T., Hanibuchi, T., Charvat, H. et al. (2022). Long-Term Exposure to Fine Particle Matter and All-Cause Mortality and Cause-Specific Mortality in Japan: The JPHC Study. BMC Public Health, 22, 466. doi:10.1186/s12889-022-12829-2.

StatsSA. (2025). Mortality and causes of death in South Africa: Findings from death notification 2022. Release P0309.3. Available at: https://www.statssa.gov.za/publications/P03093/P030932022.pdf.

Strak, M., Weinmayr, G., Rodopoulou, S., Chen, J., de Hoogh, K. andersen, Z.J., Atkinson, R., Bauwelinck, M., Bekkevold, T., Bellander, T., Boutron-Ruault, M.C., Brandt, J., Cesaroni, G., Concin, H., Fecht, D., Forastiere, F., Gulliver, J., Hertel, O., Hoffmann, B., Hvidtfeldt, U.A., Janssen, N.A.H., Jöckel, K.H., Jørgensen, J.T., Ketzel, M., Klompmaker, J.O., Lager, A., Leander, K., Liu, S., Ljungman, P., Magnusson, P.K.E., Mehta, A.J., Nagel, G., Oftedal, B., Pershagen, G., Peters, A., Raaschou-Nielsen, O., Renzi, M., Rizzuto, D., van der Schouw, Y.T., Schramm, S., Severi, G., Sigsgaard, T., Sørensen, M., Stafoggia, M., Tjønneland, A., Verschuren, W.M.M., Vienneau, D., Wolf, K., Katsouyanni, K., Brunekreef, B., Hoek, G. & Samoli, E. (2021). Long term exposure to low level air pollution and mortality in eight European cohorts within the ELAPSE project: pooled analysis. BMJ, 374, n1904. doi:10.1136/bmj.n1904.

Traini, E., Huss, A., Portengen, L., Rookus, M., Verschuren, W.M.M., Vermeulen, R.C.H. et al. (2022). A Multipollutant Approach to Estimating Causal Effects of Air Pollution Mixtures on Overall Mortality in a Large, Prospective Cohort. Epidemiology, 33, 1422. doi:10.1097/EDE.0000000000001492.

Wang, B., Eum, K.D., Kazemiparkouhi, F., Li, C., Manjourides, J., Pavlu, V., Suh, H., (2020). The impact of long-term $PM_{2.5}$ exposure on specific causes of death: exposure-response curves and effect modification among 53 million U.S. Medicare beneficiaries. Environ Health. Feb 17;19(1):20. doi: 10.1186/s12940-020-00575-0. PMID: 32066433; PMCID: PMC7026980.

World Health Organization (WHO) (2013). *Review of evidence on health aspects of air pollution - REVIHAAP Project: Final technical report.* Copenhagen: WHO Regional Office for Europe.

World Health Organisation (WHO) (2016a). Health risk assessment of air pollution: General principles. Copenhagen: WHO Regional Office for Europe.

World Health Organisation (WHO) (2016b). International Statistical Classification of Diseases and Related Health Problems, 10th Revision. Available at: http://apps.who.int/classifications/icd10/browse/2016/en.

World Health Organization (WHO) (2021). WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization.

You S, Tong YW, Neoh KG, Dai Y, Wang CH., (2016). On the association between outdoor $PM_{2.5}$ concentration and the seasonality of tuberculosis for Beijing and Hong Kong. Environ Pollut. Nov; 218:1170-1179. doi: 10.1016/j.envpol.2016.08.071. Epub 2016 Aug 29. PMID: 27595179.

1.3 Appendix C: Morbidity Memorandum

Addendum: MEMORANDUM

Sulphur Dioxide Air Pollution and Associated Morbidity Impacts

Dr Magretha Pierce

Executive Summary

This memorandum serves as an addendum to the cost-benefit analysis (CBA) previously undertaken and documents the selection, application, and verification of exposure-response functions (ERFs) used to estimate morbidity outcomes associated with ambient Sulphur dioxide (SO_2) exposure. The purpose of this addendum is to enhance transparency, consistency, and defensibility of the health evidence underpinning the morbidity component of the CBA; it does not revise model structure, re-estimate impacts, or alter the results of the original analysis.

The memo focuses exclusively on morbidity outcomes, including respiratory hospital admissions (ICD-10 J00-J99, including asthma), asthma-related emergency visits or hospitalisations, ischemic stroke admissions, and non-fatal cardiovascular hospital admissions. These outcomes were selected based on relevance to short-term SO_2 exposure, availability of peer-reviewed epidemiological evidence, and compatibility with routinely collected health data. The ERFs applied in the CBA are shown to be consistent with, and conservative relative to, estimates reported in the peer-reviewed literature.

The memo also documents additional morbidity outcomes for which epidemiological evidence exists, but which were not explicitly quantified within the CBA, including chronic obstructive pulmonary disease exacerbations, adverse birth outcomes, tuberculosis-related vulnerability, and diabetes as a susceptibility modifier. These outcomes are discussed to demonstrate completeness of health consideration and to highlight potential underestimation, while avoiding over-attribution or double counting.

Recognising the epidemiological characteristics of SO_2, the memo adopts a conservative interpretation of the evidence, noting that SO_2 often functions as an indicator of broader combustion-related pollution mixtures and that co-pollutant confounding is an important consideration. The morbidity estimates supported by this memo should therefore be interpreted as reflecting short-term exposure effects within this broader pollution context.

1. Introduction

Sulphur dioxide (SO_2) is a major air pollutant released during the combustion of coal in thermal power stations. Coal-fired electricity generation facilities, including the Eskom Medupi and Matimba power stations in South Africa's Limpopo Province, emit substantial quantities of SO_2 through their smokestacks (Chersich *et al*., 2018). SO_2 is a colourless, pungent gas that, once released into the atmosphere, can undergo chemical transformation to form secondary pollutants, including sulphate aerosols and acid rain, which extend pollution impacts far beyond the immediate facility location (Atkinson *et al*., 2014). Within the broader airshed influenced by Medupi and Matimba, ambient SO_2 concentrations may episodically exceed national ambient air quality standards, particularly under unfavourable dispersion conditions. These exceedances are associated in the epidemiological literature with acute and, to a lesser extent, chronic morbidity outcomes, especially affecting respiratory and cardiovascular systems. This memo synthesises peer reviewed epidemiological evidence linking ambient SO_2 exposure to selected morbidity indicators that are captured within South Africa's District Health Information System (DHIS2), published literature and reports. The intent is to support the selection of conservative, evidence based exposure-response functions (ERFs) for use in the associated cost-benefit analysis (CBA), while explicitly acknowledging uncertainty and co-pollutant confounding

2. Definition and Concept of Morbidity

Morbidity refers to the burden of disease, including incidence and prevalence of illness within a defined population. Unlike mortality, which measures death, morbidity captures the full spectrum of non-fatal health outcomes—including new diagnoses, hospitalisations, symptom exacerbations, disability and loss of function—that affect population health and wellbeing (World Health Organisation, 2019). Morbidity is typically measured as:

⇒ Incidence: The number of new cases of disease arising in a defined population within a specified time period (e.g., new pneumonia diagnoses per 1,000 children under 5 years annually).

⇒ Prevalence: The total number of existing disease cases at a particular point or period in time (e.g., the proportion of adults living with diabetes at the time of survey).

⇒ Hospitalisation rates: The frequency of inpatient separations (admissions, discharges, transfers and deaths) for specific diagnoses.

⇒ Outpatient attendance: The number of primary health care (PHC) clinic visits for acute or chronic disease management.

In air pollution epidemiology, SO_2 exposure has been most consistently associated with acute morbidity outcomes, particularly short-term respiratory and cardiovascular events, while evidence for chronic disease onset is more heterogeneous and pollutant specific (Orellano *et al.*, 2021; Al Ahad *et al.,* 2024) Quantifying morbidity enables health systems and the environmental health impacts of the disease burden not captured by mortality statistics alone to be determined, thereby providing a more complete picture of population health impacts.

3. Health Vulnerability and South African Context in The Medupi-Matimba 300 km² Study Area

Health vulnerability describes the differential susceptibility of individuals and populations to adverse health effects resulting from a combination of biological, socioeconomic and environmental factors (Padhi *et al.,* 2024). In South Africa, populations residing within 300 km of major coal-fired power stations experience heightened vulnerability to SO_2-related morbidity for several intersecting reasons:

Socioeconomic vulnerability: Communities surrounding Medupi and Matimba are characterised by high rates of poverty, unemployment and informal settlement housing, with limited access to indoor air filtration, ventilation and air-conditioning systems (Chersich *et al*., 2018). Poor housing quality increases prolonged indoor exposure to outdoor SO_2 pollution that penetrates inadequately sealed structures.

Pre-existing disease burden: The study area has high prevalence of HIV infection (estimated 15-25% in some health subdistricts), tuberculosis co-infection and chronic conditions including hypertension, diabetes and chronic obstructive pulmonary disease (COPD). These pre-existing conditions amplify the respiratory and cardiovascular effects of SO_2 exposure (Padhi *et al*., 2024).

Age and developmental vulnerability: Young children (under 5 years) and adolescents have rapidly developing respiratory systems and spend more time engaging in outdoor physical activity, thereby increasing their exposure to ambient SO_2. Pregnant women are vulnerable to SO_2-related intrauterine growth restriction and preterm birth (Wilkie *et al*., 2024). Elderly populations (>60 years) have reduced lung function reserves and increased cardiovascular fragility (Zhang et al., 2023).

Healthcare system limitations: Health facilities in resource-limited settings around Medupi and Matimba often have limited capacity for advanced diagnostics, chronic disease management, rehabilitation and mental health services, thereby reducing the ability to detect and treat SO_2-related morbidity early (Al Ahad *et al.*, 2024).

Environmental cumulative burden: Beyond SO_2, populations in the study area are exposed to multiple air pollutants (particulate matter, nitrogen dioxide, ozone) from coal combustion, traffic, and biomass burning, creating a cumulative pollution burden that exceeds what any single-pollutant analysis captures (Nascimento *et al.,* 2020).

These vulnerabilities do not imply that SO_2 acts in isolation; rather, they indicate that SO_2 may contribute to morbidity within a broader context of cumulative air pollution exposure and social disadvantage.

4. Health Data Sources Relevant to SO_2 Morbidity

South Africa's National Department of Health Information System (DHIS2) database aggregates routine health service data from all public sector health facilities, capturing indicators including outpatient visits by diagnosis (ICD-10 coded), hospitalisations, lengths of stay and disease-specific clinical outcomes. DHIS2 data are collected at facility, subdistrict and district levels and are available on a monthly, quarterly and annual basis.

The National Health Laboratory Service (NHLS) provides aggregated laboratory test results (e.g., HbA1c for diabetes screening, troponin-T for acute cardiac injury, CD4 counts for HIV monitoring) that can be linked to patient residence and used as proxies for disease incidence and prevalence.

While DHIS2 and NHLS data are suitable for identifying temporal and spatial patterns in morbidity, they do not capture individual level exposure histories and should therefore be interpreted as indicators of population level associations rather than causal proof.

5. Selected SO_2-Related Morbidity Outcomes

The following paragraphs summarise the key morbidity outcomes and their linkages to SO_2 exposure:

5.1 Acute Lower Respiratory Infections and Pneumonia in Children Under 5

Short-term increases in ambient SO_2 concentrations have been associated with increases in acute respiratory infections, including pneumonia, in young children. Time-series studies report relative increases in paediatric respiratory admissions per interquartile range or per 10 $\mu g/m^3$ increase in daily SO_2, after adjustment for seasonality and meteorological factors (Nascimento *et al*., 2020; Liu *et al.,* 2022). These findings support the use of child pneumonia incidence as a sensitive but non-specific indicator of short-term air-pollution impacts, recognising that SO_2 effects cannot be fully disentangled from co-pollutants.

5.2 Respiratory Hospital Admissions (ICD-10 J00-J99 Derived Indicator)

Respiratory diseases as a whole—including acute bronchitis, bronchiolitis, pneumonia, asthma exacerbations and chronic obstructive pulmonary disease—are captured within ICD-10 J-codes. The DHIS2 indicator "inpatient respiratory admission rate" (derived from hospital discharge summaries with primary diagnosis in ICD-10 range J00-J99) represents the total number of inpatient separations (discharges, deaths and transfers) with a respiratory diagnosis. Systematic reviews and meta-analyses indicate small but statistically significant increases in respiratory hospital admissions associated with short-term SO_2 exposure, typically on the order of 1-3% per 10 $\mu g/m^3$ increase in daily concentrations (Al Ahad *et al*., 2024; Zhou *et al*., 2022). These effect sizes are modest and should be interpreted as marginal contributions within a multi-pollutant exposure environment.

5.3 Mental Health Condition Treatment Rates

Recent cohort and meta-analytic studies suggest associations between long-term SO_2 exposure and increased risk of depression and anxiety disorders (Ahad *et al*., 2023; Song *et al*., 2025). This evidence is considered emerging. Associations are biologically plausible but remain subject to residual confounding and exposure misclassification. The DHIS2 indicator "PHC mental health condition Rx rate" captures the proportion of PHC clients treated for mental health conditions (including depression, anxiety, psychosis and substance abuse disorders) per total PHC attendance.

5.4 Tuberculosis Outcomes

Tuberculosis remains a major contributor to morbidity and mortality in South Africa, particularly in settings with high HIV prevalence and socioeconomic vulnerability. Emerging epidemiological evidence suggests that exposure to ambient air pollution, including sulphur dioxide, may exacerbate TB disease progression and adversely affect treatment outcomes, including among patients with drug-resistant TB. A prospective cohort study has reported increased risks of treatment failure and mortality among DR-TB patients associated with higher ambient SO_2 exposure (Zhao *et al.*, 2024). These findings are biologically plausible, given evidence that SO_2 induces airway inflammation and impairs immune responses relevant to mycobacterial control. However, the available evidence does not support directly attributing TB incidence or DR-TB emergence to SO_2 exposure in a manner suitable for standalone exposure-response modelling. TB outcomes are therefore not monetised separately in the present cost-benefit analysis. Instead, TB prevalence is considered an important vulnerability factor that may increase the severity, duration, and cost of pollution-related respiratory morbidity. In settings with a high burden of tuberculosis, including drug-resistant TB, SO_2-related health impacts are reflected through worsened clinical outcomes and increased healthcare utilisation within measured respiratory and cardiovascular morbidity endpoints, including hospital admissions and length of stay; TB is therefore treated as a susceptibility-modifying condition rather than a separately monetised outcome.

5.5 Type 2 Diabetes Incidence and Prevalence

Yang et al. (2020) conducted a large cohort study examining long-term exposure to ambient air pollution and risk of type 2 diabetes mellitus, finding a hazard ratio of 1.06 (95% CI 1.00-1.13), corresponding to a 6% increase in diabetes incidence per unit increase of 1 $\mu g/m^3$ in SO_2. The DHIS2 indicator (or NHLS lab-based proxy) "Fasting Plasma Glucose / HbA1c - type 2 diabetes" captures prevalence and new diagnoses. The mechanism linking SO_2 to diabetes likely involves systemic inflammation, oxidative stress and impaired pancreatic beta-cell function (Yang *et al.*, 2020). However, the evidence linking SO_2 specifically to diabetes incidence is less consistent than for particulate matter, with reported effect sizes being small.

Diabetes prevalence in the study area is an important contextual factor that may increase susceptibility to pollution-related cardiovascular and respiratory morbidity, as well as healthcare utilisation and costs.

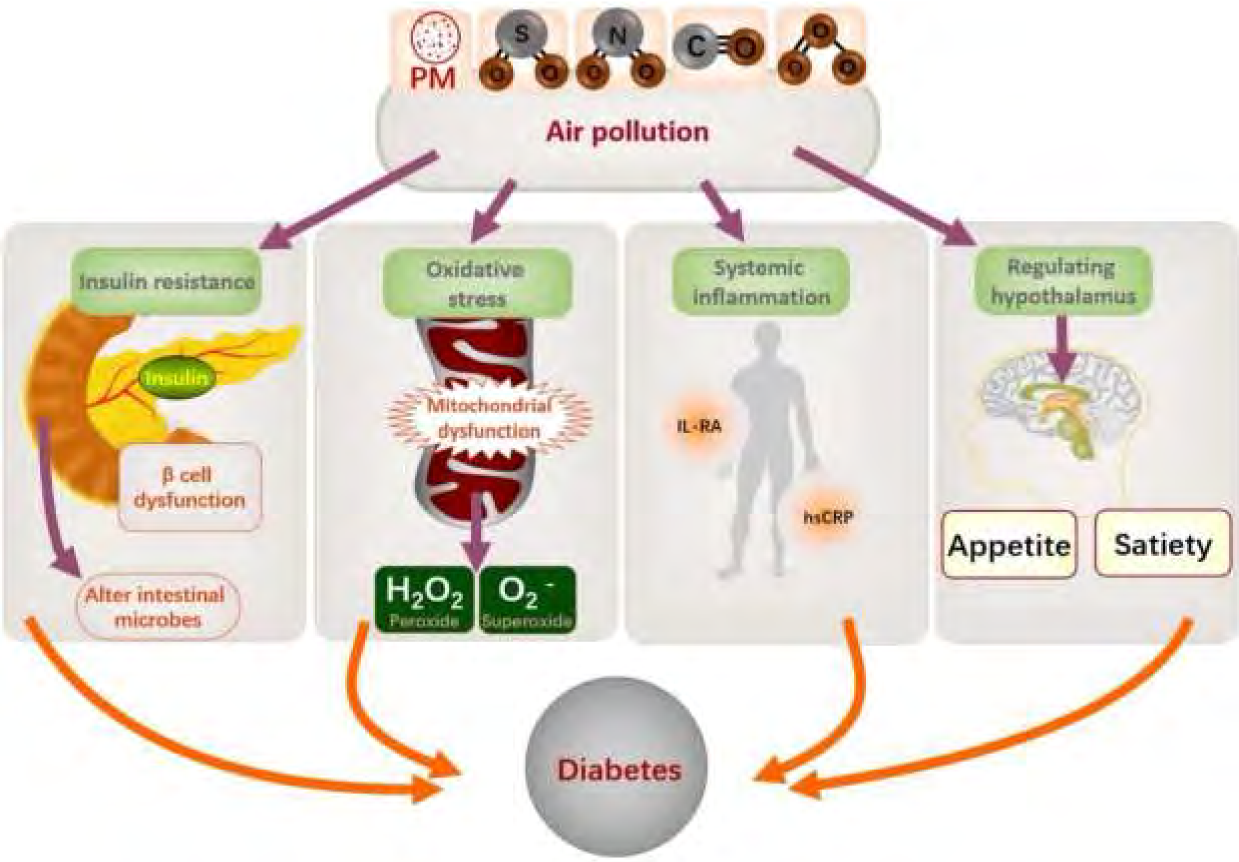

Figure 1   Mechanisms of Diabetes (Type 2) health impact by air pollution.

5.6 Cardiovascular Events (AMI/ACS)

Troponin-T and high-sensitivity troponin-I are biomarkers of acute myocardial injury and are used to diagnose acute myocardial infarction and acute coronary syndromes. Short-term SO_2 exposure has been associated with increased hospital admissions for acute myocardial infarction and other acute coronary events in multicity timeseries analyses (Mustafić *et al.*, 2012; Zhang *et al.*, 2014). Reported relative risks are generally below 1.05 per 10 µg/m^3 increase. Evidence supports SO_2 as a potential trigger for acute cardiovascular events, although the magnitude of effect is small and is subject to confounding by correlated pollutants.

5.7 Adverse Birth Outcomes

The effects of adverse birth outcomes can persist for a person's entire life (Bianchi and Restrepo, 2022, Paret *et al*., 2014; Gluckman *et al*., 2005). PTB is the main cause of death in newborn babies and is associated with a high risk of childhood disability (Howson *et al.,* 2013). Birth weight is an important indicator of foetal growth, development, and nutritional status; low birth weight is also associated with low economic and social development in the given country or region. Considered a chronic disease, low birth weight is one of the major risk factors associated with global disease burden (Bianchi and Restrepo, 2022). Multiple studies have examined associations between ambient SO_2 exposure during pregnancy and adverse birth outcomes. Meta-analyses report associations between maternal SO_2 exposure during pregnancy and increased risk of low birth weight and preterm birth, particularly with higher exposure contrasts or trimester-specific peaks (Li *et al.,* 2017; Lin *et al.,* 2004). The evidence base for birth outcomes is among the stronger morbidity pathways for SO_2, though effect estimates vary across exposure metrics and study settings.

The DHIS2 indicator "Live birth under 2500 g in facility rate" captures the proportion of infants born weighing less than 2500 g, which includes both preterm and intrauterine growth-restricted infants. SO_2-induced placental inflammation and oxidative stress impair fatal growth and trigger premature labour. In the study area, pregnant women exposed to elevated SO_2 would experience increased risk of adverse birth outcomes, with corresponding increases in neonatal intensive care admissions and long-term child health complications (Li *et al*., 2017).

6. SO_2 Exposure-Response Functions (ERFs)

Exposure-response functions (ERFs) quantify the relationship between changes in ambient SO_2 concentrations and changes in the risk of specific health outcomes. ERFs used in this assessment are derived from peer-reviewed epidemiological studies, including time-series, case-crossover and cohort designs, and are expressed as relative risks, hazard ratios, or odds ratios per defined increment in SO_2 concentration.

The proposed ERFs selected for quantitative application in the cost-benefit analysis are presented in bold in Table 1A. Selection is based on the methodological quality of the underlying studies, relevance of the exposure window, consistency of findings across multiple settings and the availability of compatible baseline health data.

Additional ERFs from the published literature are presented for comparison and contextual interpretation in Table 1B, but are not applied quantitatively, either due to emerging evidence, overlapping health endpoints, or heightened susceptibility to co-pollutant confounding.

Table 1A Core SO_2 exposure-response functions for morbidity outcomes.

Morbidity outcome	Exposure window	ERF	Reference
Respiratory hospital admissions (ICD-10 J00-J99, incl. asthma)	Short-term (lag 0-1 days)	RR = 1.07 (95% CI: 1.021-1.120)	Zhou *et al.* (2022)
Asthma emergency visits / hospitalisations	Short-term (same day-lag 1)	RR = 1.030 (95% CI: 1.010-1.050)	Meng *et al.* (2021)
Ischaemic stroke hospital admissions (non-fatal)	Short-term (lag 0-1 days)	RR = 1.0127 (95% CI: 1.0034-1.0221)	Zhang *et al.* (2020)
Cardiovascular hospital admissions (non-fatal)	Short-term (lag 0-3 days)	RR = 1.02 (95% CI: 1.004-1.032)	Bell *et al.* (2014)

Table 1B Supportive/contextual SO_2 exposure-response functions for morbidity outcomes.

Morbidity outcome	Exposure window	ERF[1]	Reference
COPD exacerbations	Short-term	RR = 1.03 (95% CI: 0.995-1.058)	Wang *et al.* (2024)
Adverse birth outcomes (preterm birth, low birth weight)	Prenatal	RRs = 1.02-1.10 across studies	Stieb *et al.* (2012); Sun *et al.* (2023)
Tuberculosis severity & DR-TB treatment outcomes	Chronic	HR ≈ 1.20-1.40	Zhao *et al.* (2024)
Diabetes mellitus (Type 2)	Long-term	HR = 1.06 (95% CI: ~1.01-1.11)	Yang *et al.* (2020)

7. Conclusion

Sulphur dioxide emissions from coal-fired power stations such as Medupi and Matimba pose risks to population health through multiple morbidity pathways. Evidence-based exposure-response functions, coupled with DHIS2 health indicator data, enable quantification of excess respiratory, mental health, cardiovascular, infectious disease and maternal-neonatal outcomes attributable to elevated SO_2 concentrations in the 300 km^2 study area. Integration of air quality monitoring, health system data and epidemiological evidence provides a framework for health impact assessment, cost-benefit analysis of pollution control interventions and prioritisation of public health responses to protect community health in coal-fired power station impact zones.

[1] RR = relative risk; HR = hazard ratio; CI = confidence interval

8. References

Ahad, A.M., Padhi, B.K. and Gaidhane, A.M., 2023. Ambient air pollution and mental disorders: a global systematic review and meta-analysis with focus on sulfur dioxide. Environmental Research, 228, 115858.

Al Ahad, A.M., Demšar, U., Sullivan, F. and Kulu, H., 2024. Long-term exposure to sulfur dioxide and hospital admissions for respiratory diseases: a systematic review and meta-analysis. Environmental Research.

Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C. and Walton, H.A., 2014. Epidemiological time series studies of $PM_{2.5}$ and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax, 69(7), pp.660-665.

Bianchi ME and Restrepo JM. (2022) Low Birthweight as a Risk Factor for Non-communicable Diseases in Adults. Front. Med. 8:793990. doi: 10.3389/fmed.2021.793990

Cao, Y., Liu, H., Zhang, L., Li, C., Wang, J., Chen, R., Chen, X. and Kan, H., 2022. Short-term exposure to ambient air pollution and length of hospital stay for respiratory diseases: a multi-city time-series study in China. Science of the Total Environment, 845, 157267.

Chersich, M.F., Wright, C.Y., Venter, F. and Masilela, N., 2018. Associations between ambient air pollution and adverse health outcomes in HIV-infected adults: a cohort study in Johannesburg, South Africa. International Journal of Environmental Research and Public Health, 15(9), 1880.

Dugandzic, R., Dodds, L., Stieb, D. and Smith-Doiron, M., 2006. The association between low level exposures to ambient air pollution and term low birth weight: a retrospective cohort study. Environmental Health, 5, 3. https://doi.org/10.1186/1476-069X-5-3

Gluckman PD, Cutfield W, Hofman P, Hanson MA. The fetal, neonatal, and infant environments-the long-term consequences for disease risk. Early Hum Dev. 2005 Jan;81(1):51-9. doi: 10.1016/j.earlhumdev.2004.10.003. Epub 2004 Nov 19. PMID: 15707715.

Li, X., Huang, S., Jiao, A., Yang, X., Yun, J., Wang, Y., Xue, X., Chu, Y., Liu, F., Liu, Y. and Lu, Y., 2017. Association between ambient fine particulate matter and preterm birth or term low birth weight: an updated systematic review and meta-analysis. Environmental Pollution, 227, pp.596-605.

Lin, C.M., Lee, P.C., Teng, S.W., Chou, H.C., Hwang, B.F., Tsai, C.S. and Chen, P.C., 2004. Association between maternal exposure to elevated ambient sulfur dioxide during pregnancy and term low birth weight. Environmental Research, 96(1), pp.41-50.

Liu, P.H., Huang, K.C., Tseng, Y.L., Chiu, I.M., Pan, H.Y. and Cheng, F.J., 2022. Association between air pollution and risk of hospital admission for pediatric pneumonia in a tropical city, Kaohsiung, Taiwan. Aerosol and Air Quality Research, 22, 220121.

Liu, F., Wu, J., Gao, Z., Li, S., Zhang, Y., Chen, G., Guo, Y. and Zeng, Y., 2023. Short-term exposure to ozone, nitrogen dioxide and sulfur dioxide and hospital admissions for lower respiratory infections among children: a time-series study in Guangzhou, China. Ecotoxicology and Environmental Safety, 263, 115250.

Mustafić, H., Jabre, P., Caussin, C., Murad, M.H., Escolano, S., Tafflet, M., Perier, M.C., Marijon, E., Vernerey, D., Empana, J.P. and Jouven, X., 2012. Main air pollutants and myocardial infarction: a systematic review and meta-analysis. The Journal of the American Medical Association. 307(7), pp.713-721.

Nascimento, A.P., Santos, J.M., Mill, J.G., Albuquerque, T.T.A., Reis Júnior, N.C., Reisen, V.A. and Pagel, É.C., 2020. Association between the incidence of acute respiratory diseases in children and ambient concentrations of SO_2, PM_{10} and chemical elements in fine particles. Environmental Research, 188, 109619.

Orellano, P., Quaranta, N., Reynoso, J., Balbi, B. and Vasquez, J., 2021. Short-term exposure to sulfur dioxide (SO_2) and all-cause and cause-specific mortality: a systematic review and meta-analysis. Environment International, 146, 106219.

Padhi, B.K., Khatib, M.N., Ballal, S., Sahu, R., Acharya, K., Agho, K.E., Gaidhane, S., Verma, R.K., Goel, A., Kumar, A. and Ahad, A.M., 2024. Association of exposure to air pollutants and risk of mortality among people living with HIV: a systematic review. BMC Public Health, 24, 3251.

Parets, S.E., Conneely, K.N., Kilaru, V., Menon, R., Smith, A.K. and Fortunato, S.J., 2014. Preterm birth and its long-term effects: methylation to mechanisms. American Journal of Medical Genetics Part B: Neuropsychiatric Genetics, 165B (2), pp.192-204.

Shah, A.S.V., Langrish, J.P., Nair, H., McAllister, D.A., Hunter, A.L., Donaldson, K., Newby, D.E. and Mills, N.L., 2013. Global association of air pollution and heart failure: a systematic review and meta-analysis. The Lancet, 382(9897), pp.1039-1048.

Song, J., Wilker, E.H., Mostofsky, E., Mittleman, M.A., Schwartz, J., Koutrakis, P. and Kioumourtzoglou, M.A., 2025. Long-term exposure to low-concentration sulfur dioxide and risk of depressive and anxiety disorders: findings from a large prospective cohort. Environment International.

Sun, D., Li, H., Zhang, Y., Wang, Y., Chen, X., Liu, Q., Wang, L. and Zhou, M., 2024. Short-term exposure to sulfur dioxide and risk of AIDS-related death in people living with HIV: a case-crossover study in China. Cited within: Padhi, B.K., Khatib, M.N., Ballal, S., Sahu, R., Acharya, K., Agho, K.E., Gaidhane, S., Verma, R.K., Goel, A., Kumar, A. and Ahad, A.M., 2024. Association of exposure to air pollutants and risk of mortality among people living with HIV: a systematic review. BMC Public Health, 24, 3251.

World Health Organization, 2019. Monitoring health for the Sustainable Development Goals (SDGs). Geneva: World Health Organization.

Yang, Y., Li, R., Li, W., Wang, M., Cao, Y., Wu, Z., Guo, C., Chen, R. and Kan, H., 2020. Long-term exposure to ambient sulfur dioxide and risk of type 2 diabetes mellitus: a cohort study. Environmental Pollution.

Zhang, X., Li, J., Wang, Q., Shen, H., Chen, G., Zhang, Y., Zheng, C., Li, B., Jiang, S., Wang, H. and Zhao, X., 2014. Short-term effects of sulfur dioxide on hospital admissions for acute myocardial infarction: a multi-city time-series study in China. Environmental Research, 135, pp.456-463.

Zhao, C.N., Xu, Z., Wang, P., Liu, J., Wang, R., Pan, H.F. and Bao, F., 2024. Associations between air pollutants and acute exacerbation of drug-resistant tuberculosis: evidence from a prospective cohort study. BMC Infectious Diseases, 24(1), 121.

Zhou, X., Gao, Y., Wang, D., Chen, W. and Zhang, X., 2022. Association between sulfur dioxide and daily inpatient visits with respiratory diseases in Ganzhou, China: a time series study based on hospital data. Frontiers in Public Health, 10, 854922.

Wilkie, A., Luben, T., Rappazzo, K., Foley, K., Woods, C., Serre, M., Richardson, D. and Daniels, J., 2024. Long-term ambient sulfur dioxide exposure during gestation and preterm birth in North Carolina, 2003-2015. Atmospheric Environment, 333, 120669.

Yang, H., Huang, J., Li, L., Xu, C., Li, Z., Zhang, W., Wang, Y., Wang, S., Liu, X., Wang, G. and Wang, Y., 2021. Short-term effects of air pollutants on hospital admissions for respiratory diseases among children: a time-series study in China. Environmental Research, 198, 111253.

6.4 Appendix D: Dispersion modelling Memorandum

DISPERSION MODELLING TECHNICAL MEMORANDUM IN SUPPORT OF THE MINIMUM EMISSION STANDARD (MES) HEALTH BENEFIT COST ANALYSIS (BCA) STUDY AT MEDUPI POWER STATION

Draft
12 January 2026

uMOYA-NILU

Report issued by:

uMoya-NILU Consulting (Pty) Ltd
P O Box 20622
Durban North, 4016
South Africa

Report issued to:

Prime Africa Consult
The Factory, 274 Brander Street,
Jan Niemand Park, 0186
Pretoria, South Africa

Report Details

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Prepared by:	uMoya-NILU Consulting (Pty) Ltd, P O Box 20622, Durban North 4016, South Africa
Authors:	Atham Raghunandan and Mark Zunckel

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GLOSSARY OF TERMS AND ACRONYMS

DEA	Department of Environmental Affairs
DFFE	Department of Forestry, Fisheries and the Environment
FGD	Flue-gas desulphurisation
g/s	Grams per second
kPa	Kilo Pascal
MES	Minimum Emission Standards
mg/Nm^3	Milligrams per normal cubic meter refers to emission concentration, i.e. mass per volume at normal temperature and pressure, defined as air at 20ºC (293.15 K) and 1 atm (101.325 kPa)
NAAQS	National Ambient Air Quality Standards
USEPA	United States Environmental Protection Agency
µm	Micro meter (1 µm = 10^{-6} m)

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1. INTRODUCTION

Prime Africa Consult has been appointed by Eskom Holdings SOC Ltd (Eskom) to perform the Minimum Emission Standard (MES) Health Benefit Cost Analysis (BCA) Study at Medupi Power Station. In support of and as input to the BCA Study, uMoya-NILU Consulting was sub-contracted to model, quantify and document the spatial distribution of ambient SO_2 concentrations and their secondary particulate matter (PM_{10} and $PM_{2.5}$) effects from Medupi and Matimba Power Stations under five emission-abatement and operational scenarios. These scenarios include modelling Medupi emissions only and modelling emissions from Medupi and Matimba together (cumulatively). All modelling complies with the DFFE Code of Practice for Air Dispersion Modelling (DEA, 2014a) and is suitable for use as inputs to Prime Africa's Health BCA Study.

This dispersion modelling memorandum includes model outputs and describes the model configuration, inputs, the treatment of secondary PM formation and uncertainty analysis. Outputs from this dispersion modelling study have been drawn into the Health BCA Report (Prime Africa Consult, 2025).

2. TERMS OF REFERENCE

Scope of Work

Model Configuration

- Use US-EPA approved version of CALPUFF coupled with TAPM or equivalent mesoscale meteorology.
- Define model domains and receptor grids consistent with the 2024 Waterberg modelling (4 356 km² and 11 664 km² domains).

  [*Note: The TAPM and CALPUFF modelling domains have been reconfigured to accommodate a much larger focus area. TAPM is set-up in a nested configuration of two domains, where the outer domain is 720 km by 720 km at a 24 km grid resolution and the inner domain is 360 km by 360 km at a 12 km grid resolution. The CALPUFF modelling domain now covers an area of 108 900 km^2, where the domain extends 330 km (west-east) by 330 km (north-south). It consists of a uniformly spaced receptor grid with 1.25 km spacing, giving 69 696 grid cells (264 x 264 grid cells).*]
- Confirm stack parameters, emission rates and physical characteristics with Prime Africa and Eskom before each model run.
- Model SO_2 dispersion and secondary PM formation resulting from atmospheric oxidation of SO_2; other pollutants are held constant.
- Baseline Medupi and Matimba emissions modelled in 2024 will be reused and not re-modelled, unless otherwise agreed with Eskom.
- CALPUFF simulations will include both Medupi-only, Matimba-only and cumulative for Medupi–Matimba.

Deliverables

- Model setup and input documentation (model domains, meteorology, emissions, assumptions).

  [*Model setup and input files will be available upon request; configuration of model and modelling domain for meteorological and dispersion model is discussed in Section 6; stack and fugitive emissions and emission parameters are presented in Section 5; assumptions are listed in Section 9*]
- Complete CALPUFF model runs for SO_2 and associated secondary PM outputs (24-hour and annual averages) for all agreed scenarios.

  [*Model runs are complete for all scenarios*]
- Excel data sets (latitude, longitude, concentration) for import into GIS exposure datasets aligned to municipal wards).

  [*Data sets were sent to Prime Africa Consult*]
- Isopleth maps (annual average SO_2 and secondary PM concentrations) for inclusion in the Health CBA report.

  [*Presented and discussed in Section 7.3*]
- Technical memorandum describing model configuration, secondary PM formation treatment and uncertainty analysis.

  [*Model configuration – Section 6; secondary PM formation (SO_2 oxidation rates, secondary PM yield factors and chemical transformation settings) – Section 6.3; uncertainty analysis – Section 8.2. A concise methodology note incorporating these sections is Presented in Section 10*]

- Preparation of a concise methodology note (as per uMoya-NILU proposal) forming part of the Technical Memorandum.
  [*A concise methodology note is Presented in Section 10*]
- Support to Prime Africa during two public or authority meetings (virtual or in-person).
  [*To be done*]
- Preparation of responses to comments following the public-review period.
  [*To be done*]
- Participation in one technical workshop and up to two Steering Committee meetings to present modelling results.
  [*To be done*]

Quality and Standards

- Comply with the DEA Code of Practice for Air Dispersion Modelling (2014).
- Ensure inputs and assumptions are consistent with Eskom's 2024 CALPUFF datasets and modelling architecture.
- Document all assumptions related to SO_2 oxidation rates, secondary PM yield factors and chemical transformation settings.
- Apply internal uMoya-NILU QA/QC review before submission to Prime Africa.

3. LOCATION OF POWER STATIONS, LAND USE CONTEXT AND RECEPTOR IDENTIFICATION

3.1 Location

Medupi and Matimba are located in the Waterberg-Bojanala Priority Area, in the Waterberg District Municipality and are about 6 km apart. They are also located west-southwest and west of the town of Lephalale respectively. Medupi is on the Farm Naauwontkomen about 16 km from Lephalale. Matimba is on the Farm Grootestryd about 13 km from Lephalale. Their relative location is illustrated in Figure 3-1.

3.2 Description of surrounding land use

The DFFE Code of Practice for Air Dispersion Modelling in Air Quality Management in South Africa (DEA, 2014a) recommends the Land Use Procedure as sufficient for determining the urban/rural status of a modelling domain. The classification of the study area as urban or rural is based on the Auer method (Auer, 1978), as specified in the USEPA guideline on air dispersion models (USEPA, 2005). From the Auer's method, areas typically defined as rural include residences with grass lawns and trees, large estates, metropolitan parks and golf courses, agricultural areas, undeveloped land and water surfaces. An area is defined as urban if it has less than 35% vegetation coverage or it falls into one of the use types in Table 3-1.

Table 3-1: Land types, use and structures and vegetation cover

Type	Use and Structures	Vegetation
I1	Heavy industrial	Less than 5 %
I2	Light/moderate industrial	Less than 5 %
C1	Commercial	Less than 15 %
R2	Dense single / multi-family	Less than 30 %
R3	Multi-family, two-story	Less than 35 %

Generally, the individual power stations are located in rural areas where the surrounding land use is primarily agricultural and includes coal mining. The surrounding land use includes amongst others, urban areas with residential, commercial and recreational areas, industrial areas, agriculture, mining, forestry, undeveloped areas and conservation areas.

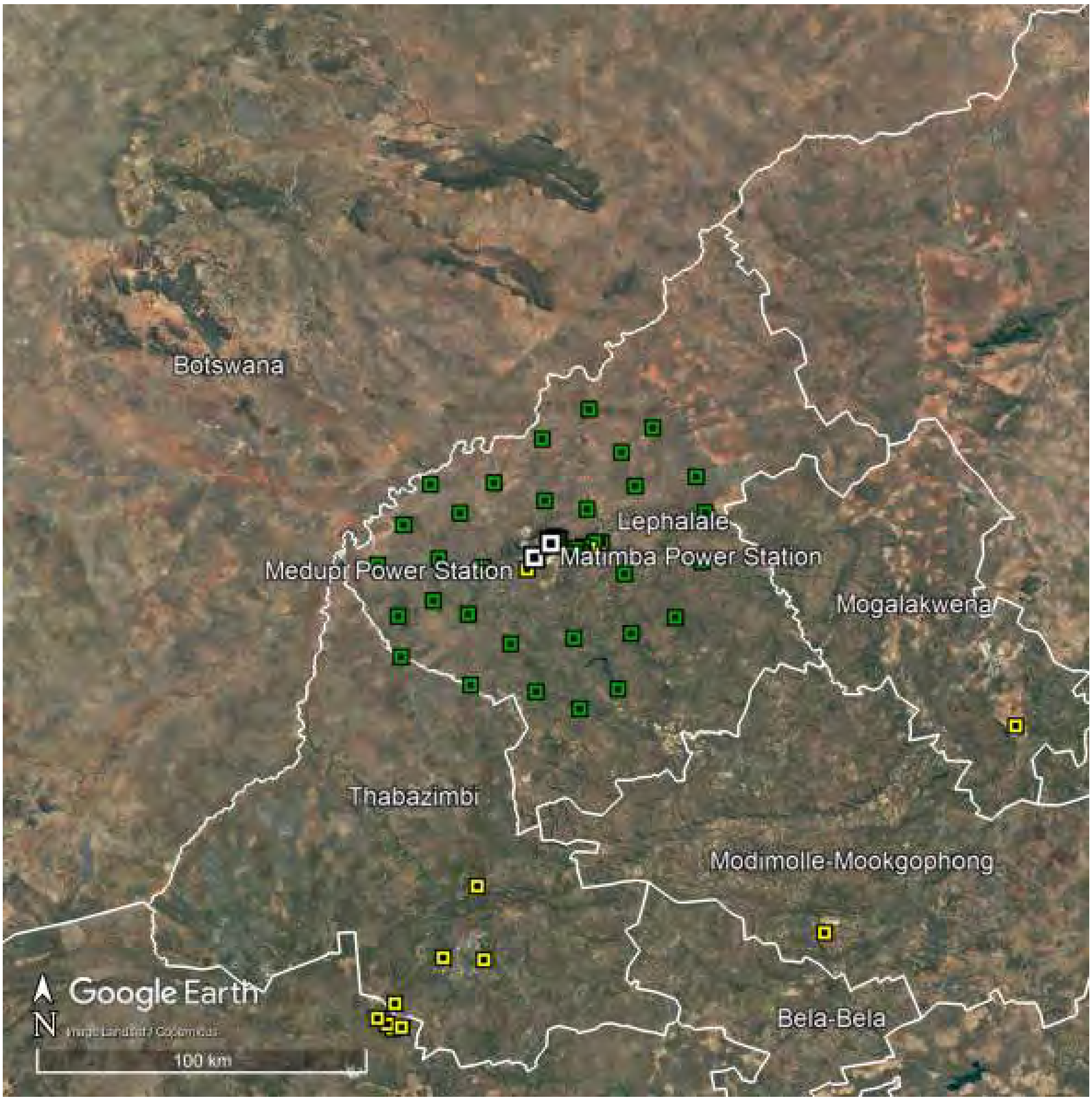

Figure 3-1: Relative location of the Medupi and Matimba coal-fired Power Stations in the modelling domain shown by white squares, with sensitive receptors shown by green squares and air quality monitoring stations shown by yellow squares (Google Earth, 2025)

3.3 Receptor Identification

The US Environmental Protection Agency (USEPA, 2024a) recognise sensitive receptors as areas which include, but are not limited to, hospitals, schools, daycare facilities, elderly housing and convalescent facilities or specialised healthcare facilities. These are areas where the occupants are more susceptible to the adverse effects of exposure to toxic chemicals, pesticides and other pollutants. The California Air Resources Board (CARB, 2024) identify sensitive receptors as children, elderly, asthmatics and others who are at a heightened risk of negative health outcomes due to exposure to air pollution.

The locations where these sensitive receptors congregate are considered sensitive receptor locations and therefore include hospitals, schools and day care centres and other such locations. Fifty-one (51) sensitive receptor points were identified within a 50 km radius of Medupi and Matimba (Table 3-2). Thirteen (13) ambient air quality monitoring stations (AQMSs) were also identified, within a 160 km radius of Medupi and Matimba (Table 3-2).

Table 3-2: Location of AQMSs and sensitive receptors

Receptor	UTMx	UTMy
Eskom Marapong AQMS - Monitoring Station	564043.96	7383714.82
Eskom Medupi AQMS - Monitoring Station	554985.15	7374551.69
SAWS Lephalale-NAQI AQMS - Monitoring Station	573617.23	7380785.92
Mokopane AQMS - Monitoring Station	701598.05	7327078.46
Thabazimbi AQMS - Monitoring Station	539646.74	7280276.20
Modimolle AQMS - Monitoring Station	643847.29	7265609.61
Mobile-Norplats AQMS - Monitoring Station	541542.32	7258123.21
Smashblock AQMS - Monitoring Station	529300.47	7258797.68
Bierspruit AQMS - Monitoring Station	514800.45	7244966.61
ES_Mantserre AQMS - Monitoring Station	509479.21	7240518.95
Fridge Plant AQMS - Monitoring Station	516713.06	7237831.41
Hostel AQMS - Monitoring Station	514190.59	7237432.32
4B Decline AQMS - Monitoring Station	512648.64	7238763.45
1-Phegelelo Senior Secondary	563060.27	7384176.92
2-Contractors Village	561293.06	7383583.06
3-Ditheku Primary School	562975.84	7384275.27
4-Ditheko Primary School	564690.88	7383857.99
5-Marapong Training Centre	563086.96	7383464.90
6-Marapong Clinic	564192.87	7383463.50
7-Tielelo Secondary School	562969.19	7384034.60
8-Grootegeluk Medical Centre - community centre	563209.97	7383420.19
9-Lephalale College	569911.07	7380729.80
10-Nelsonskop Primary School	563913.17	7383542.34
11-Hansie En Grietjie Pre-Primary School	569673.28	7380665.51
12-Sedibeng Special School for the Deaf and Disabilities	570930.07	7379737.60
13-Kings College	568333.03	7379207.08
14-Bosveld Primary School	569400.16	7379307.54
15-Lephalale Medical Hospital	562937.47	7383633.06
16-Ellisras Hospital	571712.64	7381272.63
17-Laerskool Ellisras Primary School	576066.50	7382618.99
18-Hoerskool Ellisras Secondary School	575189.24	7382497.00
19-Marlothii Learning Academy	575454.69	7382358.78
20-Hardekool Akademie vir C.V.O	577372.18	7382410.93
21-Lephalale Clinic	576043.80	7382373.65
22-Ons Hoop	573074.97	7392407.88
23-Woudend	573770.56	7422152.34
24-Ramabara's	584098.22	7373113.67
25-Ga-Shongoane	608321.44	7391281.64
26-Bulge River	570570.94	7332997.73
27-Kaingo Mountain Lodge	582064.36	7338855.39

Receptor	UTMx	UTMy
28-Community	557517.78	7338134.27
29-Kiesel	517255.71	7348639.09
30-Kremetartpan	537357.10	7361299.51
31-Mbala Private Camp	549971.72	7352418.06
32-Steenbokpan	541767.06	7375229.05
33-Receptor	535000.63	7391410.32
34-Sandbult	528615.79	7377834.21
35-Hardekraaltjie	526176.47	7399998.52
36-Receptor	560399.30	7395004.97
37-Receptor	545208.51	7400387.73
38-Receptor	559689.84	7413300.41
39-Receptor	583381.64	7409353.03
40-Receptor	587467.86	7399237.20
41-Ditaung	605601.90	7401959.87
42-Letlora	592779.39	7416528.43
43-Receptor	526898.56	7365393.83
44-Glenover	516499.93	7360781.12
45-Oxford Safaris	510472.00	7376086.60
46-Receptor	518190.18	7387977.95
47-Tholo Bush Estate	586072.95	7355406.24
48-Receptor	568867.89	7354020.76
49-Receptor	599331.14	7360082.91
50-Cheetah Safaris	537952.03	7340196.11
51-Rhinoland Safaris	607227.84	7376566.59

4. NATIONAL AMBIENT AIR QUALITY STANDARDS

National Ambient Air Quality Standards (NAAQS) (DEA, 2009, 2012) apply to the pollutants emitted by Medupi and Matimba. The NAAQS consists of a 'limit' value and a permitted frequency of exceedance. The limit value is the fixed concentration level aimed at reducing the harmful effects of a pollutant. The permitted frequency of exceedance represents the acceptable number of exceedances of the limit value expressed as the 99th percentile. Compliance with the ambient standard implies that the frequency of exceedance of the limit value does not exceed the permitted tolerance. The NAAQS for SO_2, PM_{10} and $PM_{2.5}$ are presented in Table 4-1.

Table 4-1: NAAQS for pollutants relevant to Medupi

Pollutant	Averaging period	Limit value (µg/m^3)	Tolerance
SO_2	1 hour	350	88
	24 hour	125	4
	1 year	50	0
PM_{10}	24 hour	75	4
	1 year	40	0
$PM_{2.5}$	24 hour	40 (25[a])	4
	1 year	20 (15 [a])	0

(a): Applicable from 01 January 2030

What is the 99th percentile in a model dataset: The 99th percentile in a dataset is the value below which 99% of all data points fall – it marks the boundary for the top 1% of model predictions and separates it from the bottom 99% of the data. Therefore, in the model datasets, the top 1% of the highest values are excluded.

Use and meaning of the 99th percentile in the NAAQS: In the context of the South African NAAQS, the 99th percentile is the statistical mechanism used to define compliance for pollutants such as SO_2 or PM_{10}. The 99th percentile represents a permitted frequency of exceedance. It acknowledges that due to rare meteorological conditions or extreme operational events at facilities such as Medupi and Matimba, pollutant concentrations may sometimes exceed the prescribed "limit value" without constituting non-compliance. Statistically, the limit value must not be exceeded for more than 1% of the monitoring period, typically over a calendar year.

Rationale for use at Medupi and Matimba: Power stations experience inherent variability in emissions during start-up, shut-down and upset conditions. The 99th percentile provides a tolerance margin that accounts for these rare emission peaks while ensuring that ambient air quality remains protective of human health for 99% of the time. Compliance is determined by comparing the measured or modelled ambient concentration at the 99th percentile with the applicable NAAQS limit. If the 99th percentile value exceeds the standard, the facility or area is deemed to be in non-compliance. The use of the 99th percentile shifts regulatory attention away from simple average concentrations, which may obscure short-term pollution spikes toward a "typical worst-case" scenario. This is particularly important for pollutants such as SO_2, where short-term exposure to high concentrations can cause immediate respiratory health effects.

5. ATMOSPHERIC EMISSIONS

5.1 Emission scenarios

Five emission scenarios are assessed to support the Minimum Emission Standard (MES) Health Benefit Cost Analysis (BCA) Study at Medupi Power Station, undertaken by Prime Africa Consult. These are:

MES exemption scenarios – Medupi revised CBA

Scenario A: Actual historical emissions

Modeling based on actual monthly tonnage emitted per stack per power station for the period 2022-2024.

a. This is the "as is" /baseline scenario.
b. In the case of Medupi, the historical baseline reflects mostly 5 out of the 6 units in operation (Unit 4 was extended inoperability due to the turbine-generator explosion incident). As such a future baseline assessment accounting for all six units in operation at the forecasted load factor is modelled in Scenario B.
c. The historical (Scenario A) and future baseline (Scenario B) also reflect the actual SO_2 emissions (i.e. plant operating without FGD), which are lower than the requested and modelled emission limit values.
d. Matimba is included in the modelling for the cumulative impact in the region.

Scenario B: Future baseline

a. In the case of Medupi, the historical baseline reflects mostly 5 out of the 6 units in operation (Unit 4 was extended inoperability due to the turbine-generator explosion incident). As such a future baseline assessment accounting for all six units in operation at the forecasted load factor is modelled in this Scenario (Scenario B).
b. The historical (Scenario A) and future baseline (Scenario B) also reflect the actual SO_2 emissions (i.e. plant operating without FGD), which are lower than the requested and modelled emission limit values.
c. Matimba is included in the modelling for the cumulative impact in the region.

Scenario C: Eskom plan wet FGD

Predicted monthly tonnage emitted per stack post 2032 assuming:

a. Medupi has been retrofitted with wet FGD complying to the ELV of 1 000 mg/Nm^3 new plant standard but modelled at 80% of the ELV (800 mg/Nm^3).
b. Matimba is included in the modelling for the cumulative impact in the region.
c. As per Ministers decision condition 7.32 all other pollutants constant.

Scenario D: Eskom plan semi-dry FGD

Predicted monthly tonnage emitted per stack post 2036 assuming:

a. Medupi has been retrofitted with semi-dry FGD complying to the ELV of 1 000 mg/Nm^3 new plant standard but modelled at 80% of the ELV (800 mg/Nm^3)
b. Matimba is included in the modelling for the cumulative impact in the region.
c. As per Ministers decision condition 7.32 all other pollutants constant.

Scenario E: Eskom plan dry FGD

Predicted monthly tonnage emitted per stack post 2036 assuming:

a. Medupi has been retrofitted with dry FGD complying with an alternate ELV of 2 500 mg/Nm^3 but modelled at 80% of the proposed limit value (2 000 mg/Nm^3)
b. Matimba is included in the modelling for the cumulative impact in the region.
c. As per Ministers decision condition 7.32 all other pollutants constant.

Notes:

a. The Energy Output for all scenarios uses the Upper Load forecast (long term tax plan) – 70%.
b. The existing emissions for SO_2, NO_X and mostly PM are lower than the modelled inputs and as such the modelled emissions represent a worst-case scenario.
c. As per Ministers decision condition 7.32 all other pollutants initially PM, NO_X $PM_{2.5}$ fugitive sources etc. are held constant.

5.2 Point Source Parameters

The physical stack parameters and emission parameters for stacks at Medupi and Matimba are listed in Table 5-1Error! Reference source not found. and

Table 5-2 respectively.

Table 5-1: Medupi and Matimba physical stack parameters

Stack ID	Point Source Code	Source Name	Stack Orientation	Latitude (dec deg)	Longitude (dec deg)	Height of Release (m)		Diameter at Stack Tip (m)
						Above Ground	Above nearest building	
Medupi Power Station								
Stack 1 [a]	Boiler unit 1-3	SV unit 1-3	Vertical	557 231	7 378 553	220	200	15.42
Stack 2 [a]	Boiler unit 4-6	SV unit 4-6	Vertical	557 271	7 378 342	220	200	15.42
Matimba Power Station								
Stack 1 [b]	Boiler unit 1-3	SV unit 1-3	Vertical	562 317	7382 199	250	225	12.64
Stack 2 [b]	Boiler unit 4-6	SV unit 4-6	Vertical	562 259	7382 446	250	225	12.64

(a) Individual boiler flues at Medupi have a diameter of approximately 8.9 m. The combined stack diameter is 15.42 m

(b) Individual boiler flues at Matimba have a diameter of approximately 7.3 m. The combined stack diameter is 12.64 m

Table 5-2: Medupi and Matimba stack emission parameters

Scenario	Stack ID	Actual Gas Exit Temp (K)	Actual Gas Volumetric Flow (Am^3/s)	Normal Gas Volumetric Flow (Nm^3/s) [a]	Actual Gas Exit Velocity (m/s) [b]
Medupi Power Station					
Scenario A	Stack 1	406.07	3 464.20	1 931.23	18.55
	Stack 2 [c]	403.29	2 407.67	1 351.49	19.34
Scenario B	Stack 1	420.22	4 615.46	3 224.86	24.73
	Stack 2	420.22	4 615.46	3 224.86	24.73
Scenario C	Stack 1	343.15	3 732.68	2 928.28	20.00
	Stack 2	343.15	3 732.68	2 928.28	20.00
Scenario D	Stack 1	400.22	4 615.46	3 303.26	24.73
	Stack 2	400.22	4 615.46	3 303.26	24.73
Scenario E	Stack 1	410.22	4 615.46	3 222.70	24.73
	Stack 2	410.22	4 615.46	3 222.70	24.73
Matimba Power Station					
Scenario A	Stack 1	404.04	3 342.86	1 872.95	26.64
	Stack 2	406.17	3 153.38	1 757.52	25.13
Scenario B	Stack 1	408.15	3 892.41	2 643.61	31.00
	Stack 2	408.15	3 892.41	2 643.61	31.00
Scenario C	Stack 1	408.15	3 892.41	2 643.61	31.00
	Stack 2	408.15	3 892.41	2 643.61	31.00
Scenario D	Stack 1	408.15	3 892.41	2 643.61	31.00
	Stack 2	408.15	3 892.41	2 643.61	31.00
Scenario E	Stack 1	408.15	3 892.41	2 643.61	31.00
	Stack 2	408.15	3 892.41	2 643.61	31.00

(a): Normal flow corrected to 10% O_2, 101 kPa and 273.15 K

(b): The average of the actual gas exit velocity was used in the simulations

(c): With respect to the Medupi Stack 2, Unit 4 was offline for the entire period between 2022-2024 and hence the equivalent stack diameter and flue gas volume need to reflect that. With three units, the equivalent diameter is 15.42 m, and with two units it is 12.59 m. The actual and normal gas volumetric flow for Medupi Stack 2 is therefore based on an equivalent stack diameter of 12.59 m.

5.3 Point Source Emission Rates

The estimated emission rates and equivalent emission concentrations that are used in the dispersion modelling for the two stacks are shown in Table 5-3 for Medupi and Matimba. As noted in the Section 5.1, Scenario A is based on actual historical emission data for Medupi and Matimba; while in Scenario B-E, all boiler units are assumed to operate continuously, i.e. 24 hours a day and the maximum anticipated emissions during each period are used for simulation in the model.

Table 5-3: Annual emissions from the Medupi and Matimba Power Stations and the corresponding emission concentrations

Scenario	Stack	Emission rate (tonnes/annum)			Emission concentration @ 10% O_2 and average load (mg/Nm^3)		
		NO_x	SO_2	PM	NO_x	SO_2	PM
Medupi Power Station							
A [a]	Stack 1	28 982	202 621	2 181	349	2 437	26
	Stack 2 [c]	13 120	92 199	1 145	225	1 584	20
B	Stack 1	42 714	199 330	2 848	600	2 800	40
	Stack 2	42 714	199 330	2 848	600	2 800	40
C	Stack 1	38 785	51 714	2 586	600	800	40
	Stack 2	38 785	51 714	2 586	600	800	40
D	Stack 1	43 752	58 336	2 917	600	800	40
	Stack 2	43 752	58 336	2 917	600	800	40
E	Stack 1	42 685	142 284	2 846	600	2 000	40
	Stack 2	42 685	142 284	2 846	600	2 000	40
Matimba Power Station							
A [a]	Stack 1	27 437	168 859	3 700	340	2 094	46
	Stack 2	27 343	133 934	5 256	361	1 770	69
B	Stack 1	35 015	163 403	2 334	600	2 800	40
	Stack 2	35 015	163 403	2 334	600	2 800	40
C	Stack 1	35 015	163 403	2 334	600	2 800	40
	Stack 2	35 015	163 403	2 334	600	2 800	40
D	Stack 1	35 015	163 403	2 334	600	2 800	40
	Stack 2	35 015	163 403	2 334	600	2 800	40
E	Stack 1	35 015	163 403	2 334	600	2 800	40
	Stack 2	35 015	163 403	2 334	600	2 800	40
MES [b]					750	1 000	50

(a): Average from actual monthly emissions

(b): DEA, 2020

(c): With respect to the Medupi Stack 2, Unit 4 was offline for the entire period between 2022-2024 and hence the equivalent stack diameter and flue gas volume need to reflect that. With three units, the equivalent diameter is 15.42 m, and with two units it is 12.59 m. The emission concentrations for Medupi Stack 2 is therefore based on an equivalent stack diameter of 12.59 m.

Methodology for determining $PM_{2.5}$ emissions

In terms of the determination of fine particulate matter emissions ($PM_{2.5}$), it is noted that Eskom utilises the dry bottom boiler emission factors from the United States Environmental Protection Agency (US EPA AP42) (US EPA, 1995) to determine the fine particulate matter (PM) emissions ($PM_{2.5}$). The ratio of the $PM_{2.5}$ to PM_{10} is used to calculate $PM_{2.5}$ from the total PM measured from the Continuous Emission Monitoring System (CEMS) equipment at the respective smokestacks. The utilisation of CEMS equipment is a more accurate representation of site-specific PM and therefore constitutes a Tier 3 method of reporting.

The USEPA defines dry bottom boilers as those burning coals with high fusion temperatures resulting in dry ash. In wet bottom boilers, coals with low fusion temperatures are used, resulting in molten ash or slag. Eskom coal fired power stations are therefore considered to have dry bottom boilers. Eskom has either Electrostatic Precipitators (ESPs) or Fabric Filter Plants (FFPs) installed as air pollution control devices in all its coal fired units. The following ratios determined from dry bottom emission factors in the US EPA AP42 are used:

- ESP controlled - 0.024 lb/ton for $PM_{2.5}$ and 0.054 lb/ton for PM_{10} [ratio = 0.44]
- FFP controlled - 0.01 lb/ton for $PM_{2.5}$ and 0.02 lb/ton for PM_{10} [ratio = 0.5]

The above ratios for PM_{10}:$PM_{2.5}$ have been applied accordingly at the power stations as follows:

- Medupi has FFPs installed on both stacks, hence the PM_{10}:$PM_{2.5}$ ratio is 1:0.50
- Matimba has ESPs installed on both stacks, hence the PM_{10}:$PM_{2.5}$ ratio is 1:0.44

5.4 Point Source Maximum Emission Rates (Start-Up, Shut-Down, Upset and Maintenance Conditions)

Medupi and Matimba are required to conduct continuous emission measurements. Maximum emissions during start-up, shut-down, maintenance or upset conditions are accounted for in the actual monthly emissions provided to the modelling team. These conditions have been incorporated into the simulations for Scenario A: Actual historical emissions.

5.5 Fugitive Emissions

The methodology to estimate emission rates of particulates from the coal stockyard, ash dumping and gypsum disposal activities for the respective power stations are described in this section.

A general equation for emission estimation is: $E = A \times EF \times (1-ER/100)$

where: E = emissions;
A = activity rate;
EF = emission factor; and
ER = overall emission reduction efficiency (%)

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of the pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kg of particulate emitted per tonne of coal crushed). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality and are generally assumed to be representative of long-term averages for all facilities in the source category (USEPA, 2024b).

The emission factors used for the calculation of particulates in this study are the most recent factors published in the United States Environmental Protection Agency (USEPA), AP 42, Fifth Edition, Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources, Chapter 13: Section 13.2.4 Aggregate Handling and Storage Piles; Section 13.2.5 Industrial Wind Erosion; (USEPA, 2024b).

Wind entrainment of dust, PM_{10} and $PM_{2.5}$ from the coal stockpiles, ash dumps and gypsum disposal facilities are a function of the physical size of the facility and the nature of the exposed surface, i.e. the moisture content, silt content, amount of vegetation cover, size of the particles on the surface and wind speed. Characteristics of the coal stockpiles, ash dumps and gypsum disposal facilities at the respective power stations are shown in Table 5-4.

Coal stockpiles: As a mitigation measure, water is sprayed onto the coal stockpiles occasionally to reduce dust generation. In this assessment, the coal stockpiles are assessed under worst case conditions (e.g. drought conditions), where it is assumed that no water will be sprayed onto the coal stockpiles and 100% of the area is exposed to wind erosion.

Ash dumps: Ash dumps, by nature, are generally in a damp state depending on rainfall conditions and if the ash is pumped onto the ash dump in a fluid state or trucked in. Rising green walls will provide vegetation cover on the sides and it is expected that most of the ash dump area exposed at the top will include a wet beach area. These initiatives, together with occasional wetting will reduce the amount of dust entrainment from the ash dump. In this assessment, the ash dumps are modelled under worst case conditions (e.g. drought conditions), where it is assumed that they are mostly dry. At Medupi and Matimba, it is assumed that 80% and 70% of their respective surface area is exposed to wind erosion, providing a worst-case (environmentally conservative) scenario.

Gypsum disposal facilities at Medupi Power Station: The gypsum disposal facilities are proposed facilities at Medupi and are not constructed as yet. As a mitigation measure, it is assumed that water will be sprayed onto the gypsum stockpiles occasionally to reduce dust generation. In this assessment, the gypsum stockpiles are assessed under worst case conditions (e.g. drought conditions), where it is assumed that no water will be sprayed onto the stockpiles and 100% of the area is exposed to wind erosion.

Silt content and moisture content of gypsum: The moisture content of gypsum for the three FGD technology options was provided by Eskom. The silt content of gypsum (based on the silicon dioxide (SiO_2) percentages) for the three FGD technology options were determined as follows:

- Wet FGD technology option: 1.1% based on laboratory analysis undertaken by the Eskom Central Coal Laboratory using a gypsum sample from the gypsum disposal facility at the Kusile Power Station

- Semi-dry FGD technology option: Average of 31.1% (based on laboratory analyses of gypsum samples from 2 power stations using semi-dry FGD technology) (Fungaro et al. 2023)
- Dry FGD technology option: Average of 45.2% (based on laboratory analyses of gypsum samples from 9 power stations using dry FGD technology) (Su et al., 2013)

The annual emission rates for the coal stockpiles, ash dumps and gypsum disposal facilities are shown in Table 5-5.

Table 5-4: Characteristics of coal stockpiles, ash dumps and gypsum disposal facilities (GDFs) for three technology options at the Medupi and Matimba Power Stations as applicable

	Medupi Power Station						Matimba Power Station	
Parameter	Coal stockpile	Excess Coal stockpile	Ash dump	GDF: wet FGD option (Scenario C)	GDF: semi-dry FGD option (Scenario D)	GDF: dry FGD option (Scenario E)	Coal stockpile	Ash dump
Quantity of material stored (tonnes/year)	2 814 200	14 420 972	19 290 207	1 956 115	2 241 994	6 282 958	1 999 239	3 966 084
Moisture content (%)	4.5	4.5	27	10	2	1	4.5	27
Silt content (%)	2.2	2.2	80	1.1	31.1	45.2	2.2	80
Exposed surface area (m^2)	379 867	1 042 153	698 447	32 602	74 733	130 895	130 417	1 487 864
Height (m)	20	30.7	46.4	60	60	60	25	65
Dry area (%)	100	100	80	100	100	100	100	70
Dust abatement method	Wetting - Water	Wetting - Water	Spraying of dust using water during operation, topsoil and vegetation coverage at incremental heights	Wetting - Water	Wetting - Water	Wetting - Water	Wetting - Water	Spraying of dust using water during operation, topsoil and vegetation coverage at incremental heights
Material transfer method and ashing system	Conveyors (front end loaders in case of emergency)	Conveyors (front end loaders in case of emergency)	Dry (delivered by truck)	Delivered by truck or conveyors	Delivered by truck or conveyors	Delivered by truck or conveyors	Conveyors (front end loaders in case of emergency)	Dry (delivered by trucks)

Table 5-5: Fugitive emissions at the Medupi and Matimba Power Stations

Power station	Source name	Emission (tonnes/year)		
		TSP	PM_{10}	$PM_{2.5}$
Medupi	Coal Yard	18.90	9.41	3.57
	Excess Coal Yard	55.67	27.61	10.08
	Ash Dump	1 157.57	578.76	231.40
	GDF: wet FGD option (Scenario C)	1.11	0.54	0.17
	GDF: semi-dry FGD option (Scenario D)	52.09	25.94	9.91
	GDF: dry FGD option (Scenario E)	1 437.20	717.40	281.74
Matimba	Coal Yard	7.08	3.51	1.27
	Ash Dump	2 464.20	1 232.09	492.82

6. MODEL AND MODEL PARAMETERISATION

6.1 Model used

The CALPUFF suite of models are approved by the USEPA (http://www.src.com/calpuff/calpuff1.htm) and by the DEA for Level 3 assessments (DEA, 2014b). It consists of a meteorological pre-processor, CALMET, the dispersion model, CALPUFF, and the post-processor, CALPOST. It is an appropriate air dispersion model for the purpose of this assessment as it is well suited to simulate dispersion from several sources. It also has capability to simulate dispersion in the atmosphere's complex land-sea interface. More information about the model can be found in the User's Guide for the CALPUFF Dispersion Model (USEPA, 1995).

The Air Pollution Model (TAPM) (Hurley, 2000; Hurley et al., 2001; Hurley et al., 2002) is used to model surface and upper air metrological data for the study domain. TAPM uses global gridded synoptic-scale meteorological data with observed surface data to simulate surface and upper air meteorology at given locations in the domain, taking the underlying topography and land cover into account. The global gridded data sets that are used are developed from surface and upper air data that are submitted routinely by all meteorological observing stations to the Global Telecommunication System of the World Meteorological Organisation. TAPM has been used successfully in Australia where it was developed (Hurley, 2000; Hurley et al., 2001; Hurley et al., 2002). It is an ideal tool for modelling applications where meteorological data does not adequately meet requirements for dispersion modelling. TAPM modelled output data is therefore used to augment the site-specific surface meteorological data for input to CALPUFF.

6.2 TAPM and CALPUFF parameterisation

The TAPM diagnostic meteorological model is used to generate a 3-dimensional temporally and spatially continuous meteorological field for 2022, 2023 and 2024 in hourly increments for the modelling domain.

TAPM is set-up in a nested configuration of two domains, centred between Medupi and Matimba. The outer domain is 720 km by 720 km at a 24 km grid resolution and the inner domain is 360 km by 360 km at a 12 km grid resolution (Figure 6-1). The nesting configuration ensures that topographical effects on meteorology are captured and that meteorology is well resolved and characterised across the boundaries of the inner domain. Twenty-seven vertical levels are modelled in each nest from 10 m to 5 000 m, with a finer resolution in the lowest 1 000 m. The subset of the entire TAPM model output in the form of pre-processed gridded surface meteorological data fields is input into the dispersion model.

The 3-dimensional TAPM meteorological output on the inner grid includes hourly wind speed and direction, temperature, relative humidity, total solar radiation, net radiation, sensible heat flux, evaporative heat flux, convective velocity scale, precipitation, mixing height, friction velocity and Obukhov length. The spatially and temporally resolved TAPM surface and upper air meteorological data is used as input to the CALPUFF meteorological pre-processor, CALMET.

The CALPUFF modelling domain covers an area of 108 900 km^2, where the domain extends 330 km (west-east) by 330 km (north-south). It consists of a uniformly spaced receptor grid with 1.25 km spacing, giving 69 696 grid cells (264 x 264 grid cells).

The topographical and land use for the respective modelling domains is obtained from the dataset accompanying the Commonwealth Scientific and Industrial Research Organisation (CSIRO) TAPM modelling package (CSIRO, 2008). This dataset includes global terrain elevation and land use classification data on a longitude/latitude grid at 30-second grid spacing from the US Geological Survey, Earth Resources Observation Systems (EROS) Data Center.

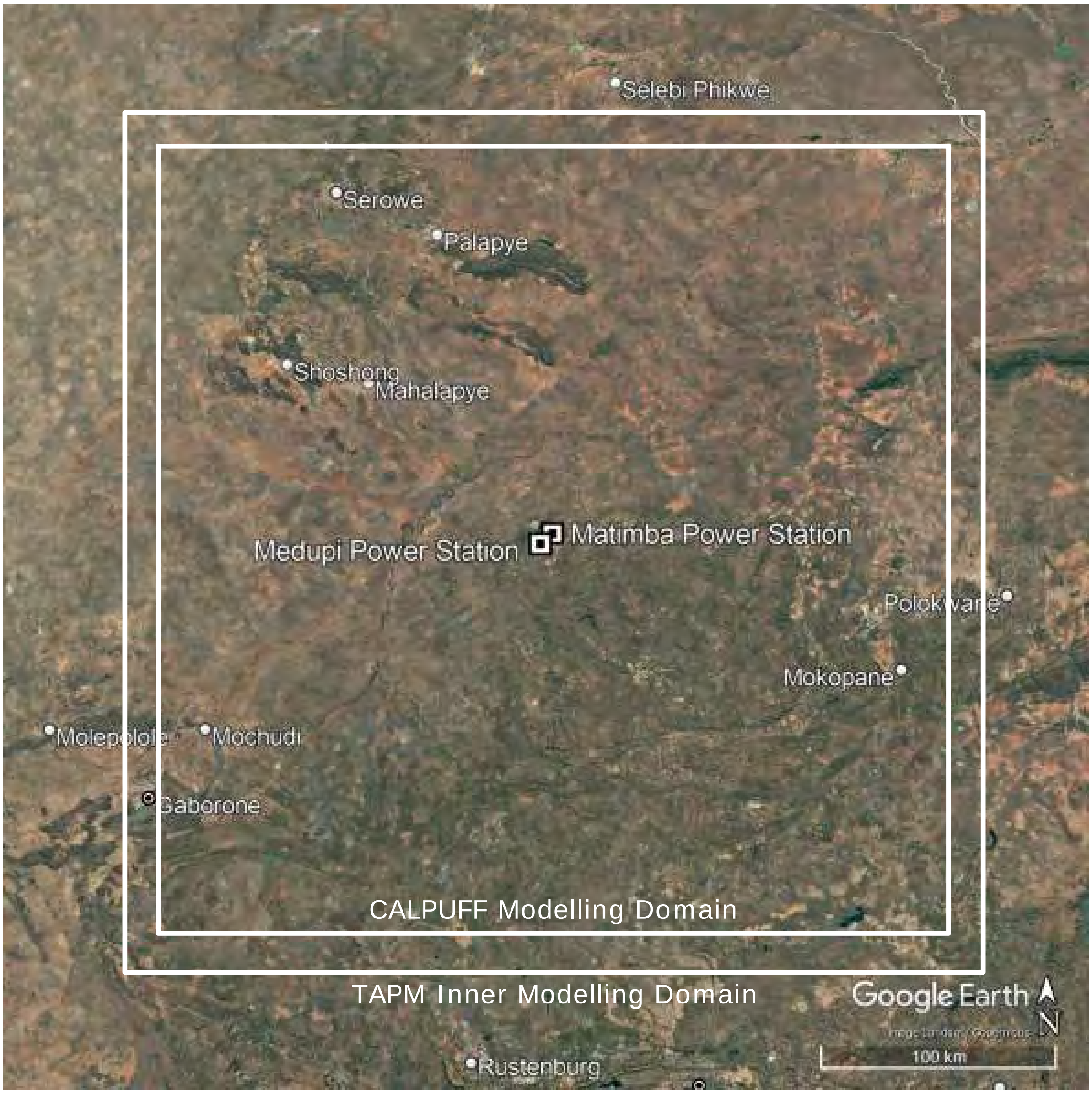

Figure 6-1: TAPM and CALPUFF modelling domains centred between Medupi and Matimba

The parameterisation of key variables that apply in CALMET and CALPUFF are indicated in Table 6-1 and Table 6-2 respectively.

Table 6-1: Parameterisation of key variables for CALMET

Parameter	Model value
12 vertical cell face heights (m)	0, 20, 40, 80, 160, 320, 640, 1000, 1500, 2000, 2500, 3000, 4000
Coriolis parameter (per second)	0.0001
Empirical constants for mixing height equation	Neutral, mechanical: 1.41 Convective: 0.15 Stable: 2400 Overwater, mechanical: 0.12
Minimum potential temperature lapse rate (K/m)	0.001
Depth of layer above convective mixing height through which lapse rate is computed (m)	200
Wind field model	Diagnostic wind module
Surface wind extrapolation	Similarity theory
Restrictions on extrapolation of surface data	No extrapolation as modelled upper air data field is applied
Radius of influence of terrain features (km)	5
Radius of influence of surface stations (km)	Not used as continuous surface data field is applied

Table 6-2: Parameterisation of key variables for CALPUFF

Parameter	Model value
Chemical transformation	Default NO_2 conversion factor is applied
Wind speed profile	Rural
Calm conditions	Wind speed < 0.5 m/s
Plume rise	Transitional plume rise, stack tip downwash and partial plume penetration is modelled
Dispersion	CALPUFF used in PUFF mode
Dispersion option	Pasquill-Gifford coefficients are used for rural and McElroy-Pooler coefficients are used for urban
Terrain adjustment method	Partial plume path adjustment

6.3 Scientific and Modelling Rationale for the Spatial Modelling Domain Limits

6.3.1 CALPUFF Dispersion Modelling for the 2025 Eskom Health BCA Study

Purpose of the modelling domain

A dispersion modelling domain defines the geographic area within which pollutant transport, dispersion and resulting ambient concentrations are quantified. The selection of appropriate spatial domain limits is a critical modelling decision, as it must balance scientific representativeness, regulatory guidance, model limitations and the specific objectives of the study. For health impact and benefit–cost assessments, the domain must be sufficiently large to capture all materially relevant population exposure attributable to the sources under assessment, while remaining computationally feasible and consistent with dispersion model constraints.

Regulatory and scientific guidance

The Code of Practice for Air Dispersion Modelling in Air Quality Management in South Africa (DEA, 2014) provides guidance on the selection of modelling domains. For large, buoyant point sources such as coal-fired power station stacks, the Code recommends domains that typically extend at least 50 km from the source, particularly in relatively flat terrain. The Code also recognises that domain size should be influenced by stack height and plume buoyancy, meteorological conditions, terrain complexity and the spatial extent of receptors of interest. The Medupi and Matimba power stations represent large buoyant sources in a predominantly flat region, supporting the need for a domain that extends well beyond the immediate vicinity of the stacks.

6.3.2 Modelling approach and domain selection: 2024 dispersion modelling domain

For the 2024 cumulative dispersion modelling undertaken by uMoya-NILU Consulting, titled Atmospheric Impact Report in Support of the Application for Exemption from the Minimum Emission Standards for Eskom's Coal-Fired Power Stations in the Waterberg (A Cumulative Assessment) (uMoya-NILU, 2024a) and Addendum (uMoya-NILU, 2024b), the CALPUFF modelling domain was defined as a 108 km × 108 km area centred between Medupi and Matimba. This domain extended approximately 54 km from the centre, ensuring that pollutant dispersion was captured within roughly a 50 km radius of each power station. This domain size was considered appropriate for evaluating compliance-based air quality impacts and cumulative concentrations in the immediate Waterberg region and was aligned with the primary objectives of that assessment.

6.3.3 Rationale for extending the modelling domain in the 2025 Eskom Health BCA Study: Different study objectives

The 2025 Eskom Health BCA Study has a fundamentally different objective from the 2024 dispersion assessment. While the 2024 study focused primarily on cumulative air quality impacts and regulatory considerations, the 2025 BCA Study requires a robust quantification of population exposure across a much wider geographic region in order to estimate health outcomes attributable to power station emissions and monetise these outcomes in a benefit–cost framework.

Health impacts can accumulate over time even at relatively low ambient concentrations, provided that exposed populations are sufficiently large. Consequently, the BCA requires the modelling domain to extend beyond the area of peak concentrations and include regions where concentrations approach low thresholds (up to about 1 $\mu g/m^3$), but where population density may still be significant.

6.3.4 Scientific justification for domain expansion

Analysis of dispersion modelling results from previous studies (uMoya-NILU, 2024a; uMoya-NILU, 2024b) demonstrates that:

- the highest ground-level concentrations from stack emissions occur within approximately 25 km of the source region;
- concentrations decrease rapidly with distance due to plume dilution and atmospheric dispersion;
- beyond the edges of the 2024 domain, ambient concentrations are already well below the NAAQS and concentrations are expected to continue to decrease further with distance.

However, for health benefit assessments, low concentrations over large populations can contribute meaningfully to total health impacts. It was therefore scientifically justified to expand the domain to ensure that:

- all spatially relevant exposure contributing to health outcomes is captured;
- by extending the modelling domain, population exposure at low but meaningful concentration levels is not excluded; and
- exposure estimates are spatially complete for subsequent health and economic valuation.

6.3.5 2025 CALPUFF modelling domain configuration

Domain extent and resolution

For the 2025 Eskom Health BCA Study, the CALPUFF modelling domain was expanded to 330 km × 330 km, covering a total area of 108 900 km^2, centred between Medupi and Matimba power stations. This represents a substantial increase relative to the 2024 study and was specifically designed to support health exposure assessment rather than compliance screening.

The domain consists of a uniformly spaced receptor grid with a 1.25 km grid resolution, resulting in 264 × 264 grid cells (69 696 grid cells in total).

Alignment with CALPUFF model constraints

The domain size and resolution were selected to remain within known CALPUFF technical limitations. CALPUFF can accommodate a maximum of 265 × 265 grid cells, and the selected 264 × 264 grid configuration represents the largest feasible domain while maintaining an acceptable spatial resolution.

6.3.6 Project-specific constraints informing domain design - Alignment with Health Benefit Cost Analysis requirements

The spatial configuration of the modelling domain was closely aligned with the needs of the BCA methodology:

- Municipal ward–level exposure assessment: Health impacts were quantified at the level of municipal wards. Many wards in the study region are only a few kilometres across, requiring a relatively fine grid resolution to ensure that each ward contains multiple modelled data points.

- Consistency with population data: Dispersion model outputs were spatially intersected with the latest (2025) gridded population datasets, aggregated by municipal and ward boundaries. A grid resolution of 1.25 km was selected as a practical compromise between spatial detail and model feasibility.
- Capturing low-concentration exposure: One of the study requirements was to quantify SO_2, PM_{10} and $PM_{2.5}$ concentrations down to approximately 1 µg/m^3, as these levels remain relevant for health impact calculations over large populations.

6.3.7 Meteorological modelling support

The expanded CALPUFF domain was supported by a correspondingly larger TAPM meteorological modelling framework. TAPM was configured with an outer domain of 720 km × 720 km at 24 km resolution and an inner domain of 360 km × 360 km at 12 km resolution, ensuring that meteorological processes influencing long-range transport were adequately captured and that boundary effects did not compromise dispersion results within the CALPUFF domain.

6.3.8 Summary

The spatial modelling domain selected for the 2025 Eskom Health BCA Study represents a scientifically sound, policy-compliant and purpose-driven enhancement relative to the 2024 study. The expanded 330 km × 330 km CALPUFF domain ensures that all relevant population exposure attributable to emissions from Medupi and Matimba is captured, including low-concentration impacts over large geographic areas. The domain design also balances dispersion science and regulatory guidance, CALPUFF model limitations, meteorological representativeness and the specific exposure-assessment needs of a health and economic impact study. Accordingly, the selected spatial limits are considered adequate, optimal and defensible for meeting the objectives of the 2025 BCA Study and for ensuring compliance with the conditions set out in the Minister’s decision on Eskom’s MES exemption issued on 31 March 2025.

6.4 Formation of secondary particulates and the calculation of Total-PM_{10} and Total-$PM_{2.5}$

The CALPUFF model incorporates an advanced system to simulate the formation, transport and deposition of secondary particulate matter, accounting for atmospheric conditions and the availability of precursor gases. Secondary particulate matter forms in the atmosphere through chemical reactions involving primary gaseous pollutants, primarily SO_2 and oxides NO_X. CALPUFF applies a simplified chemical transformation scheme to represent oxidation processes and the equilibrium between gaseous nitric acid (HNO_3) and particulate ammonium nitrate (NH_4NO_3), as well as the formation of sulphate (SO_4^{2-}).

In the modelling, total particulate matter concentrations are calculated as the sum of primary PM_{10} and secondary particulate contributions, including ammonium nitrate and ammonium sulphate formed from atmospheric reactions of SO_2 and NO_X. Secondary particulate concentrations are derived from modelled nitrate (NO_3^-) and sulphate (SO_4^{2-}) using molecular mass ratios, as follows:

NH_4NO_3 concentration = 80/62 x NO_3 = 1.29 x NO_3 concentration
$(NH_4)_2SO_4$ concentration = 132/96 x SO_4 = 1.375 x SO_4 concentration

The total ambient concentration of PM_{10} (Total PM_{10}) and $PM_{2.5}$ (Total $PM_{2.5}$) is calculated as follows:

Total PM_{10} = PM_{10} + $(NH_4)_2SO_4$ + NH_4NO_3
Total $PM_{2.5}$ = $PM_{2.5}$ + $(NH_4)_2SO_4$ + NH_4NO_3

Ambient concentrations resulting from this process are then compared with the applicable NAAQS limit values for PM_{10} and $PM_{2.5}$.

Overview of the CALPUFF MESOPUFF II Chemical Transformation Scheme

The MESOPUFF II chemical transformation scheme in CALPUFF is a pseudo first-order mechanism used to calculate the conversion of gaseous precursors, SO_2 and NO_X into secondary inorganic aerosols, specifically particulate sulphate (SO_4^{2-}) and particulate nitrate (NO_3^-) (Scire et al., 2000a; U.S. EPA, 2003).

Key Chemical Mechanisms

The MESOPUFF II scheme tracks five primary chemical species, SO_2, SO_4^{2-}, NO_X, nitric acid (HNO_3) and NO_3^- and represents their behaviour through three principal pathways (Scire et al., 2000a):

- Sulphate Formation: SO_2 is converted to particulate sulphate (SO_4^{2-}) through a transformation process that is strongly influenced by daytime solar radiation, background ozone (O_3) concentrations and ambient relative humidity (RH). Solar radiation is used as a surrogate for oxidant availability, and aqueous-phase oxidation becomes increasingly important under high-humidity or nighttime conditions (Scire et al., 2000a; U.S. EPA, 2003).
- Nitrate Formation: NO_X is converted to gaseous nitric acid (HNO_3) and organic nitrates (RNO_3). Unlike more complex chemical mechanisms such as RIVAD, the MESOPUFF II scheme treats NO_X as a single combined species rather than explicitly distinguishing between nitric oxide (NO) and nitrogen dioxide (NO_2), resulting in a simplified representation of atmospheric nitrogen chemistry (Scire et al., 2000a; U.S. EPA, 2008).
- Nitrate Equilibrium: A key feature of the MESOPUFF II scheme is the temperature and humidity-dependent equilibrium calculation between gaseous nitric acid (HNO_3) and particulate ammonium nitrate (NH_4NO_3). This equilibrium is assumed to occur instantaneously and depends on ambient temperature and the availability of background ammonia (NH_3), without explicitly modelling aerosol thermodynamics or kinetic limitations (U.S. EPA, 2003; U.S. EPA, 2008).

MESOPUFF II Chemical Transformation Scheme

In the MESOPUFF II chemical transformation scheme the following assumptions and settings are used to calculate the oxidation of SO_2 to particulate sulphate (SO_4^{2-}) and nitrogen oxides to nitrates.

SO_2 **Oxidation Rate (k_1) Assumptions**

The total SO_2 to SO_4 transformation rate (k_1) is calculated as the sum of a gas-phase oxidation rate and an aqueous-phase oxidation rate (Scire et al., 2000a; U.S. EPA, 2003).

Gas-Phase Oxidation (Daytime): The daytime gas-phase oxidation rate is determined using a power-law function of solar radiation intensity (R), background ozone concentration ([O_3]), and stability-dependent dispersion (S):
$k_1 = 36 \cdot R^{0.55} \cdot [O_3]^{0.71} \cdot S^{-1.29} + k_1(aq)$

Assumptions:

- Solar radiation is used as a proxy for hydroxyl (OH) radical concentration rather than explicitly modelling photochemical reactions.
- Higher atmospheric stability (S) generally results in lower oxidation rates due to reduced vertical mixing and limited entrainment of background oxidants (Scire et al., 2000b).

Aqueous-**Phase Oxidation ($k_1(aq)$)**

The aqueous-phase oxidation rate is added to the gas-phase rate during daytime and serves as the primary oxidation pathway during nighttime conditions.

Dependency: The aqueous-phase oxidation rate is highly sensitive to relative humidity (RH): $k_1(aq) = 3 \times 10^{-8} \cdot RH^4$

This formulation represents enhanced oxidation under cloud or fog conditions without explicitly modelling cloud chemistry (U.S. EPA, 2003).

Nighttime Rate: In the absence of solar radiation, the SO_2 oxidation rate typically defaults to a constant low value (approximately 0.1−0.2% per hour) unless elevated relative humidity significantly enhances aqueous-phase oxidation (Scire et al., 2000a).

Secondary Particulate Matter (PM) Yield Factors Stoichiometric Conversion

The model assumes a fixed, mass-based stoichiometric ratio for the conversion of gaseous precursors to secondary particulate matter. For the conversion of SO_2 to SO_4, the yield factor is approximately 1.5, based on molecular weights:
$MW(SO_4) / MW(SO_2) \approx 96 / 64 \approx 1.5$

This approach assumes complete conversion to particulate sulphate mass and does not distinguish between ammonium sulphate and ammonium bisulphate (U.S. EPA, 2008).

Chemical Transformation Settings

MCHEM Parameter: To activate the MESOPUFF II chemical transformation scheme, the MCHEM parameter must be set to 1 in the CALPUFF input file (Scire et al., 2000a).

Environmental Inputs: The scheme requires time-varying environmental inputs, typically provided by the CALMET meteorological processor, including:

- Ozone (O_3): User-supplied background concentrations (constant values, hourly data, or monthly averages) used to drive oxidation reactions.
- Ammonia (NH_3): User-provided background concentrations used to calculate the equilibrium between gaseous nitric acid and particulate nitrate.
- Humidity and Temperature: Derived from CALMET and used to calculate aqueous-phase SO_2 oxidation rates and nitrate partitioning.

Equilibrium Assumption: For nitrate formation, the model assumes an instantaneous thermodynamic equilibrium between gaseous HNO_3 and particulate NO_3, governed by ambient temperature and the availability of NH_3. Kinetic limitations and detailed aerosol thermodynamics are not explicitly modelled (U.S. EPA, 2003; U.S. EPA, 2008).

7. DISPERSION MODELLING RESULTS

The CALPUFF modelling suite accounts for the atmospheric chemical conversion of SO_2 and NO_X to secondary particulates, i.e. sulphates and nitrates in the modelling results. Consequently, the predicted PM_{10} and $PM_{2.5}$ concentrations presented here include both direct emissions of PM plus secondary particulates formed from the power station emissions.

In accordance with the Code of Practice for Air Dispersion Modelling (DEA, 2014a), the 99th percentile of predicted concentrations is utilized for short-term assessments. This statistical approach ensures that extreme outliers, often resulting from complex meteorological variability do not skew the results, providing a more representative comparison against the NAAQS. This assessment evaluates compliance by comparing the predicted 99th percentile concentrations against the respective NAAQS limit values and the permitted frequency of exceedance for each of the five scenarios.

7.1 Maximum predicted ambient concentrations

The maximum predicted annual SO_2, PM_{10} and $PM_{2.5}$ concentrations and the 99th percentile of the 24-hour and 1-hour predicted concentrations in the modelling domain are discussed here and are listed in Table 7-1 for the 5 scenarios. Exceedances of the limit value of the NAAQS are shown in red font. Exceedance of the limit value does not automatically indicate non-compliance with the NAAQS as the standards provide a tolerance in the form of a permitted number of exceedances. The South African NAAQS permits 4 exceedances of the 24-hour or daily limit value per annum, implying up to 12 permitted exceedances in a three-year modelling period. The South African NAAQS also permits 88 exceedances of the 1-hour or hourly limit value per annum, implying up to 264 permitted exceedances in a three-year modelling period.

For SO_2, the predicted concentrations are attributed only to the stack emissions. The maximum predicted annual average concentrations for the 5 scenarios are low relative to the limit values of the NAAQS. The predicted the 99th percentile of the 24-hour SO_2 concentrations and the predicted 1-hour concentrations exceeded the limit value of the NAAQS in Scenario A and Scenario B. The predicted the 99th percentile of the 24-hour SO_2 concentrations also exceeded the limit value of the NAAQS in Scenario E.

For PM_{10} and $PM_{2.5}$, the predicted concentrations are attributed to stack emissions, the low-level fugitive sources (coal stockyards, ash dumps and gypsum disposal facilities) and the contribution from secondary particulate formation. For PM_{10}, the maximum predicted annual average and 99th percentile of the 24-hour concentrations are below the limit values of the respective NAAQS in all scenarios.

For $PM_{2.5}$, the maximum predicted annual average concentrations are below the limit values of the current NAAQS (applicable up to 2029) in Scenario A and Scenario B; and the future NAAQS (applicable from 2020) in Scenario C, Scenario D and Scenario E. The 99th percentile of the 24-hour $PM_{2.5}$ concentrations exceeds the limit value of the current NAAQS in Scenario A and Scenario B; and exceeds the limit value of the future NAAQS in Scenario C, Scenario D and Scenario E.

Table 7-1: Maximum predicted ambient annual SO_2, PM_{10} and $PM_{2.5}$ concentrations in µg/m³ and the predicted 99th percentile concentrations for 24-hour and 1-hour averaging periods, with the NAAQS

Scenario and Pollutant	Averaging time		
Predicted maximum SO_2	Annual	24-hour	1-hour
Scenario A	20.8	163.0	439.2
Scenario B	18.6	169.3	376.4
Scenario C	16.6	112.1	347.2
Scenario D	12.0	104.2	250.1
Scenario E	16.1	143.4	327.6
NAAQS	50	125	350
Predicted maximum PM_{10}	Annual	24-hour	
Scenario A	18.3	72.9	
Scenario B	18.2	74.8	
Scenario C	17.9	67.7	
Scenario D	17.8	67.7	
Scenario E	18.1	72.7	
NAAQS	40	75	
Predicted maximum $PM_{2.5}$	Annual	24-hour	
Scenario A	8.1	40.5	
Scenario B	8.2	43.4	
Scenario C	7.7	35.4	
Scenario D	7.7	35.2	
Scenario E	8.0	40.2	
NAAQS	20	40	Up to 31 Dec 2029
	15	25	From 01 Jan 2030

7.2 Predicted concentrations at sensitive receptors

Fifty-one sensitive receptors were identified in the study area (Table 3-2). The predicted ambient SO_2, PM_{10} and $PM_{2.5}$ concentrations at the sensitive receptors for the five scenarios are presented in Annexure 1 with the limit value of the NAAQS. The predicted concentrations at the sensitive receptors are discussed here.

For SO_2, the predicted concentrations result from SO_2 emissions from the power station stacks. The maximum predicted annual SO_2 and the 99th percentile of the 24-hour and 1-hour concentrations are below the respective NAAQS at all identified sensitive receptors for all 5 scenarios.

For PM_{10} and $PM_{2.5}$, it must be remembered that the predicted concentrations are attributed to stack emissions and the low-level fugitive sources (coal stockyards, ash dumps and gypsum disposal facilities). In addition, the predicted PM_{10} and $PM_{2.5}$ concentrations include the contribution from secondary particulates from SO_2 and NO_2 stack emissions. This is a very conservative approach.

For PM_{10} and $PM_{2.5}$, the maximum predicted annual and the 99th percentile of the 24-hour concentrations are below the respective NAAQS at all identified sensitive receptors for all 5 scenarios.

7.3 Isopleth maps

Isopleth maps of predicted ambient SO_2, PM_{10} and $PM_{2.5}$ concentrations are presented in the following sections. The predicted concentrations are shown as isopleths, lines of equal concentration, in µg/m^3 for the respective NAAQS averaging periods. The isopleths are depicted as coloured lines on the various maps, corresponding to a particular predicted ambient concentration. Areas within red isopleths indicate an area where exceedances of the respective NAAQS limit value are predicted to occur. Sensitive receptors are represented by green squares and AQMSs are represented by white squares.

7.3.1 Sulphur dioxide (SO_2)

Isopleth maps for SO_2 concentrations are presented in Figure 7-1 to Figure 7-15.

The isopleth maps showing the predicted annual average SO_2 concentrations clearly demonstrate the influence of the predominant northeasterly winds, with dispersion generally occurring to the southwest of the power stations. In all scenarios, the highest predicted annual average SO_2 concentrations occur between 10 and 20 km from the power stations, predominantly to the southwest. Predicted annual ambient SO_2 concentrations are relatively low and remain below the NAAQS limit values across the entire modelling domain in all scenarios. For SO_2, the predicted concentrations are attributed solely to stack emissions.

For the annual, 24-hour and 1-hour averaging periods, the increase in SO_2 emissions at Medupi and Matimba from Scenario A to Scenario B is reflected in the modelled results as an increase in the affected area, with predicted exceedances of the 24-hour and 1-hour NAAQS limit values occurring to the southwest of the power stations in both scenarios. However, the predicted number of exceedances remains below the respective allowable thresholds, and compliance with the NAAQS is therefore maintained for both Scenario A and Scenario B.

The reduction in SO_2 emissions at Medupi in Scenarios C and D results in a marked reduction in the affected area. Conversely, the increase in SO_2 emissions at Medupi from Scenario D to Scenario E is reflected in an increase in the affected area. Compliance with the NAAQS is maintained in Scenarios C, D and E.

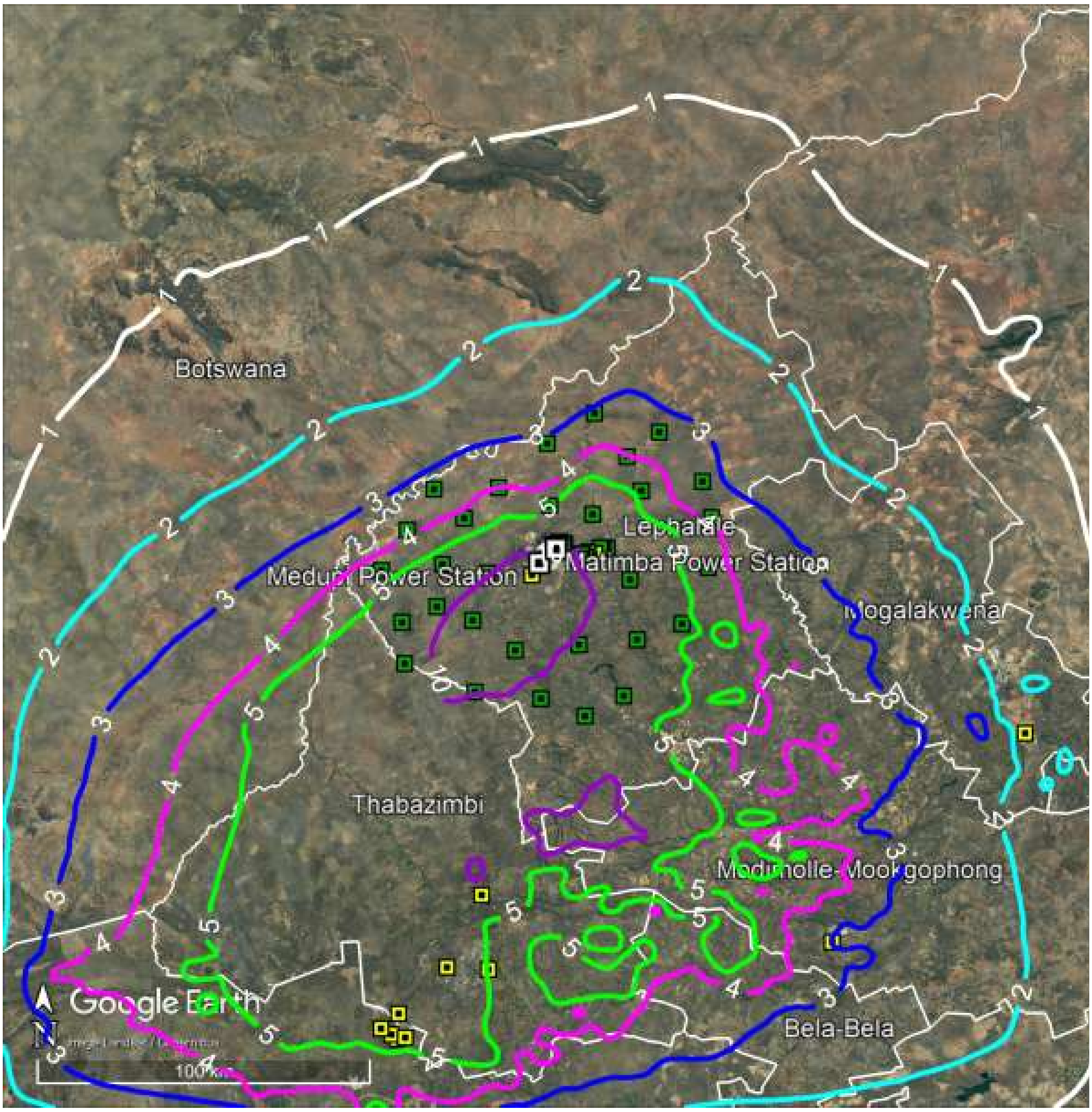

Figure 7-1: Predicted annual average SO_2 concentrations in µg/m³ for Scenario A (NAAQS Limit is 50 µg/m³)

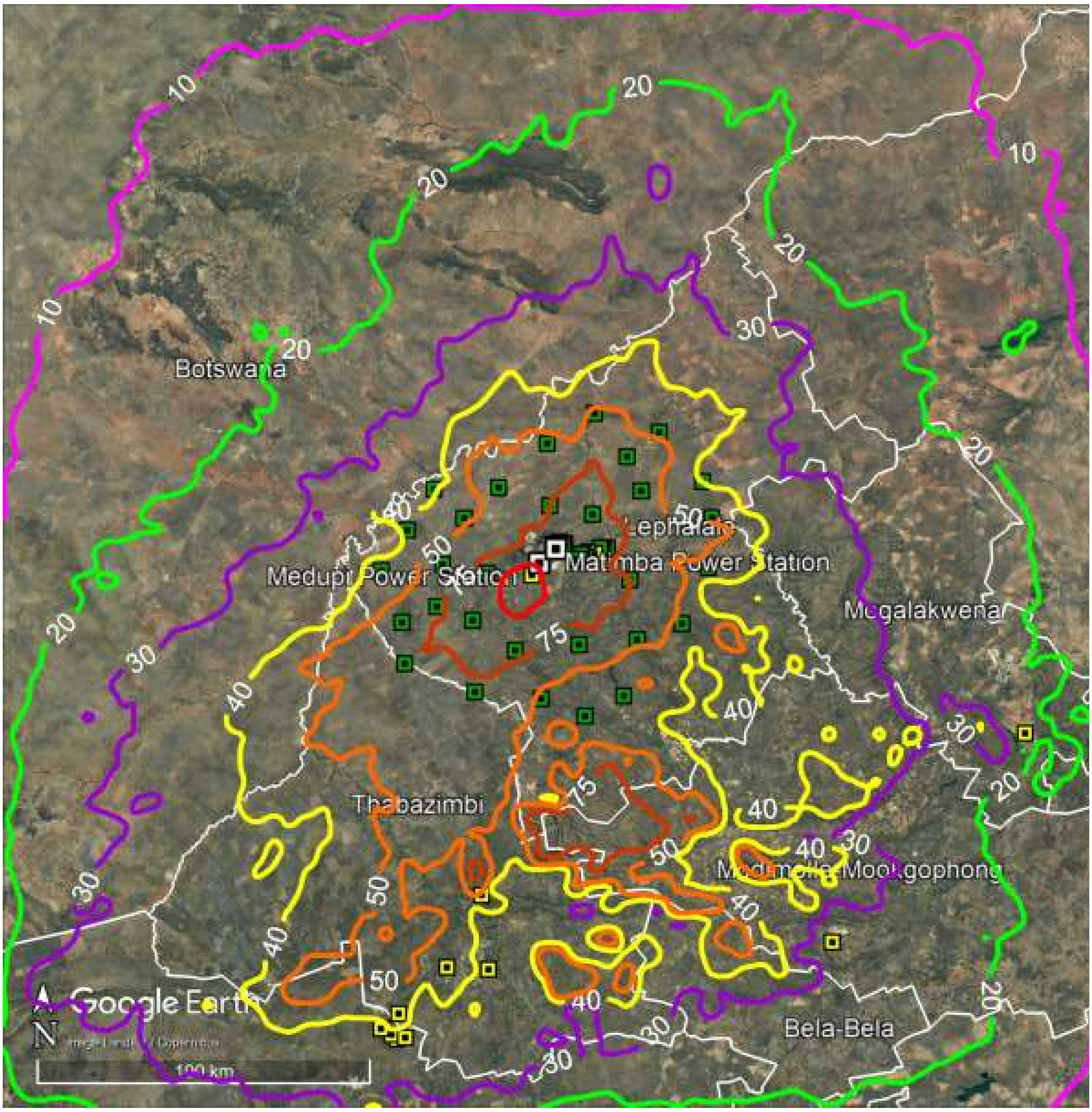

Figure 7-2: Predicted 99th percentile 24-hour SO_2 concentrations in µg/m^3 for Scenario A (NAAQS Limit is 125 µg/m^3)

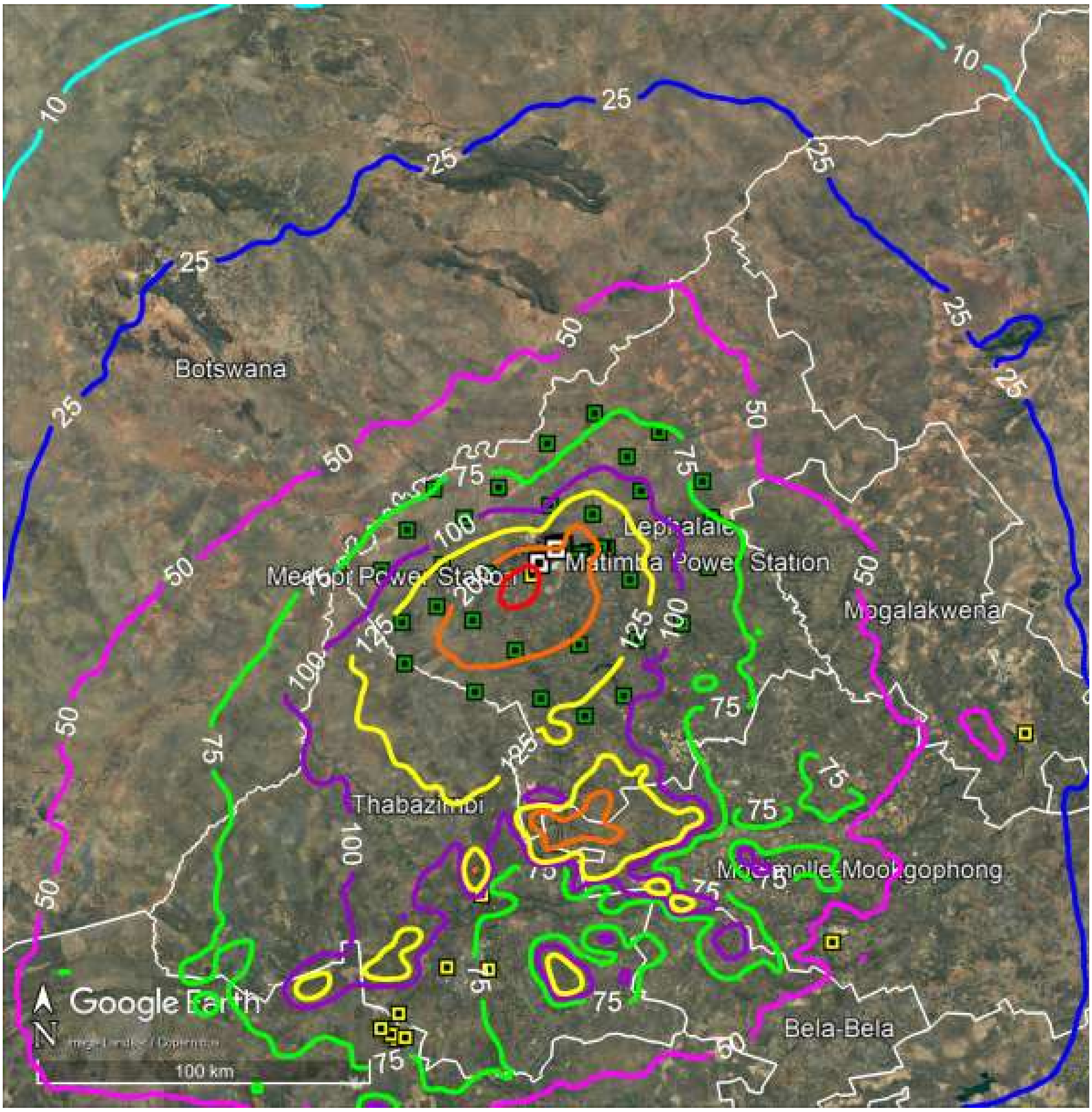

Figure 7-3: Predicted 99th percentile 1-hour SO_2 concentrations in µg/m³ for Scenario A (NAAQS Limit is 350 µg/m³)

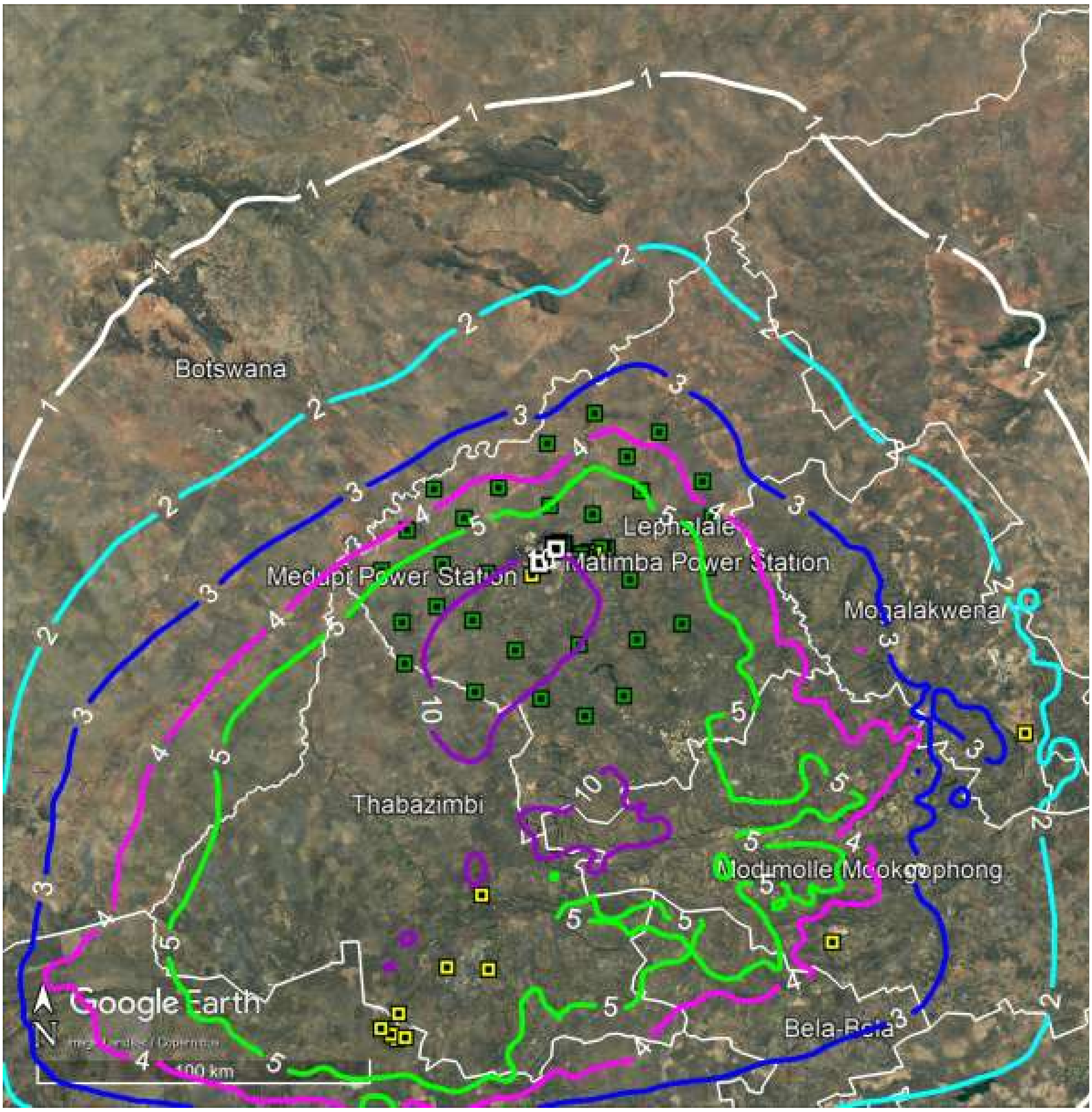

Figure 7-4: Predicted annual average SO_2 concentrations in µg/m³ for Scenario B (NAAQS Limit is 50 µg/m³)

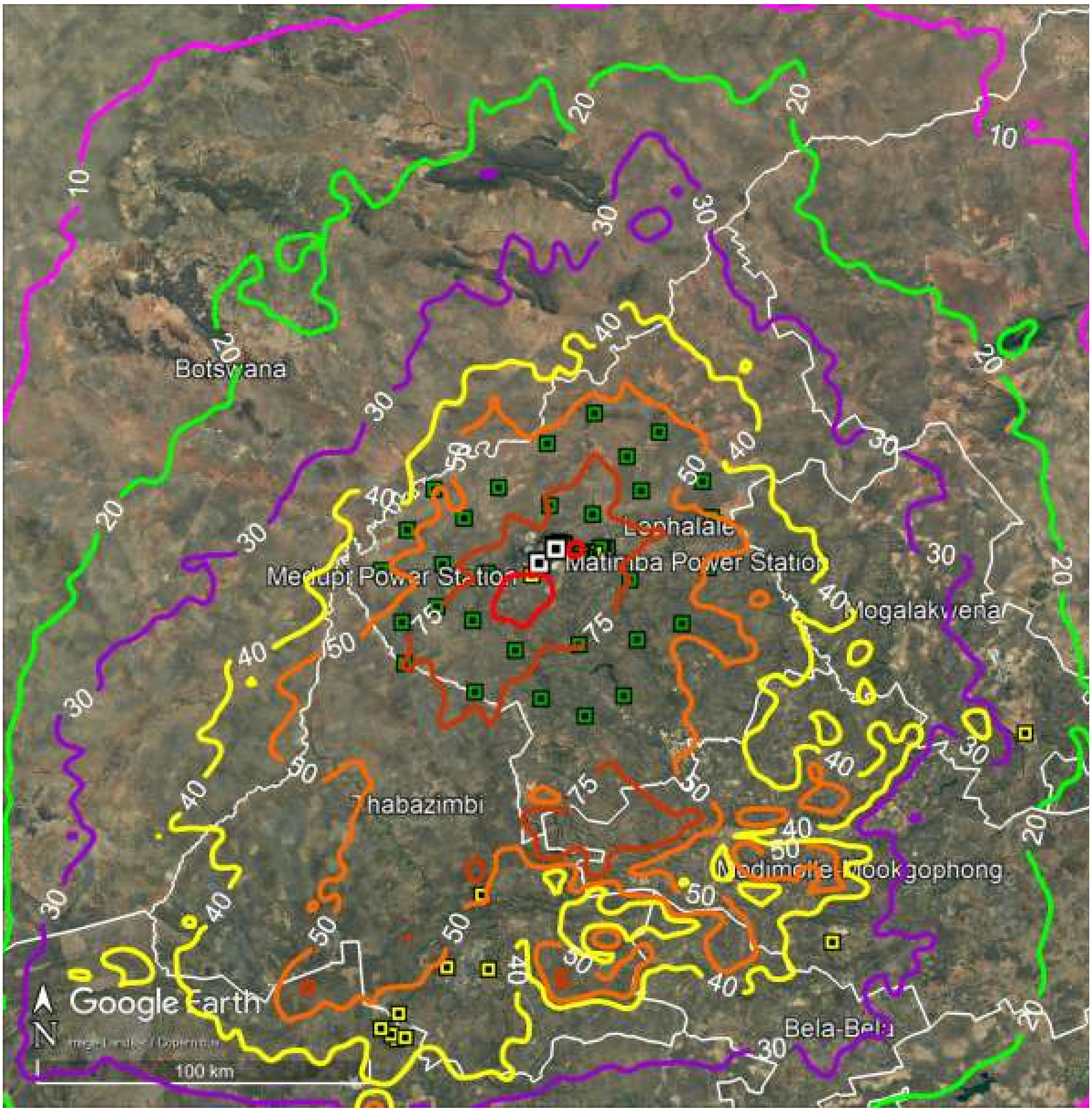

Figure 7-5: Predicted 99th percentile 24-hour SO_2 concentrations in µg/m^3 for Scenario B (NAAQS Limit is 125 µg/m^3)

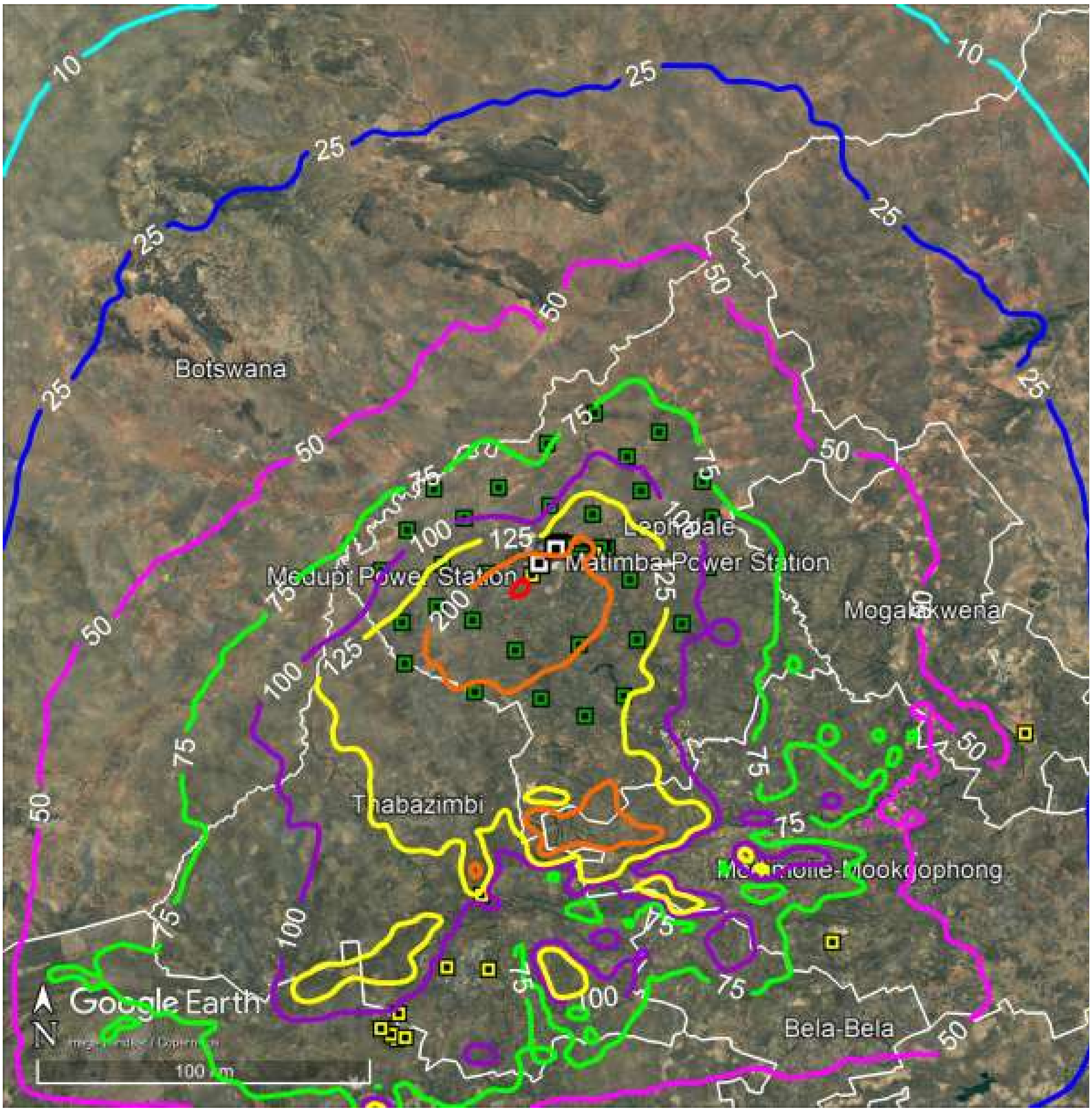

Figure 7-6: Predicted 99th percentile 1-hour SO_2 concentrations in $\mu g/m^3$ for Scenario B (NAAQS Limit is 350 $\mu g/m^3$)

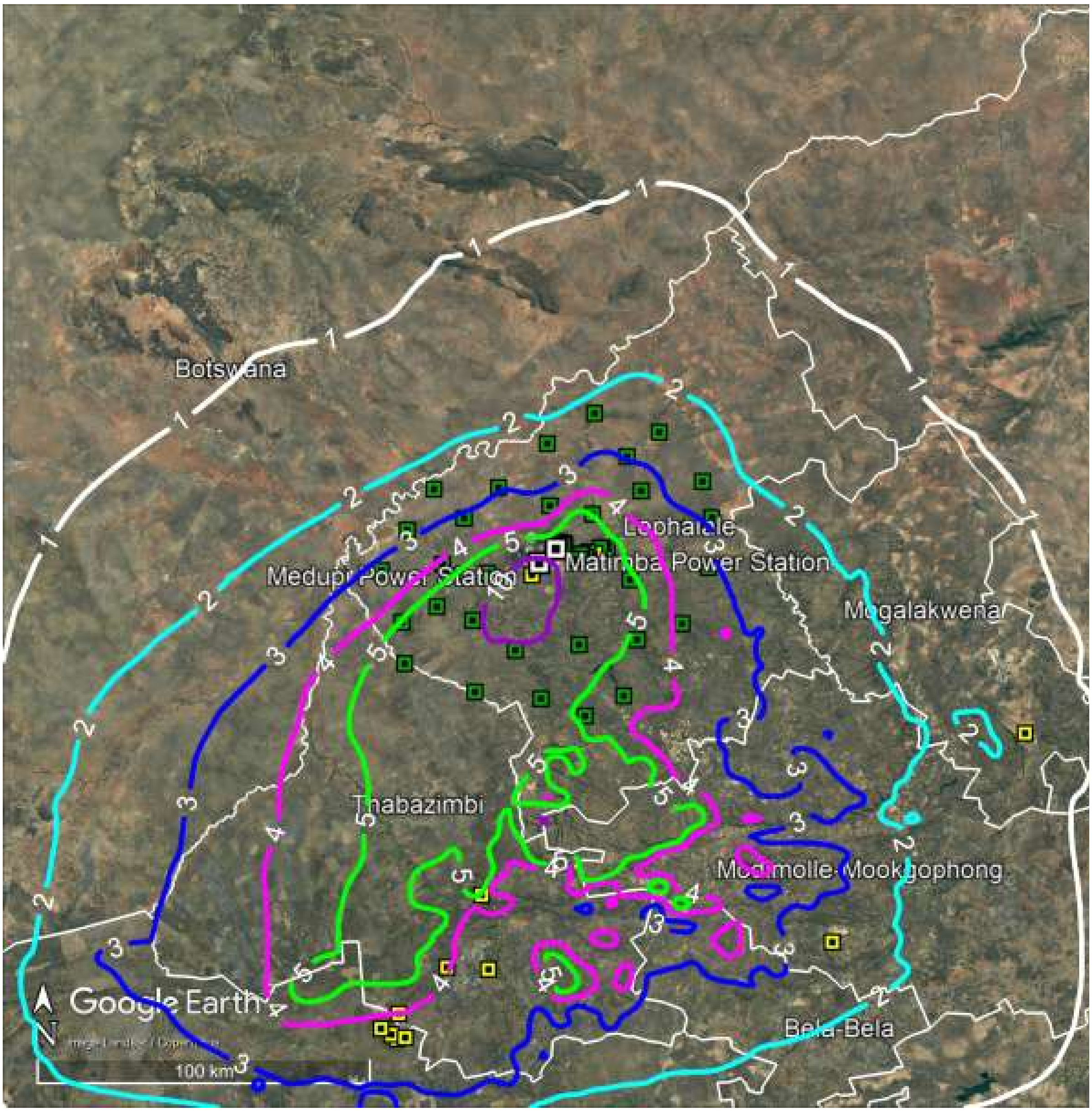

Figure 7-7: Predicted annual average SO_2 concentrations in µg/m³ for Scenario C (NAAQS Limit is 50 µg/m³)

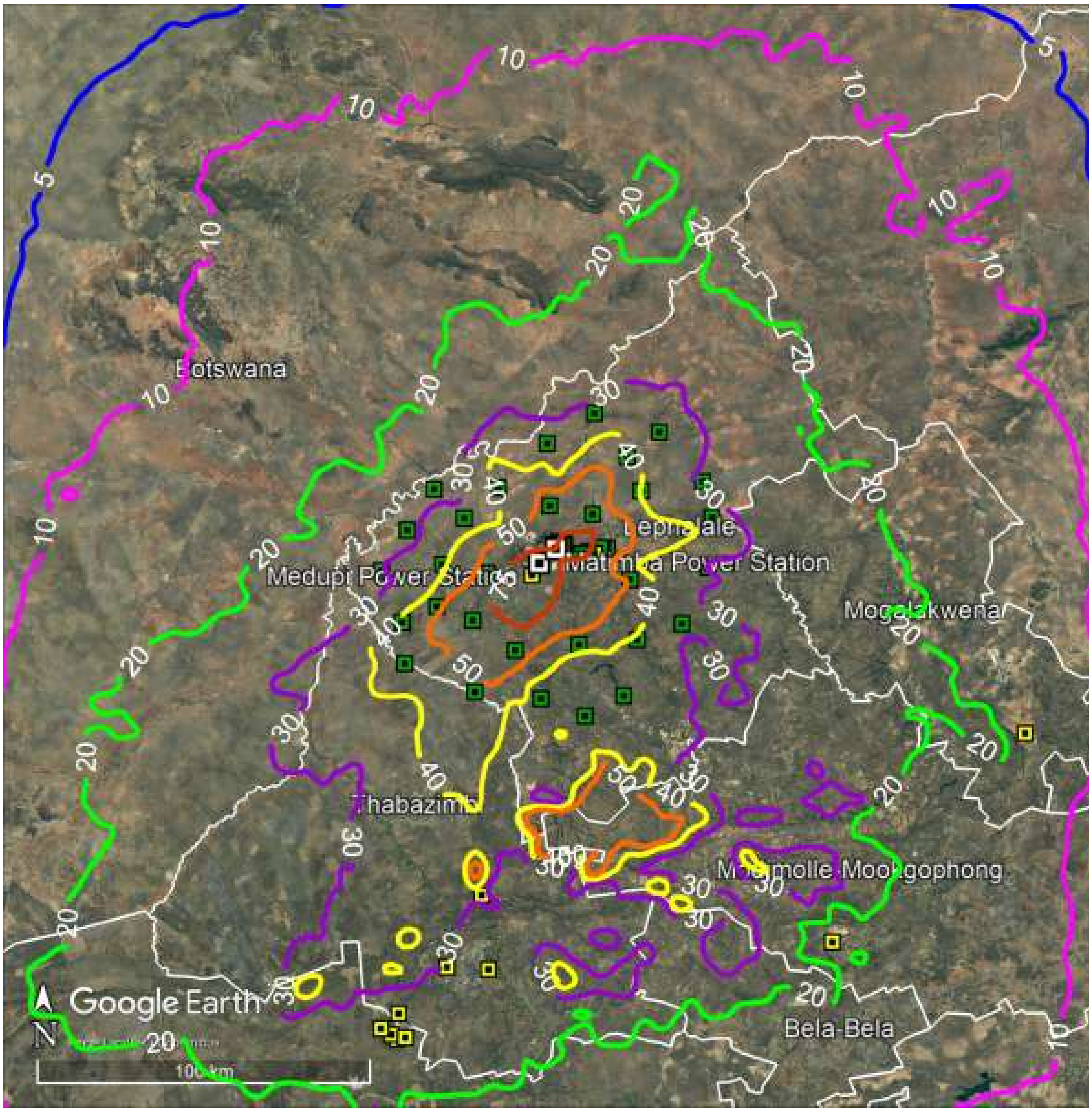

Figure 7-8: Predicted 99th percentile 24-hour SO_2 concentrations in µg/m^3 for Scenario C (NAAQS Limit is 125 µg/m^3)

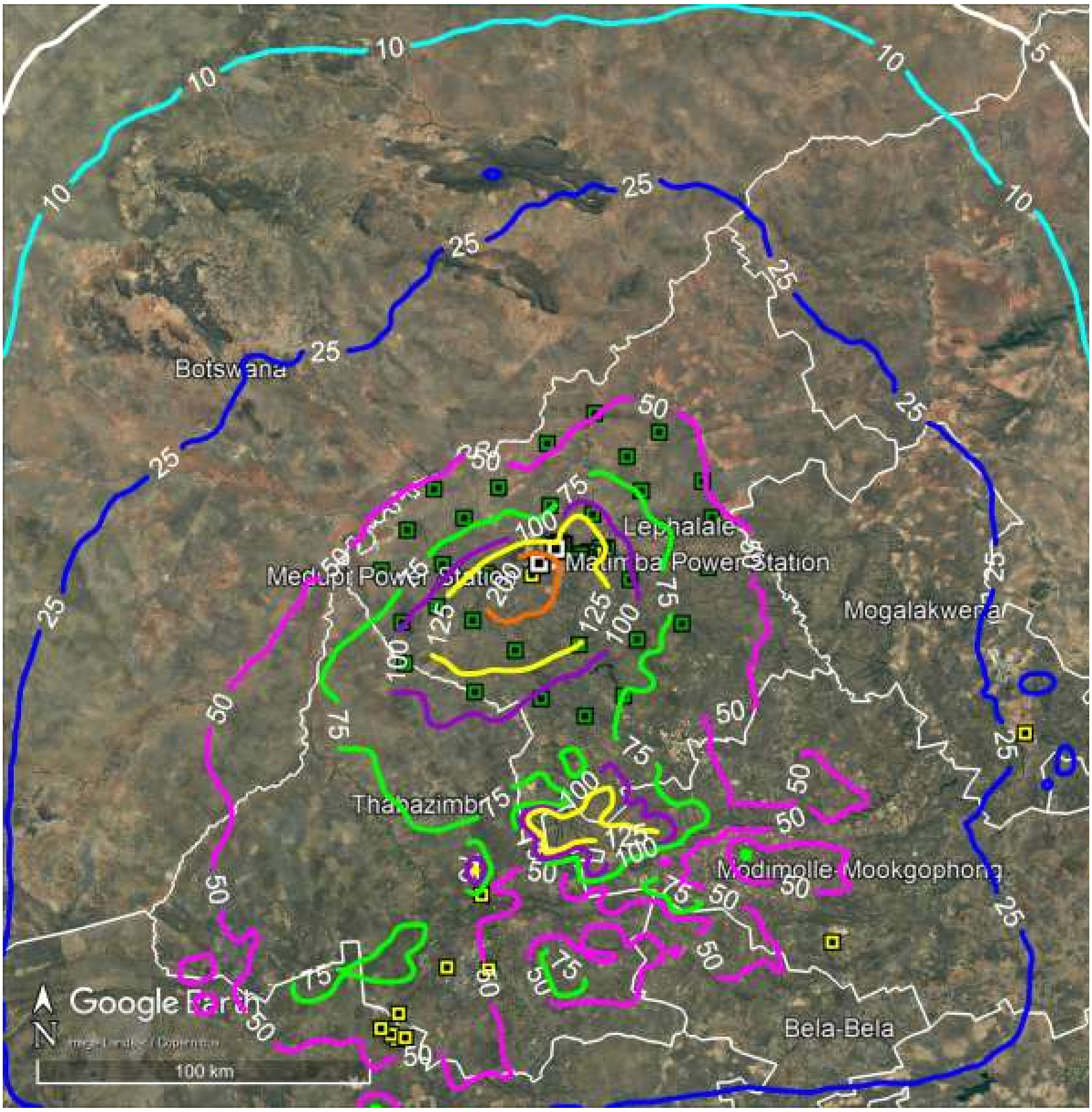

Figure 7-9: Predicted 99[th] percentile 1-hour SO_2 concentrations in µg/m³ for Scenario C (NAAQS Limit is 350 µg/m³)

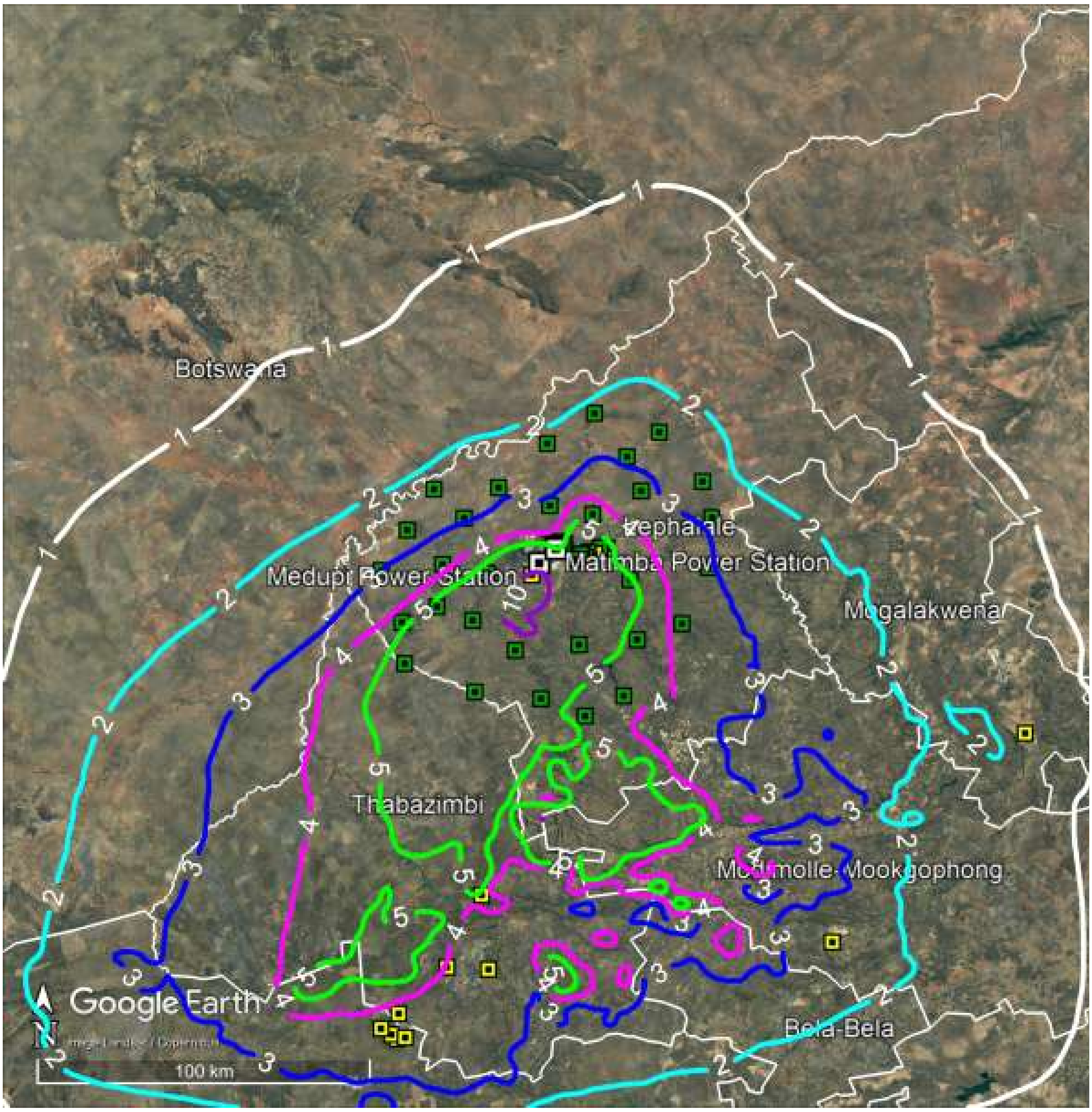

Figure 7-10: Predicted annual average SO_2 concentrations in µg/m^3 for Scenario D (NAAQS Limit is 50 µg/m^3)

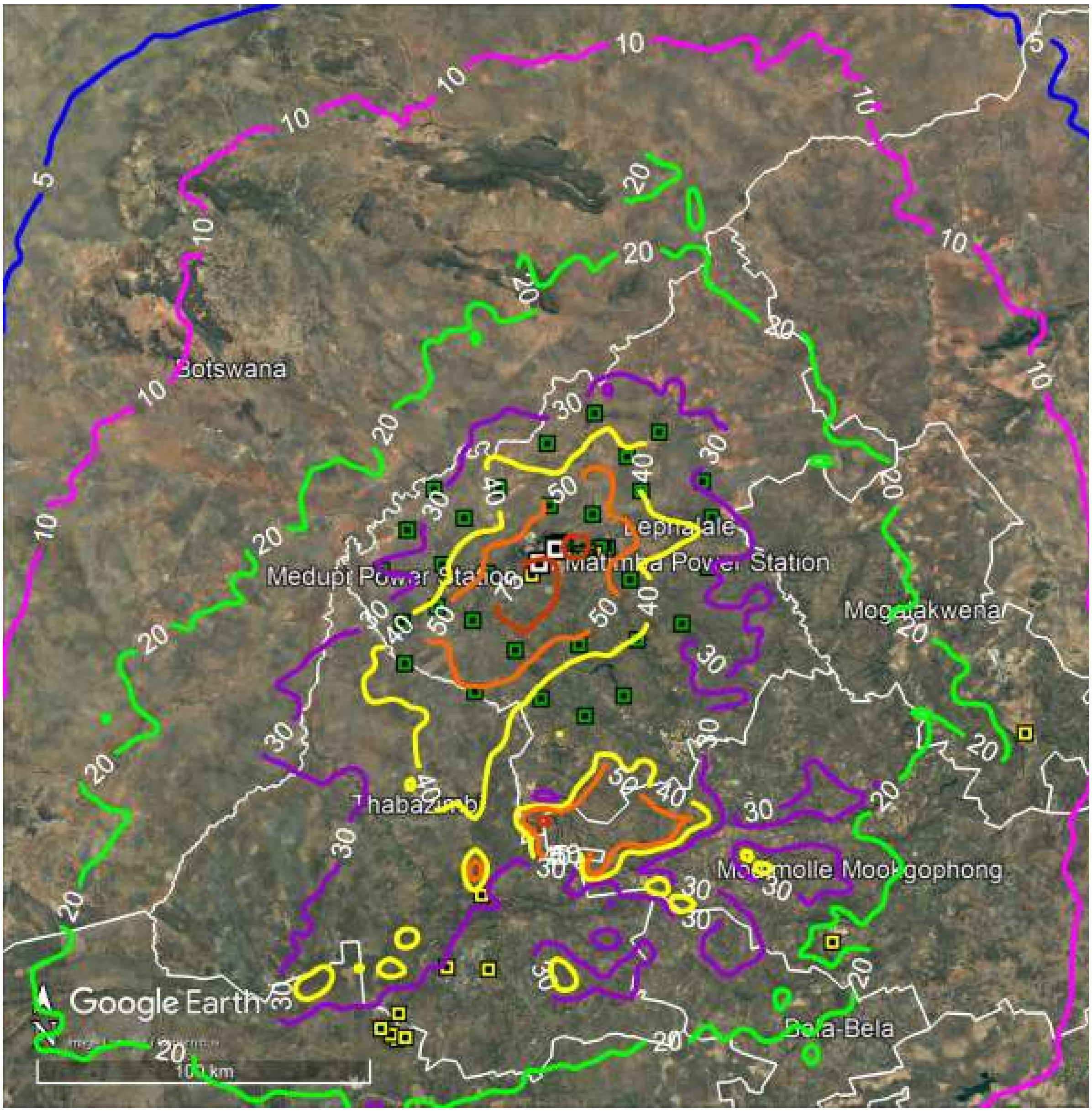

Figure 7-11: Predicted 99th percentile 24-hour SO_2 concentrations in µg/m³ for Scenario D (NAAQS Limit is 125 µg/m³)

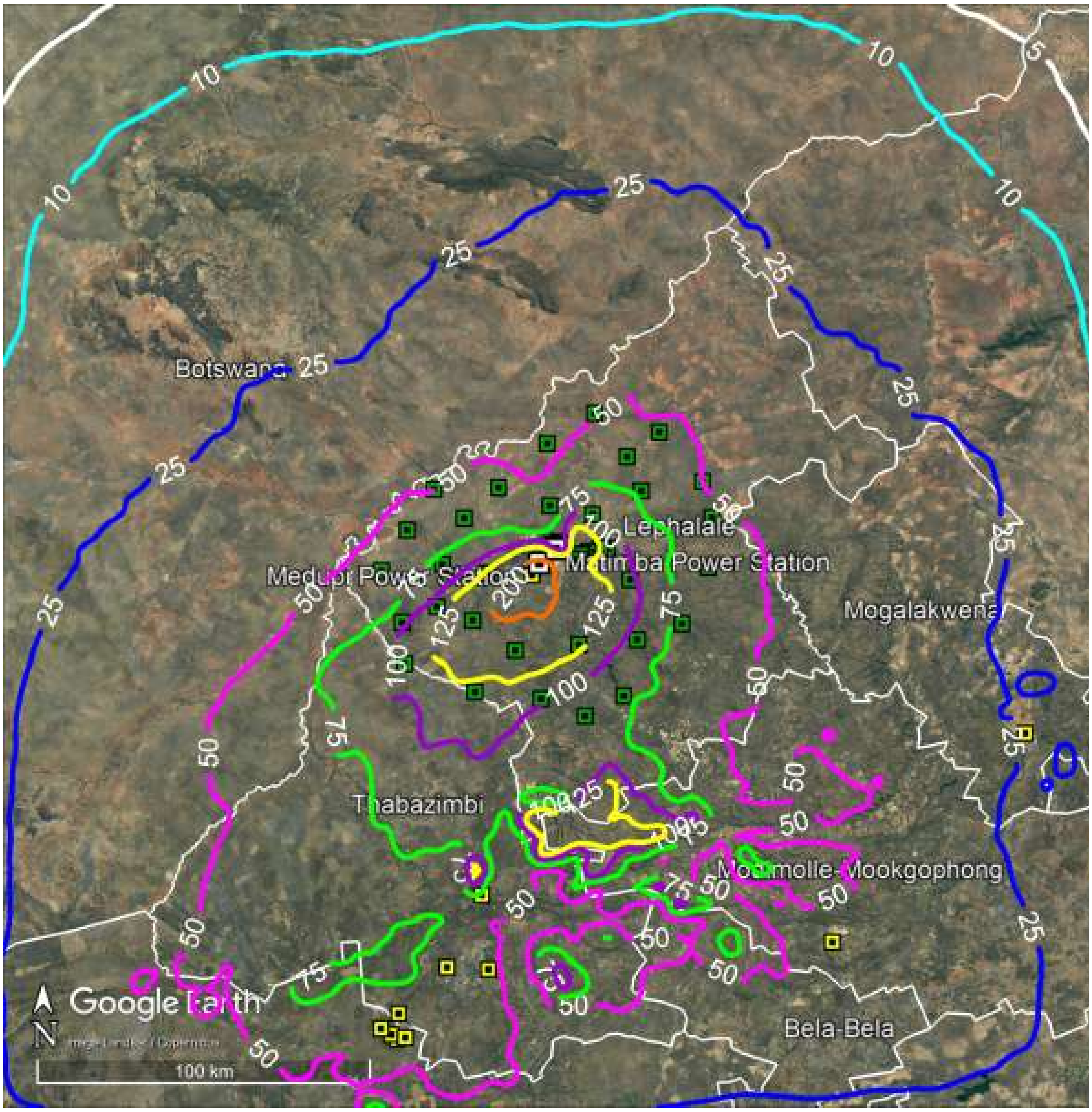

Figure 7-12: Predicted 99th percentile 1-hour SO_2 concentrations in µg/m³ for Scenario D (NAAQS Limit is 350 µg/m³)

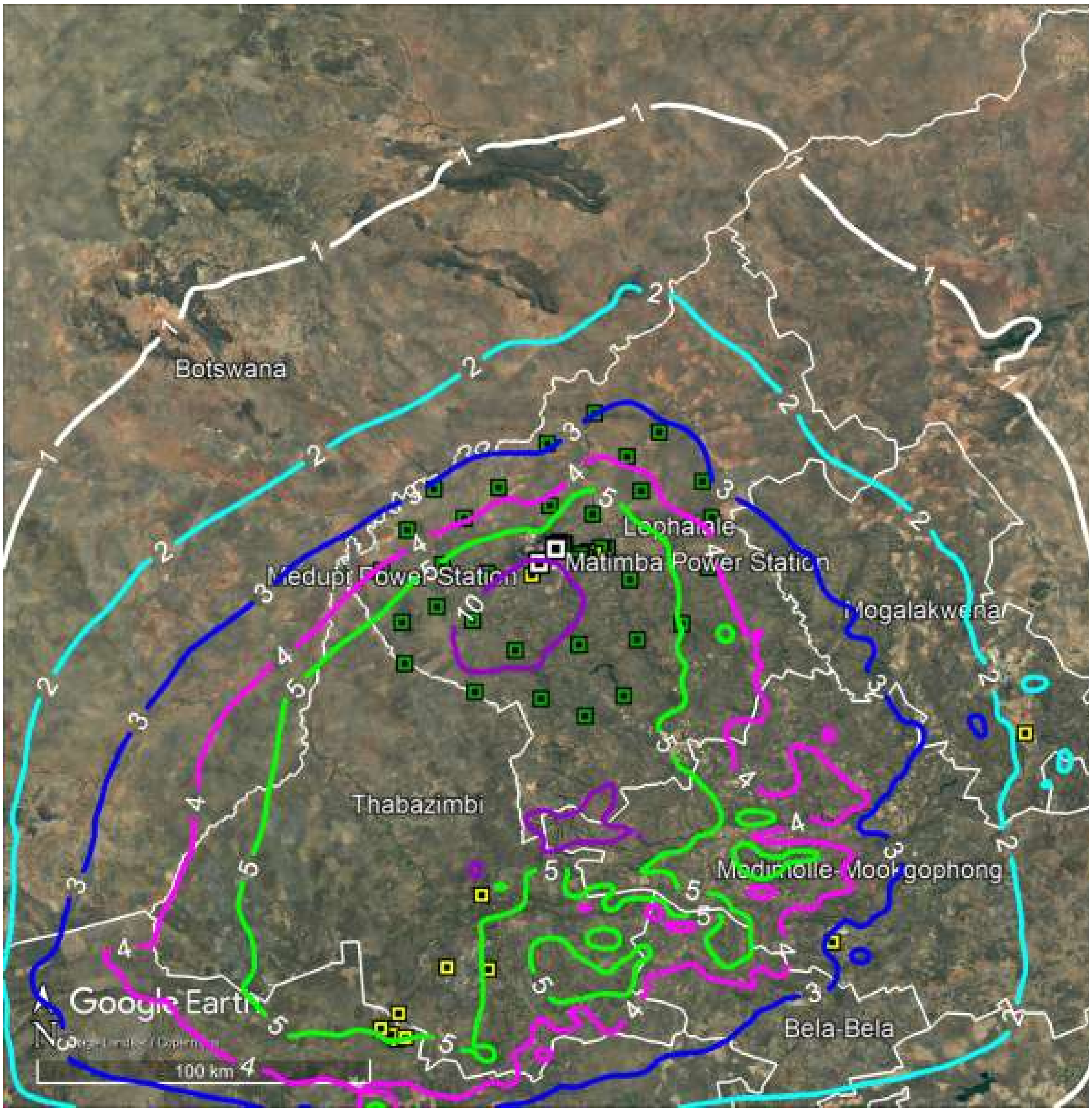

Figure 7-13: Predicted annual average SO_2 concentrations in µg/m³ for Scenario E (NAAQS Limit is 50 µg/m³)

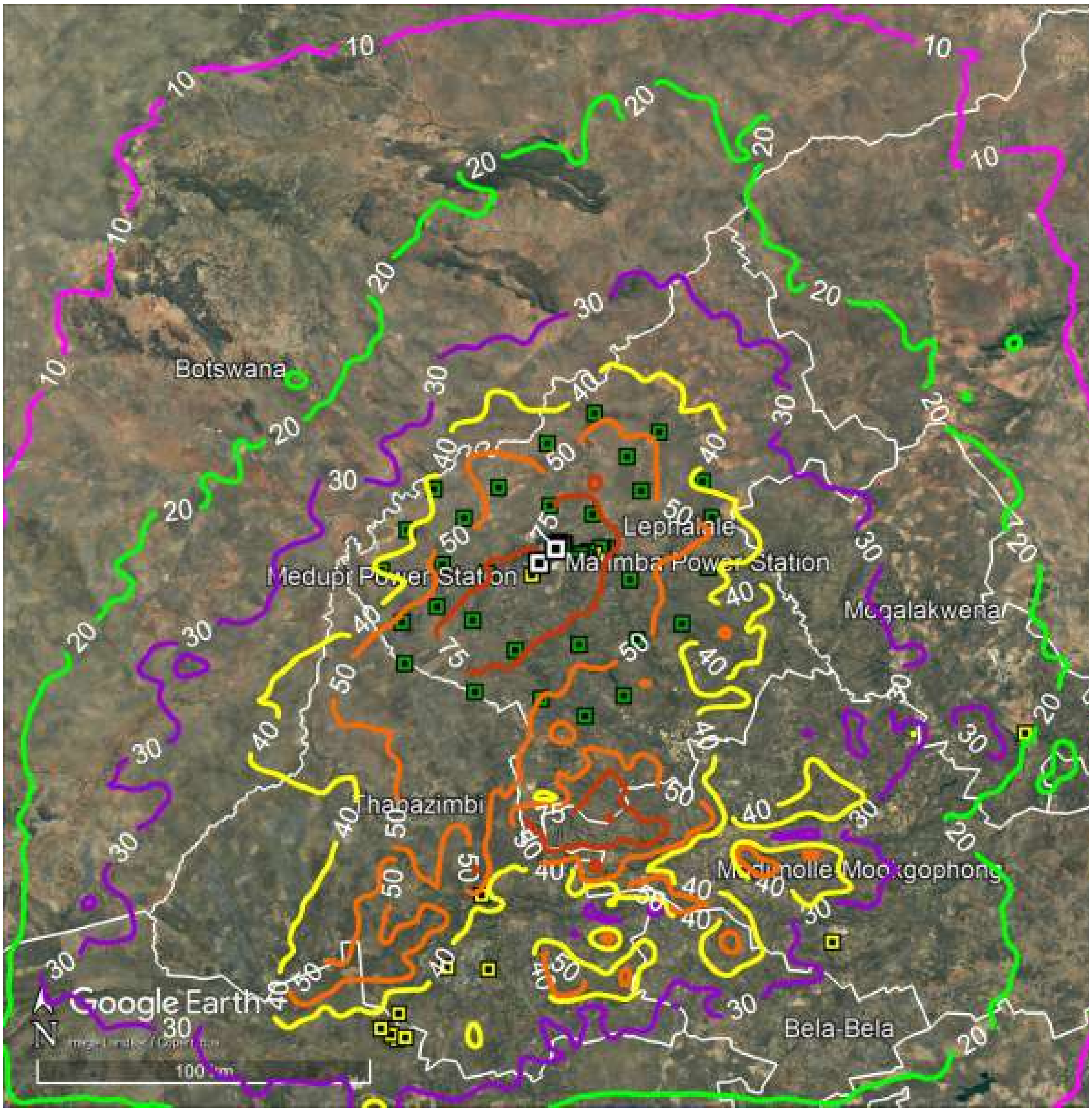

Figure 7-14: Predicted 99th percentile 24-hour SO_2 concentrations in µg/m³ for Scenario E (NAAQS Limit is 125 µg/m³)

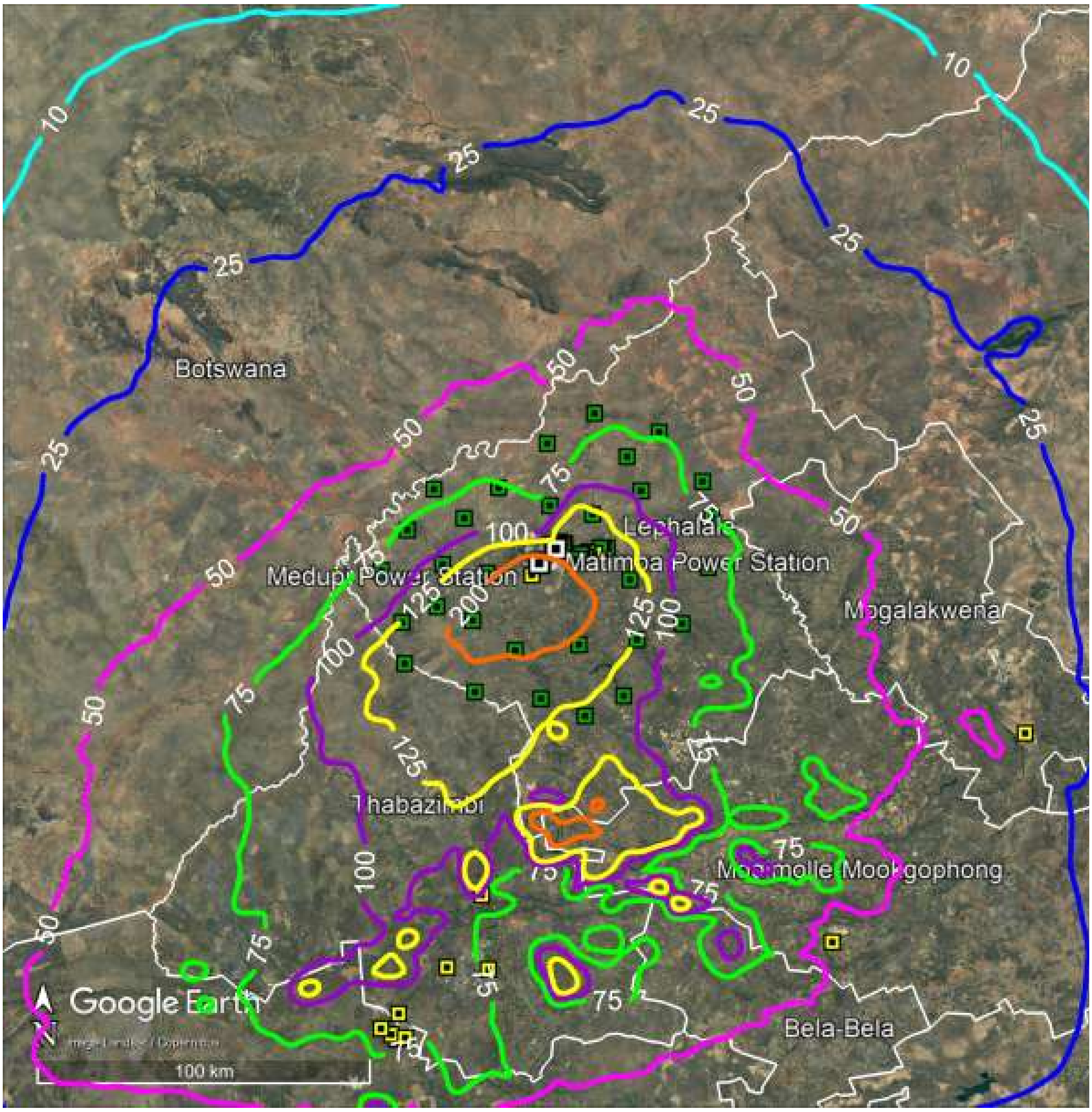

Figure 7-15: Predicted 99th percentile 1-hour SO_2 concentrations in µg/m³ for Scenario E (NAAQS Limit is 350 µg/m³)

7.3.2 Particulates (PM_{10})

Isopleth maps for PM_{10} concentrations are presented in Figure 7-16 to Figure 7-25.

The isopleth maps showing the predicted annual average PM_{10} concentrations clearly demonstrate the influence of the predominant northeasterly winds, with dispersion generally occurring to the southwest of the power stations. In all scenarios, the highest predicted annual average concentrations occur between 5 and 10 km from the power stations, predominantly to the southwest.

The predicted PM_{10} concentrations are attributed to stack emissions, low-level fugitive sources (including coal stockyards, ash dumps and gypsum disposal facilities), and contributions from secondary particulate formation. For PM_{10}, the maximum predicted annual average and 99th percentile 24-hour concentrations remain below the applicable NAAQS limit values in all scenarios.

Low-level fugitive emissions from the coal stockyard and ash dump are consistent across all scenarios and make a significant contribution to ambient PM_{10} concentrations. Fugitive emissions from the gypsum storage facility are introduced in Scenarios C, D and E and differ between these scenarios based on the respective technology options; however, they do not make a significant contribution to ambient PM_{10} concentrations. Fugitive emissions have the greatest impact on ambient concentrations close to the source, whereas the influence of stack emissions is generally observed further from the power stations.

For the annual and 24-hour predictions, the change from Scenario A to Scenario B, characterised by an increase in PM_{10} stack emissions at Medupi and a decrease at Matimba, is reflected in the modelled results as a slight increase in the affected area. A reduction in PM_{10} stack emissions at Medupi in Scenario C, followed by an increase in Scenario D, results in a marked reduction in the affected area in both scenarios. In contrast, the reduction in PM_{10} stack emissions at Medupi from Scenario D to Scenario E is reflected in the modelled results as a marked increase in the affected area.

It is evident that the influence of stack emission changes between scenarios is strongly affected by stack exit velocities and exit temperatures. The resultant ambient PM_{10} concentrations are also dependent on contributions from secondary particulates, which in turn depend on SO_2 and NO_X stack emissions. Consequently, there is no linear relationship between PM_{10} emission changes across the scenarios and the resulting ambient PM_{10} concentrations.

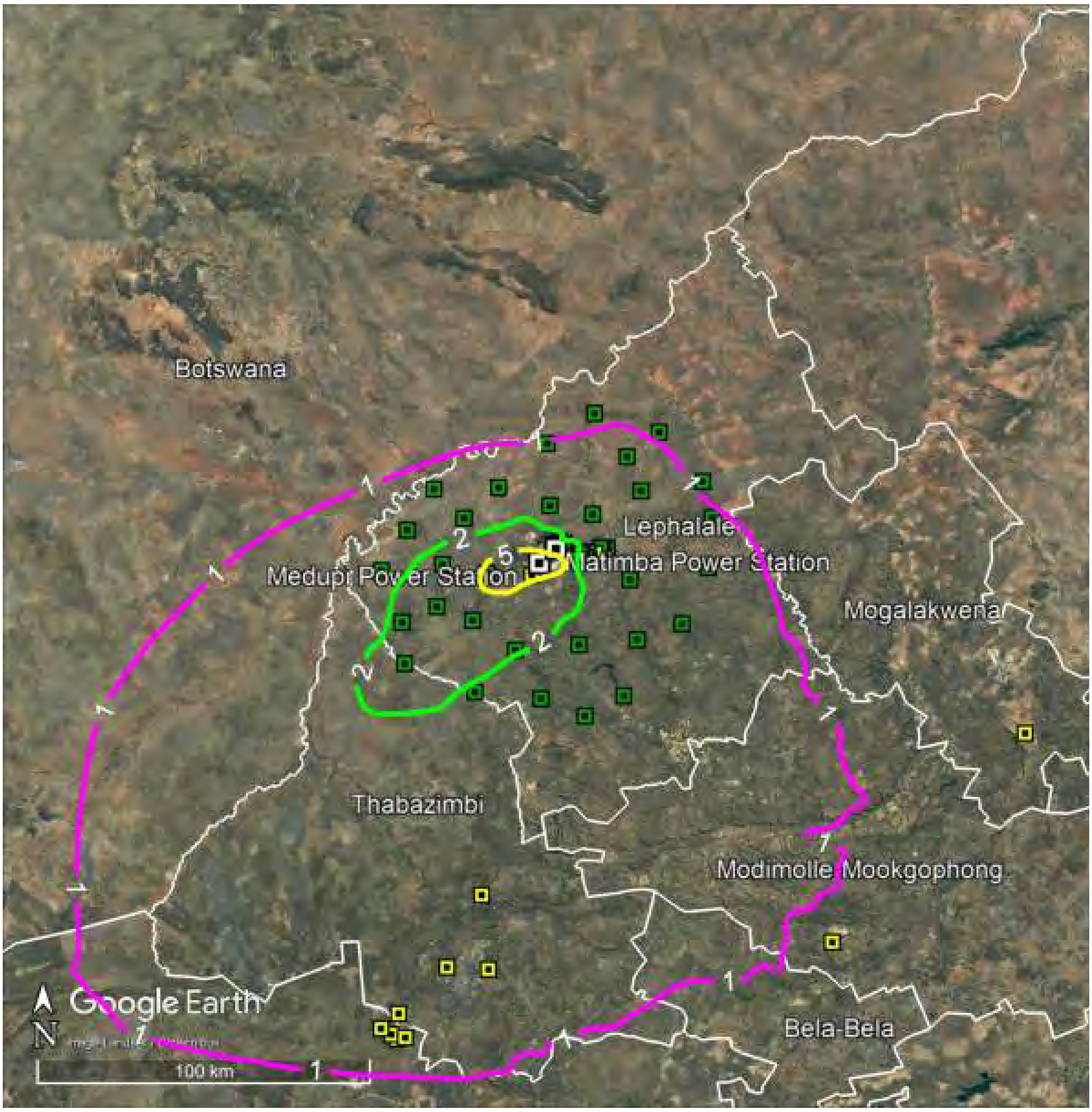

Figure 7-16: Predicted annual average PM_{10} concentrations in µg/m³ for Scenario A (NAAQS Limit is 40 µg/m³)

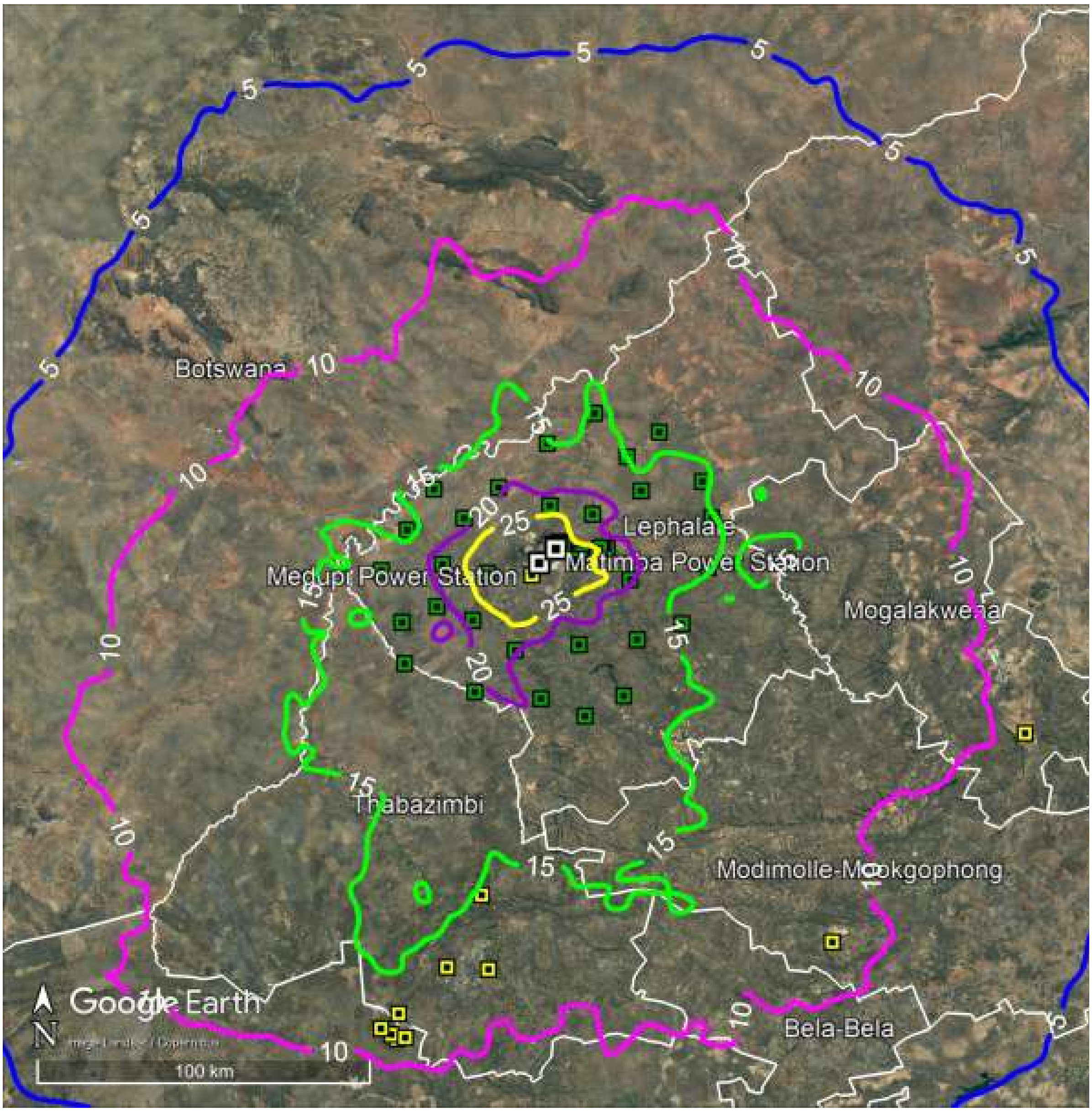

Figure 7-17: Predicted 99th percentile of the 24-hour PM_{10} concentrations in µg/m³ for Scenario A (NAAQS Limit is 75 µg/m³)

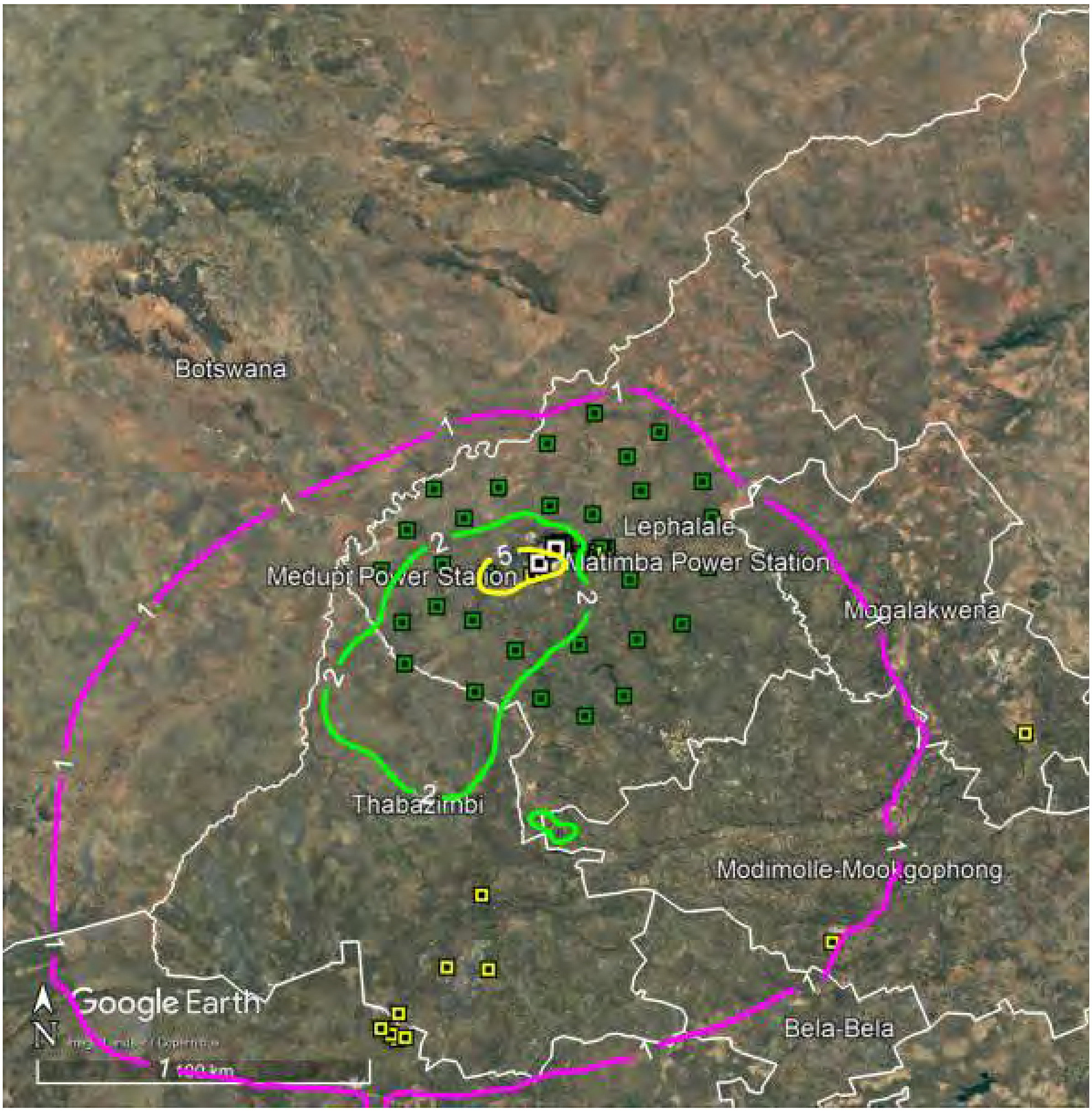

Figure 7-18: Predicted annual average PM_{10} concentrations in µg/m³ for Scenario B (NAAQS Limit is 40 µg/m³)

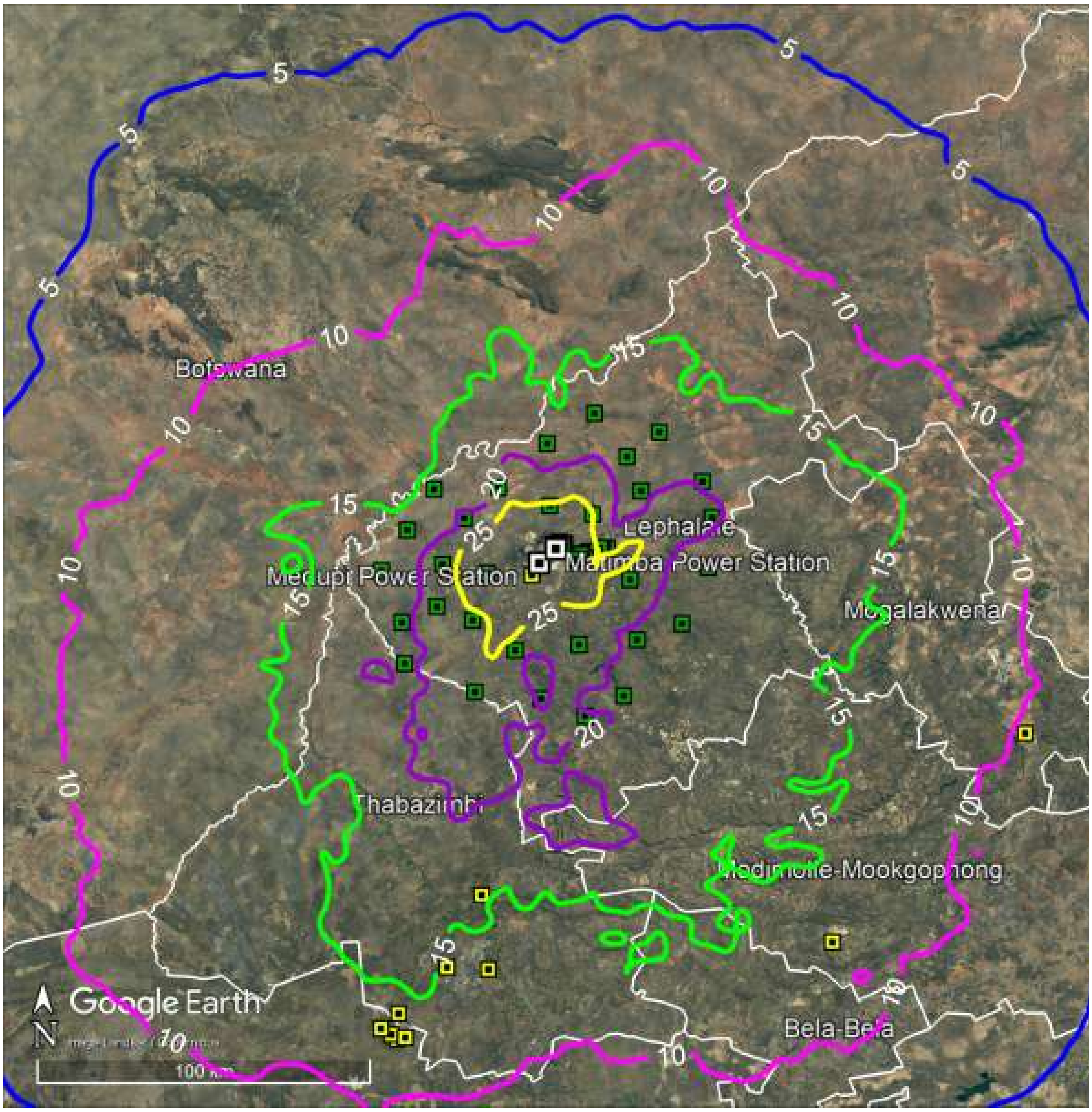

Figure 7-19: Predicted 99th percentile of the 24-hour PM_{10} concentrations in µg/m^3 for Scenario B (NAAQS Limit is 75 µg/m^3)

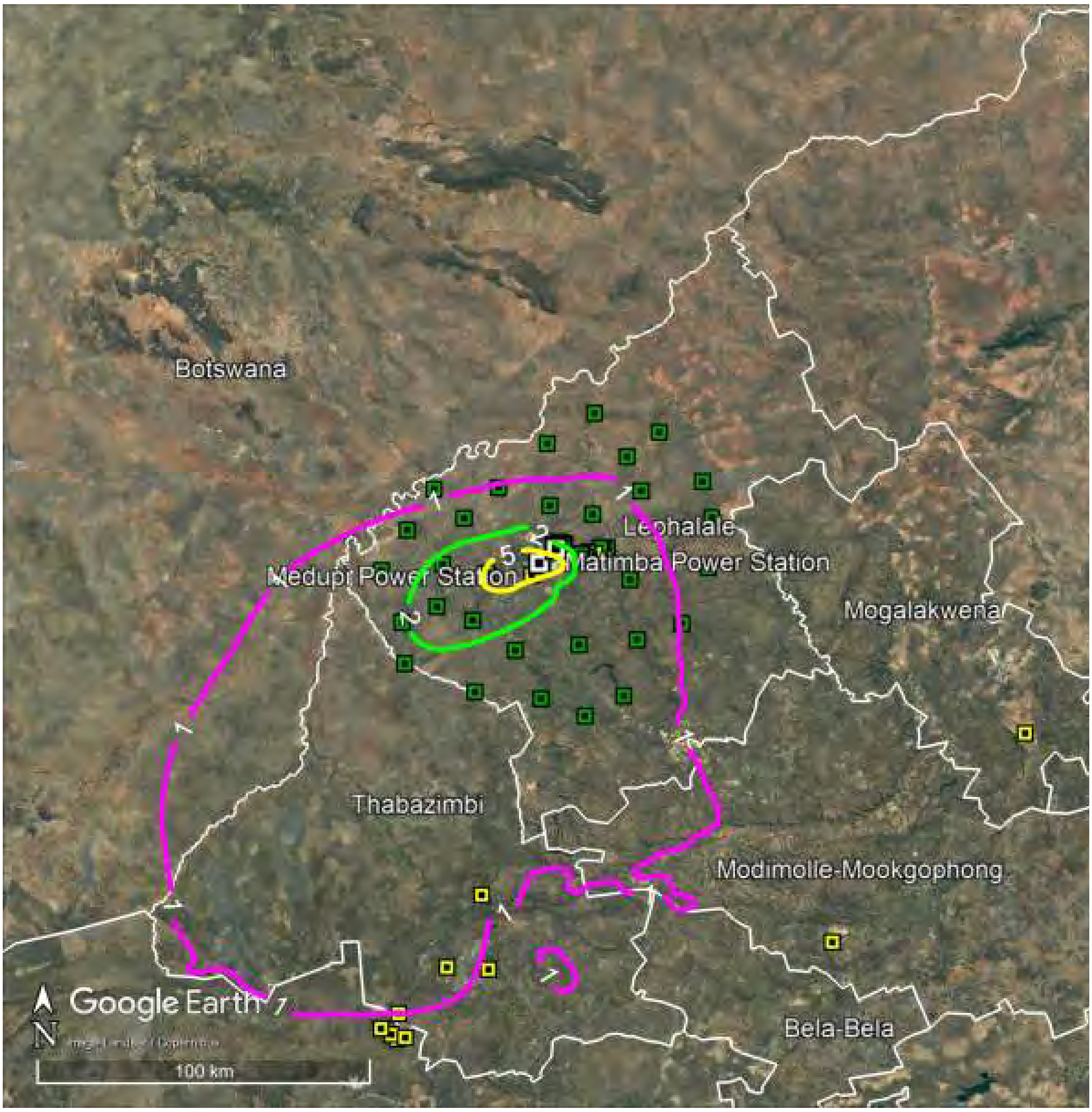

Figure 7-20: Predicted annual average PM_{10} concentrations in µg/m³ for Scenario C (NAAQS Limit is 40 µg/m³)

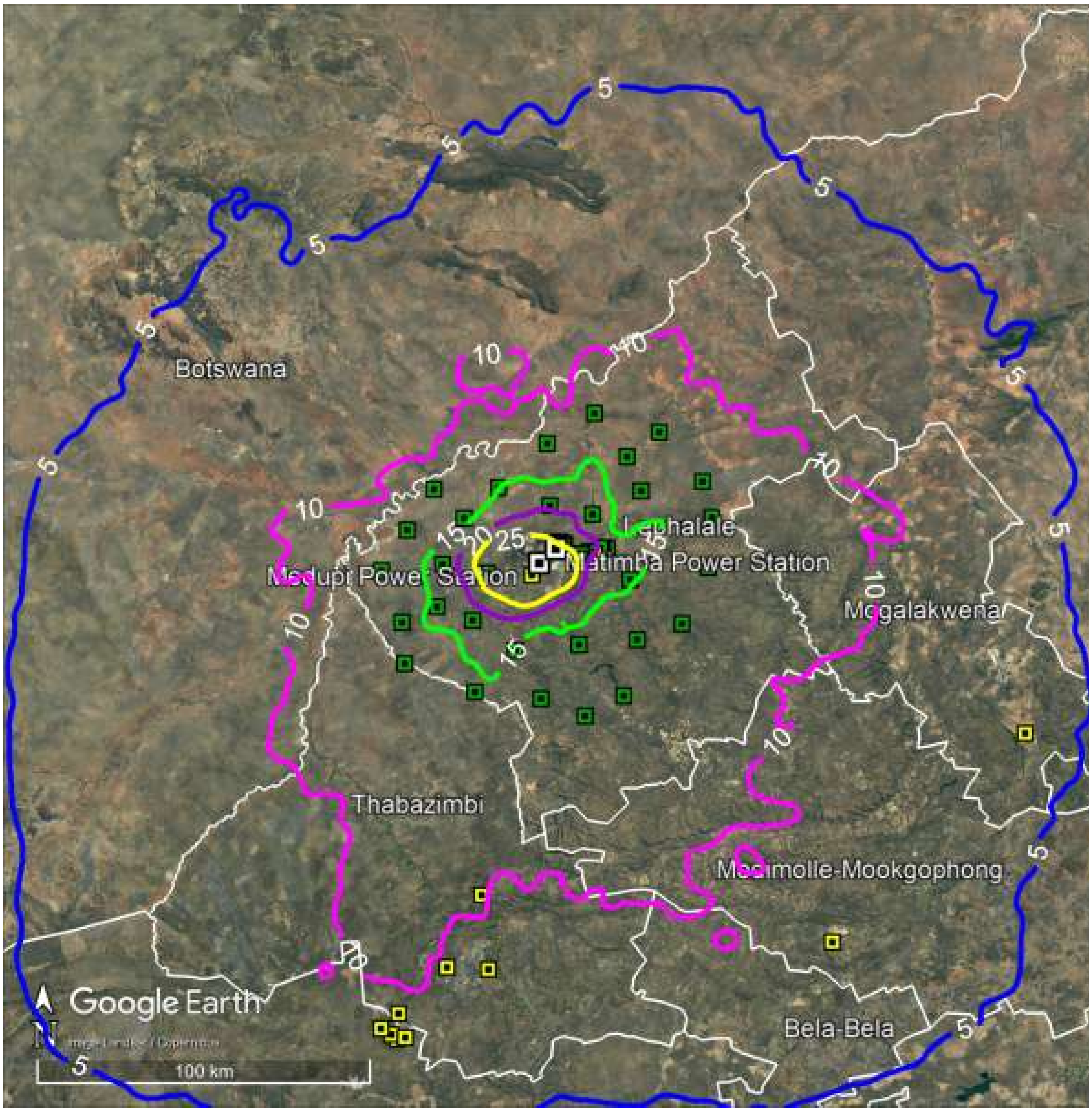

Figure 7-21: Predicted 99th percentile of the 24-hour PM_{10} concentrations in µg/m³ for Scenario C (NAAQS Limit is 75 µg/m³)

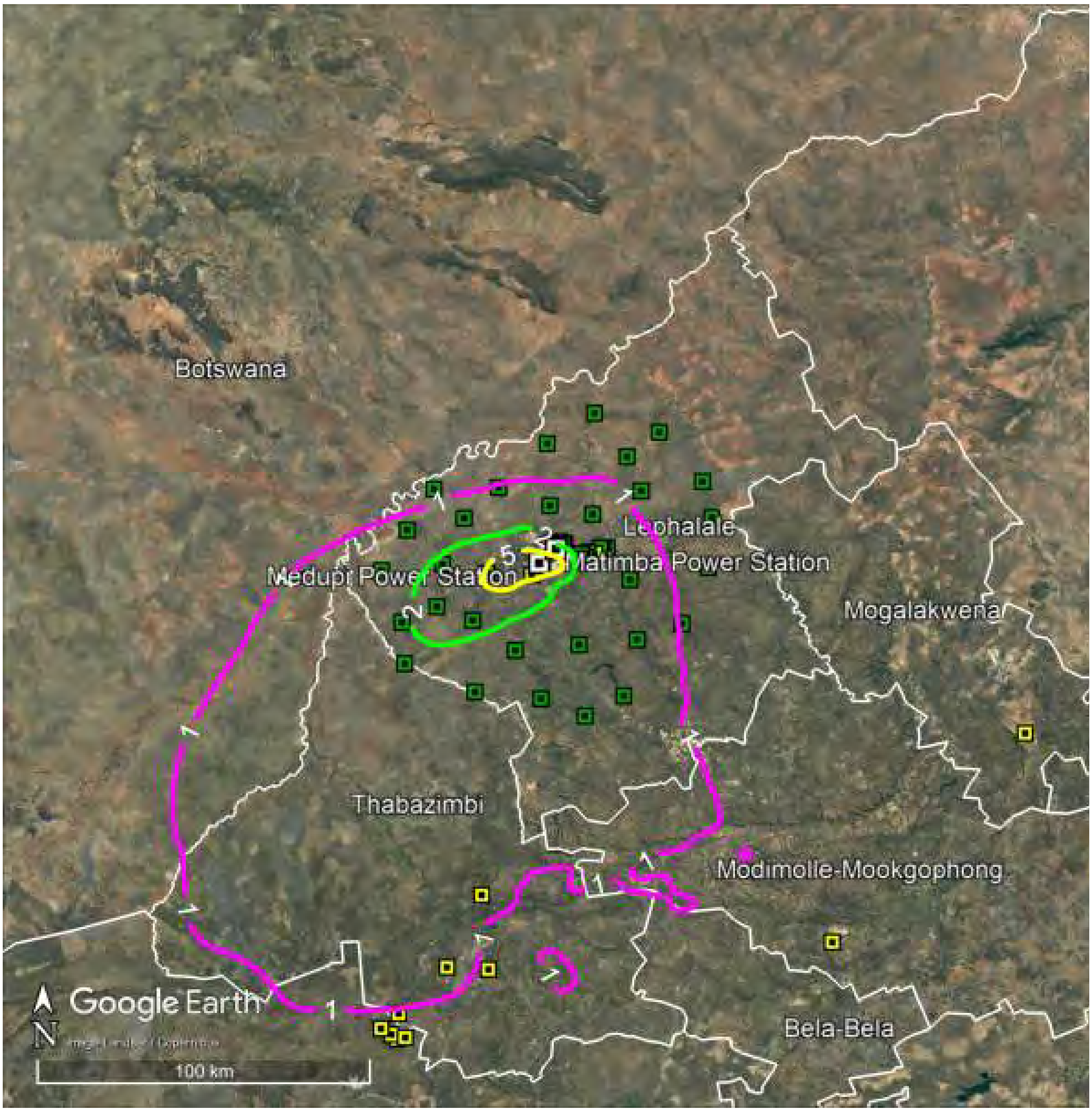

Figure 7-22: Predicted annual average PM_{10} concentrations in µg/m³ for Scenario D (NAAQS Limit is 40 µg/m³)

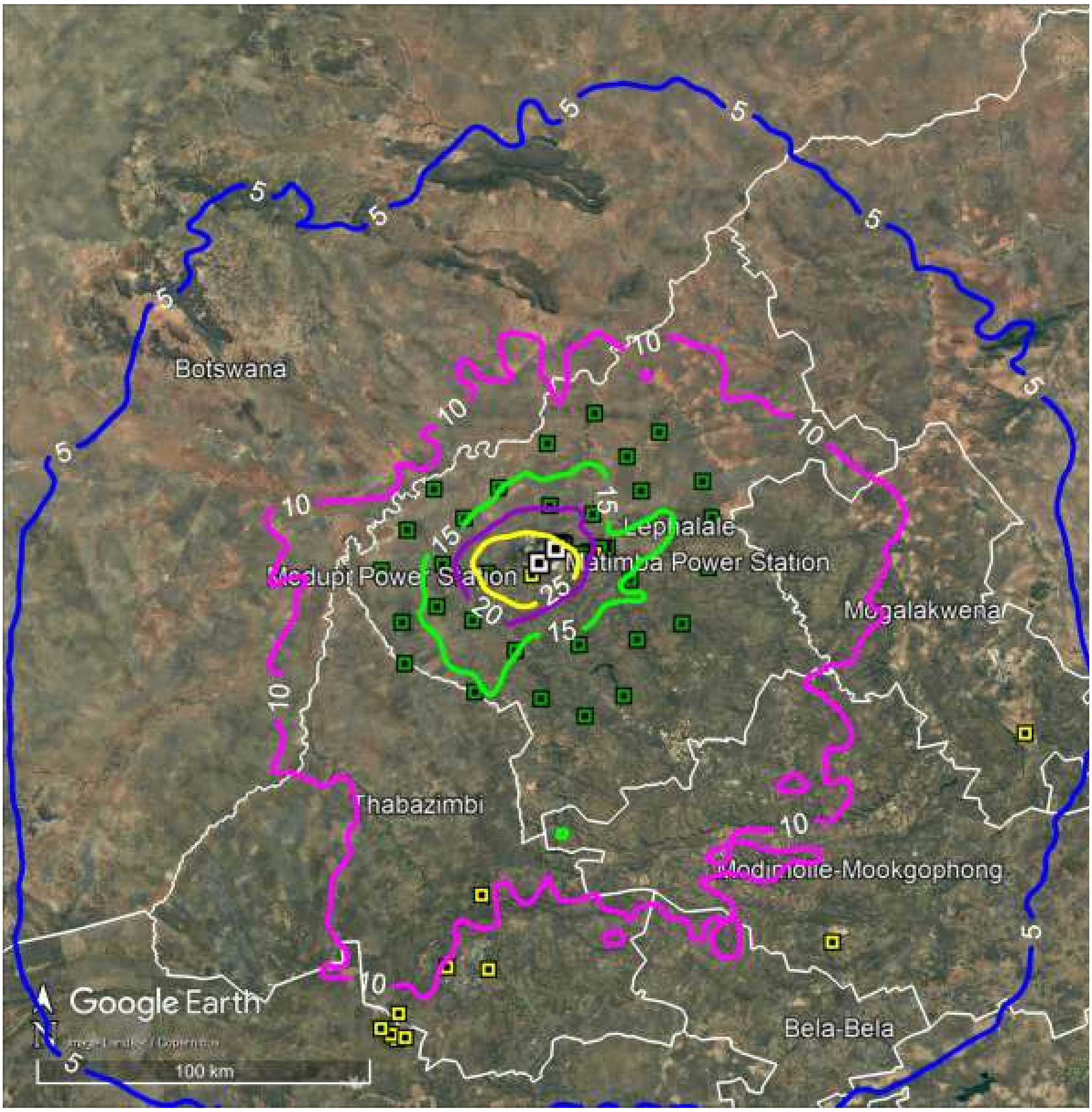

Figure 7-23: Predicted 99th percentile of the 24-hour PM_{10} concentrations in µg/m³ for Scenario D (NAAQS Limit is 75 µg/m³)

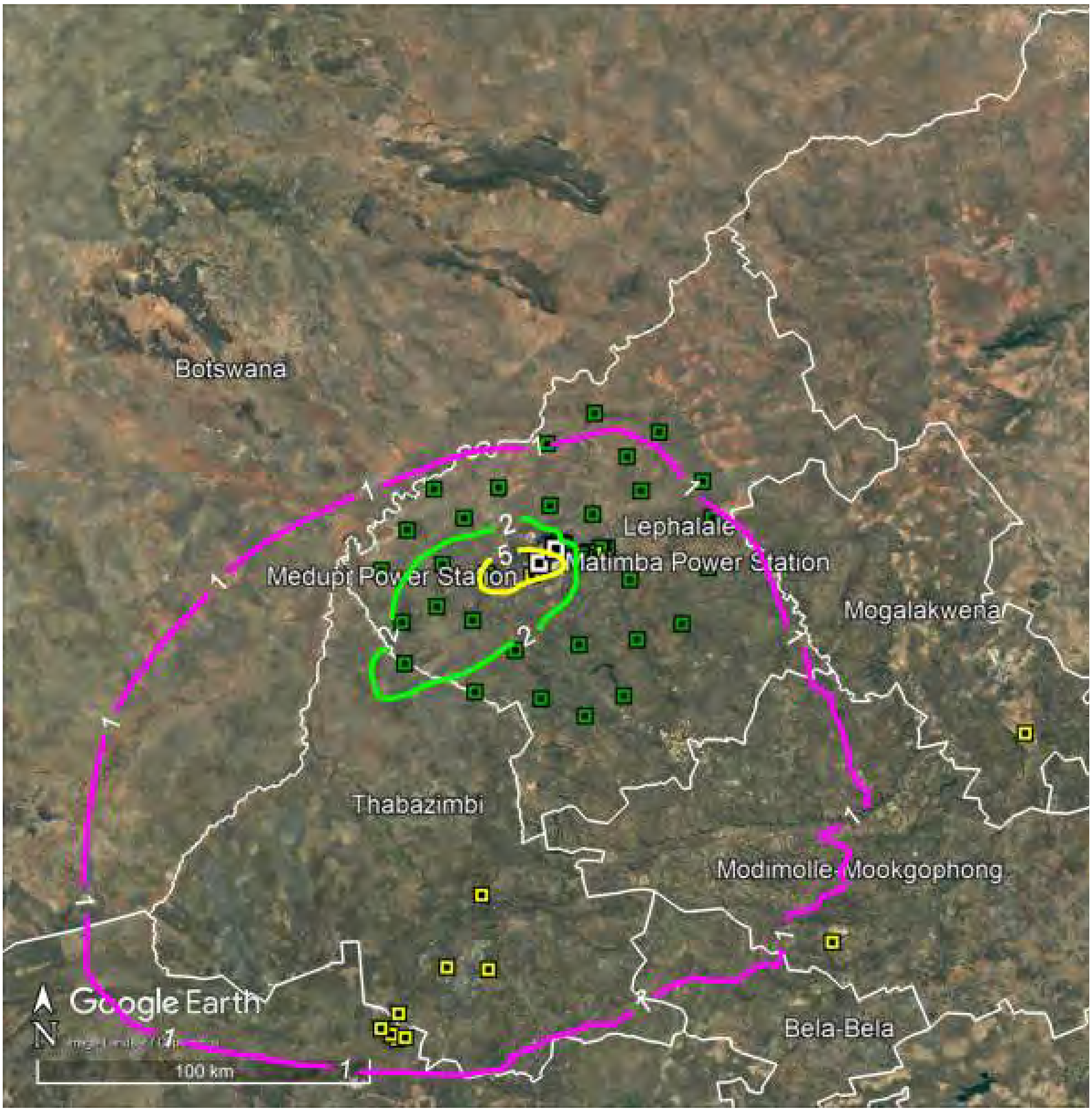

Figure 7-24: Predicted annual average PM_{10} concentrations in µg/m³ for Scenario E (NAAQS Limit is 40 µg/m³)

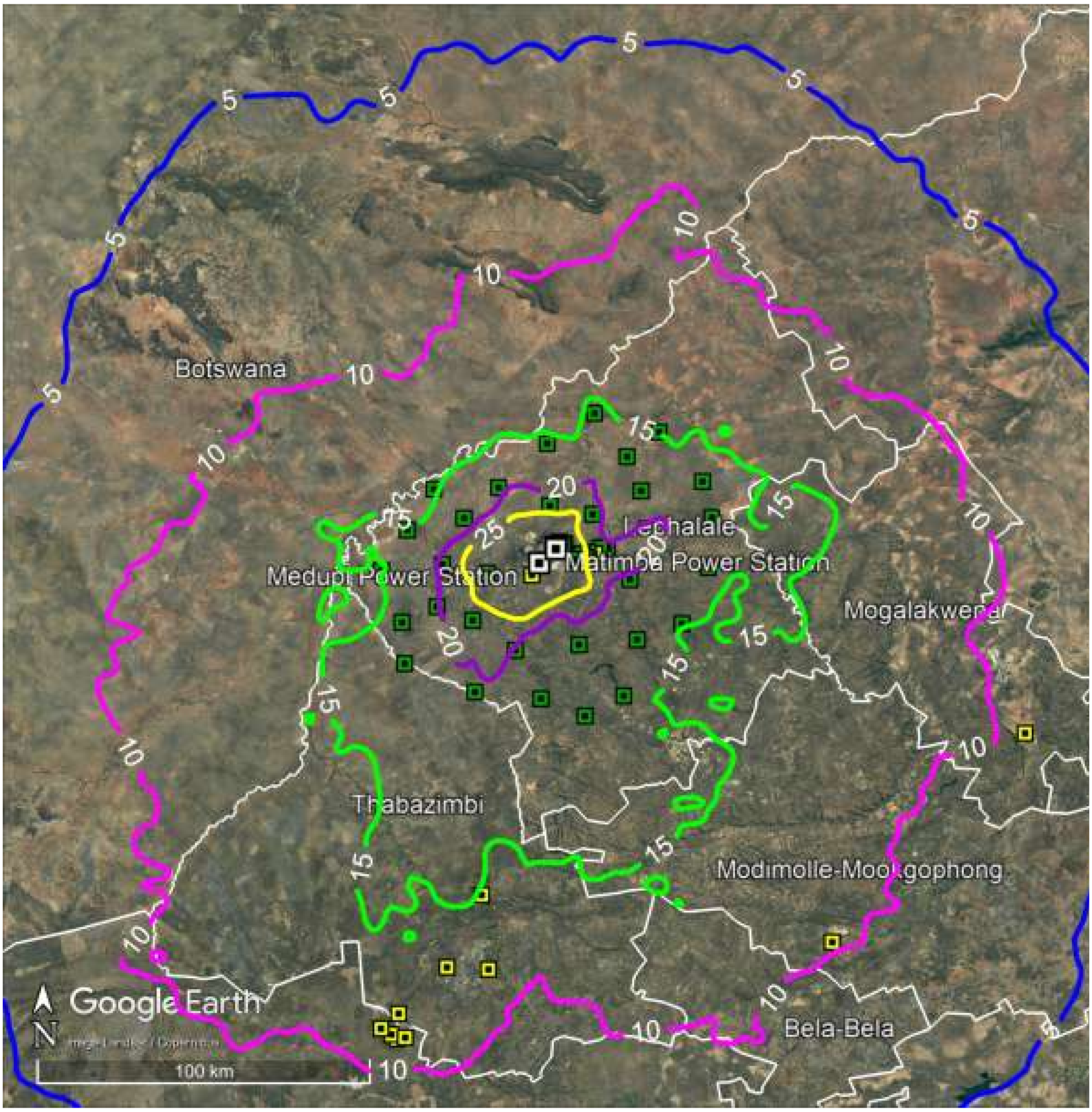

Figure 7-25: Predicted 99th percentile of the 24-hour PM_{10} concentrations in µg/m^3 for Scenario E (NAAQS Limit is 75 µg/m^3)

7.3.3 Particulates ($PM_{2.5}$)

Isopleth maps for $PM_{2.5}$ concentrations are presented in Figure 7-26 to Figure 7-35.

The predicted $PM_{2.5}$ concentrations are attributed to stack emissions, low-level fugitive sources (including coal stockyards, ash dumps and gypsum disposal facilities), and contributions from secondary particulate formation. For $PM_{2.5}$, the maximum predicted annual average concentrations remain below the applicable NAAQS limit values in all scenarios. The maximum predicted 99th percentile 24-hour concentrations remain below the current NAAQS limit value (current limit value of 40 µg/m^3) for Scenario A and B but exceeds the limit value (future limit value of 25 µg/m^3) in the vicinity of the power stations in Scenario C, D and E. In Scenario C, D and E, the predicted number of exceedances remains below the allowable threshold of 4 exceedances per year, and compliance with the NAAQS is therefore maintained for these scenarios.

Low-level fugitive emissions from the coal stockyard and ash dump are consistent across all scenarios and make a significant contribution to ambient $PM_{2.5}$ concentrations. Fugitive emissions from the gypsum storage facility are introduced in Scenarios C, D and E and differ between these scenarios based on the respective technology options; however, they do not make a significant contribution to ambient $PM_{2.5}$ concentrations. Fugitive emissions have the greatest impact on ambient concentrations close to the source, whereas the influence of stack emissions is generally observed further from the power stations.

For the annual and 24-hour predictions, the change from Scenario A to Scenario B, characterised by an increase in $PM_{2.5}$ stack emissions at Medupi and a decrease at Matimba, is reflected in the modelled results as a slight increase in the affected area. A reduction in $PM_{2.5}$ stack emissions at Medupi in Scenario C, followed by an increase in Scenario D, results in a marked reduction in the affected area in both scenarios. In contrast, the reduction in $PM_{2.5}$ stack emissions at Medupi from Scenario D to Scenario E is reflected in the modelled results as a marked increase in the affected area.

It is evident that the influence of stack emission changes between scenarios is strongly affected by stack exit velocities and exit temperatures. The resultant ambient $PM_{2.5}$ concentrations are also dependent on contributions from secondary particulates, which in turn depend on SO_2 and NO_X stack emissions. Consequently, there is no linear relationship between $PM_{2.5}$ emission changes across the scenarios and the resulting ambient $PM_{2.5}$ concentrations.

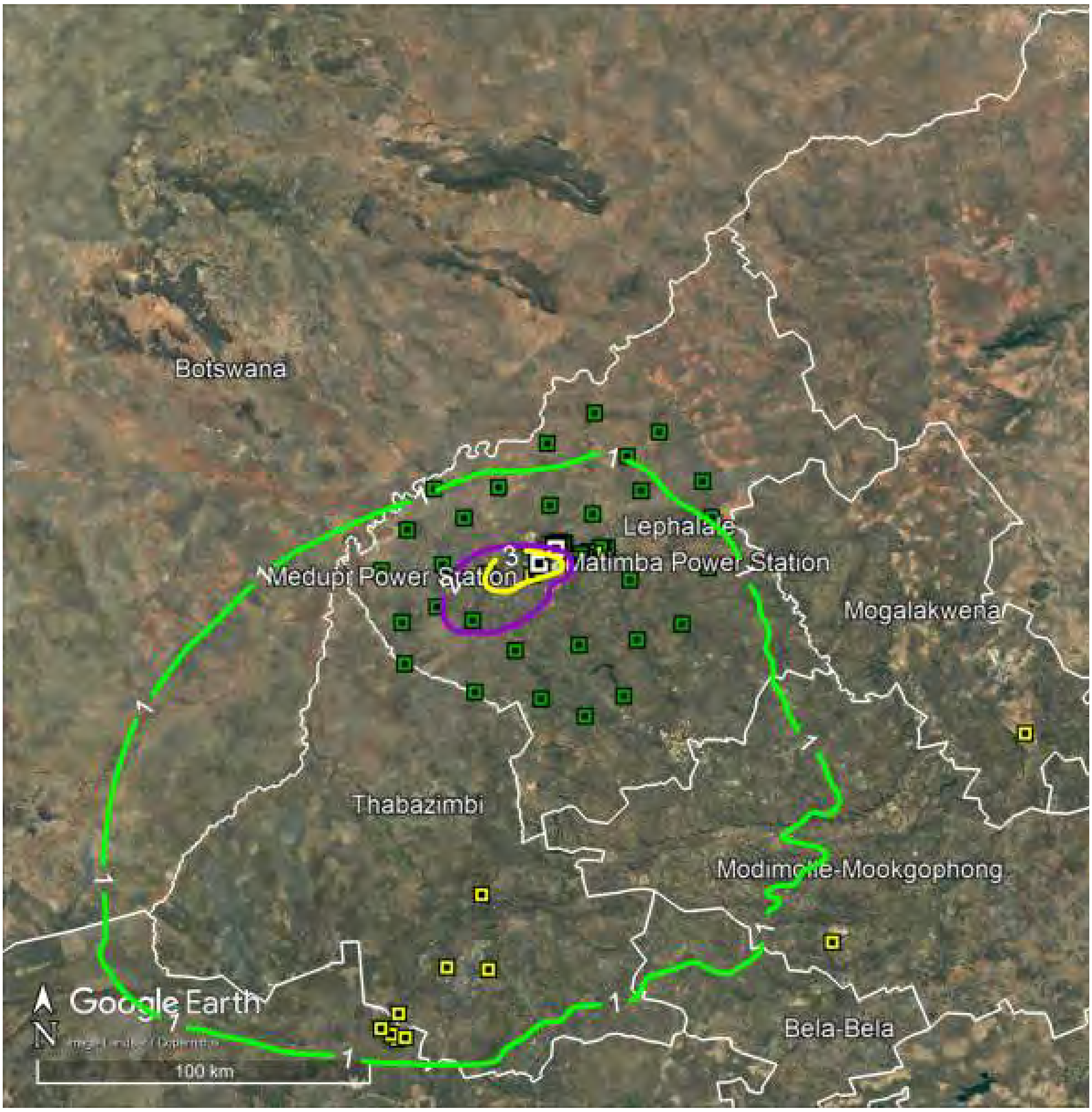

Figure 7-26: Predicted annual average $PM_{2.5}$ concentrations in µg/m^3 for Scenario A (NAAQS Limit is 20 µg/m^3)

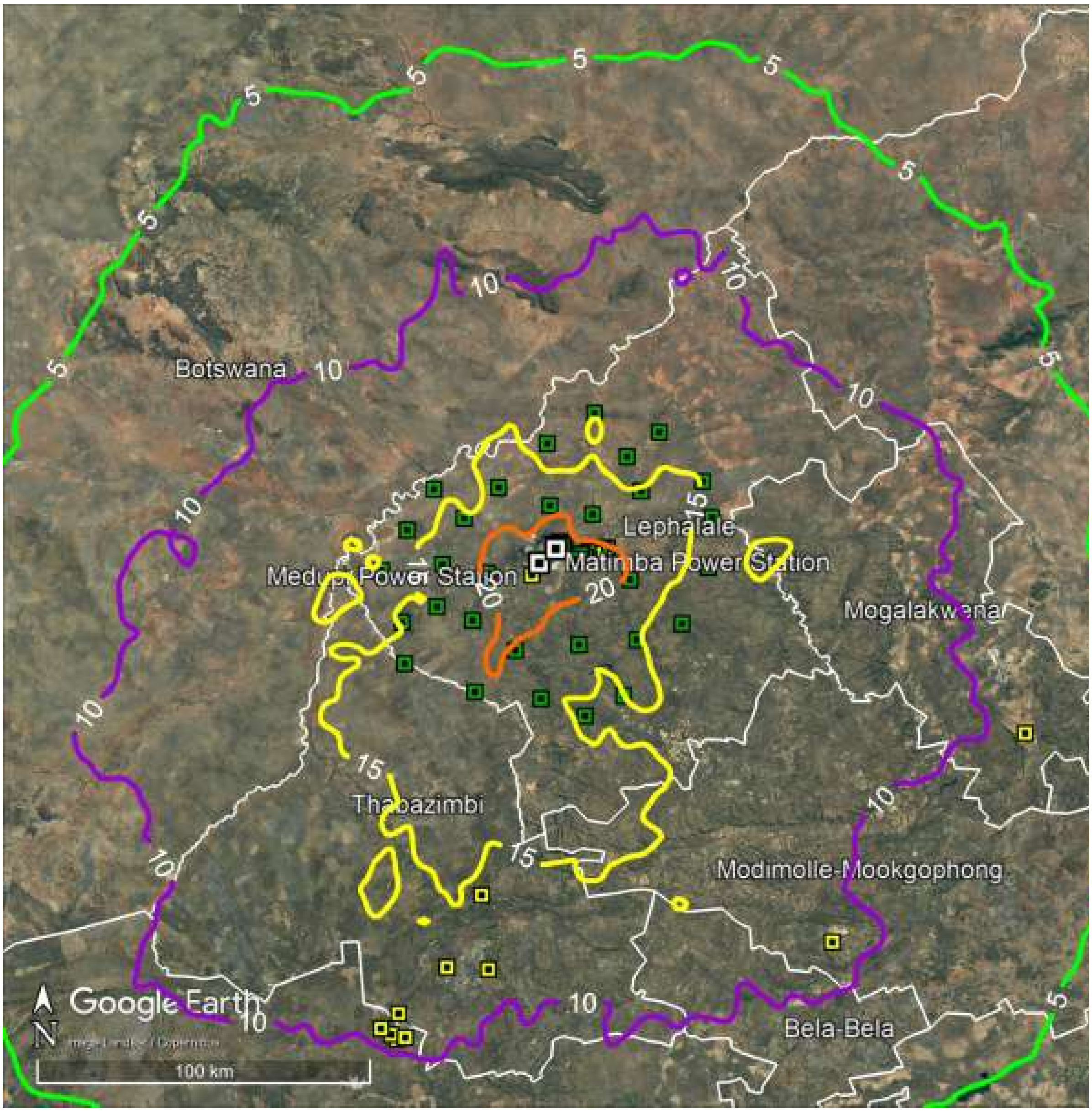

Figure 7-27: Predicted 99th percentile of the 24-hour $PM_{2.5}$ concentrations in µg/m³ for Scenario A (NAAQS Limit is 40 µg/m³)

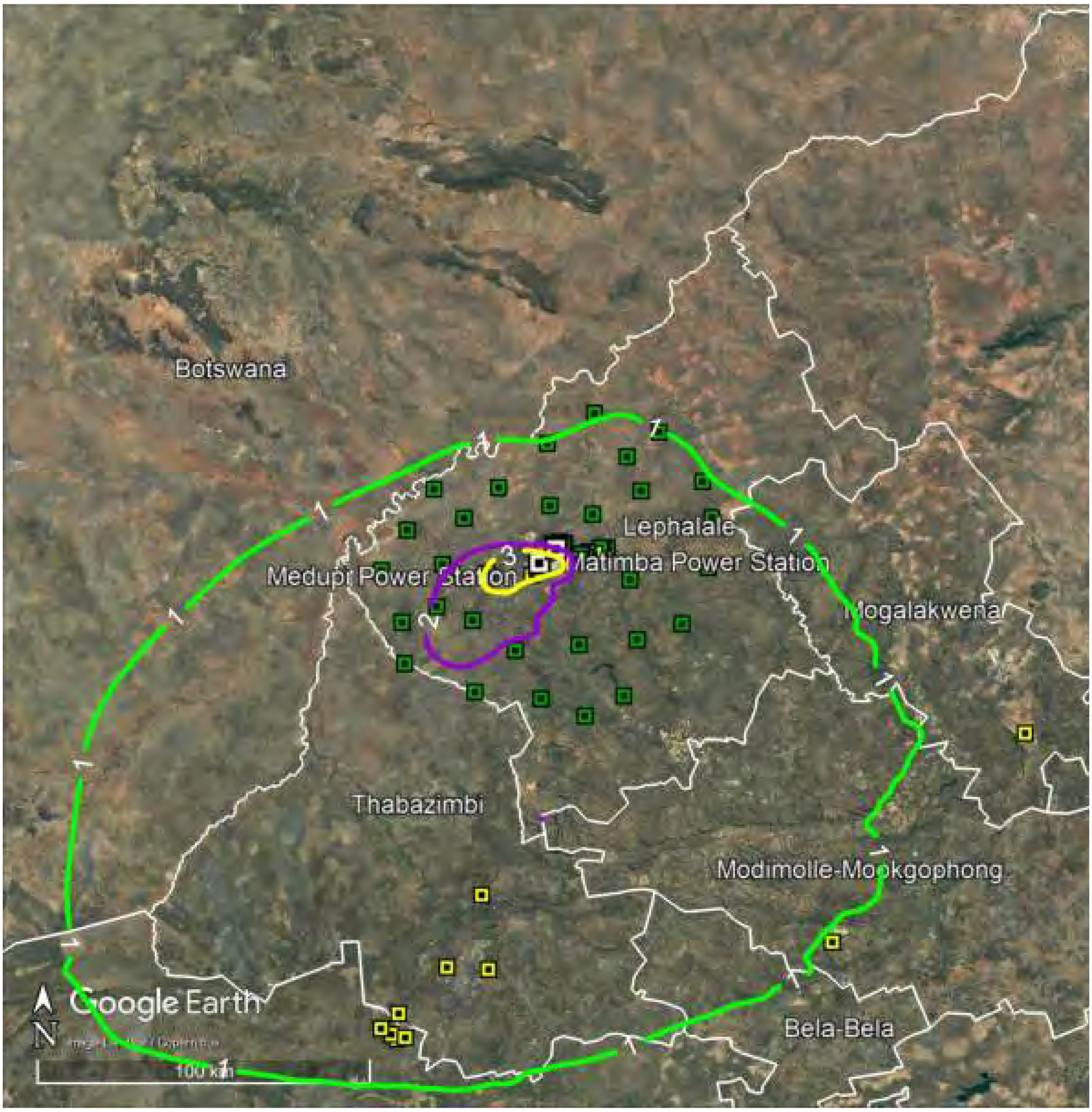

Figure 7-28: Predicted annual average $PM_{2.5}$ concentrations in µg/m³ for Scenario B (NAAQS Limit is 20 µg/m³)

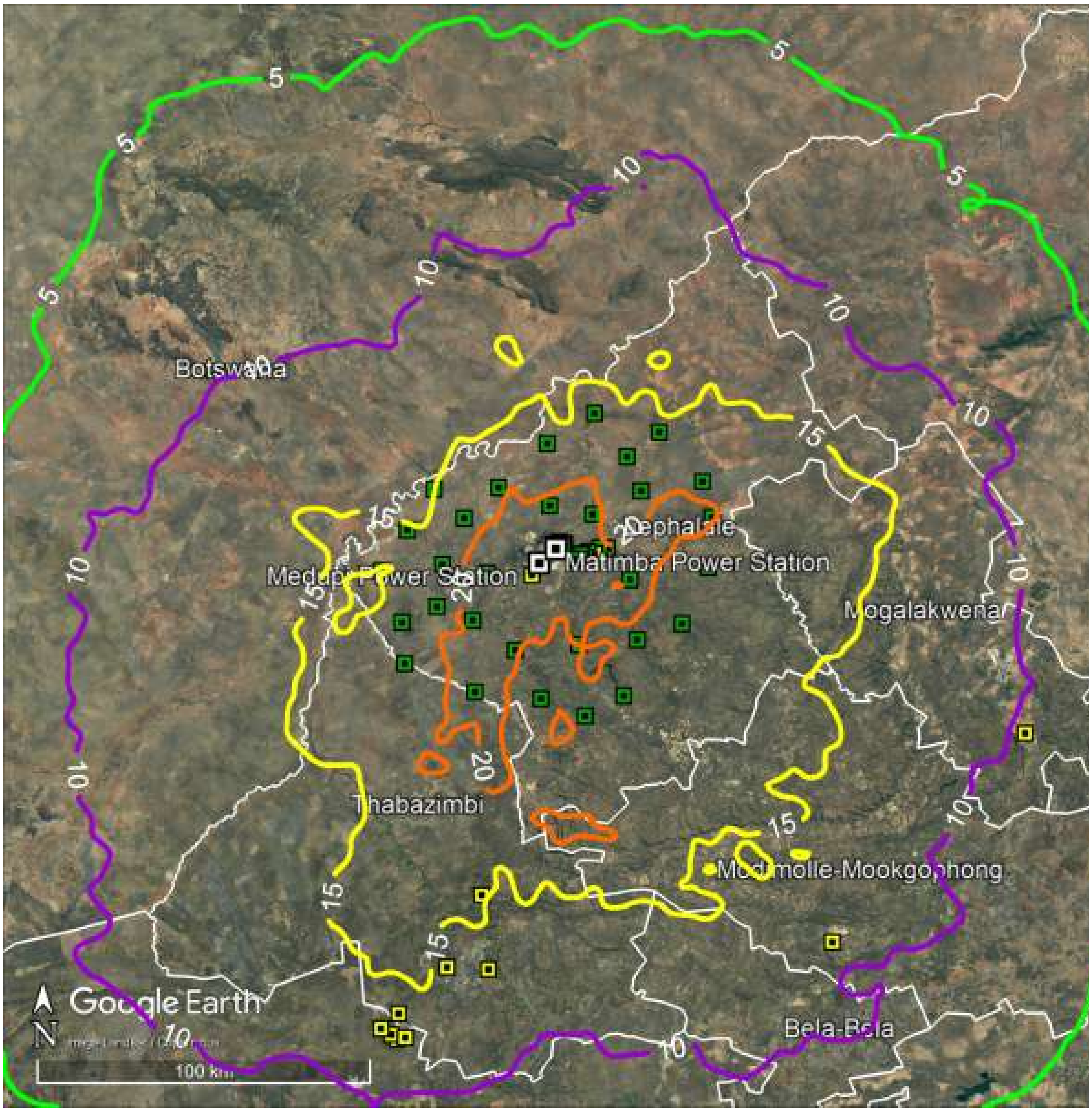

Figure 7-29: Predicted 99th percentile of the 24-hour $PM_{2.5}$ concentrations in µg/m³ for Scenario B (NAAQS Limit is 40 µg/m³)

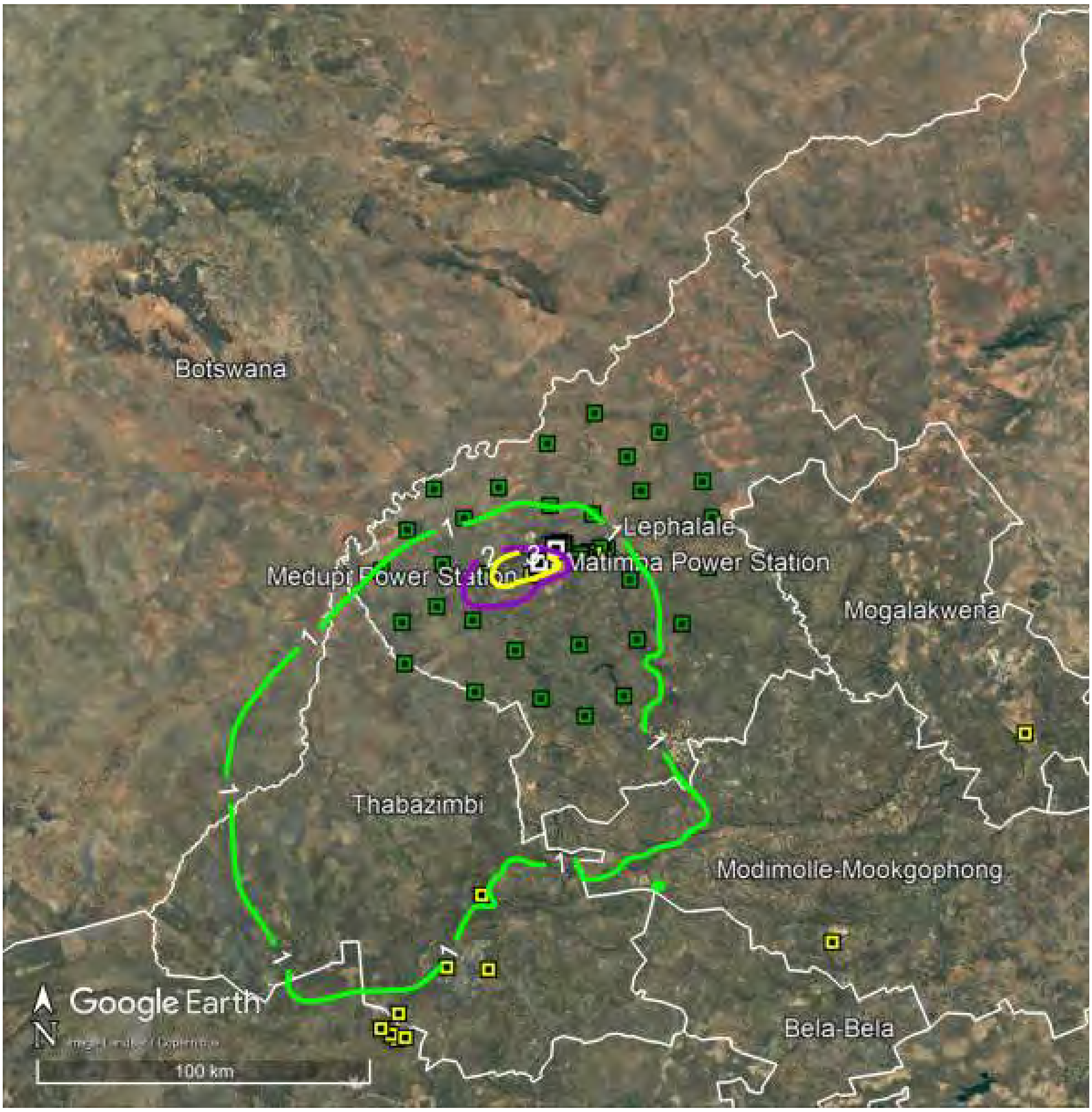

Figure 7-30: Predicted annual average $PM_{2.5}$ concentrations in µg/m^3 for Scenario C (NAAQS Limit is 15 µg/m^3)

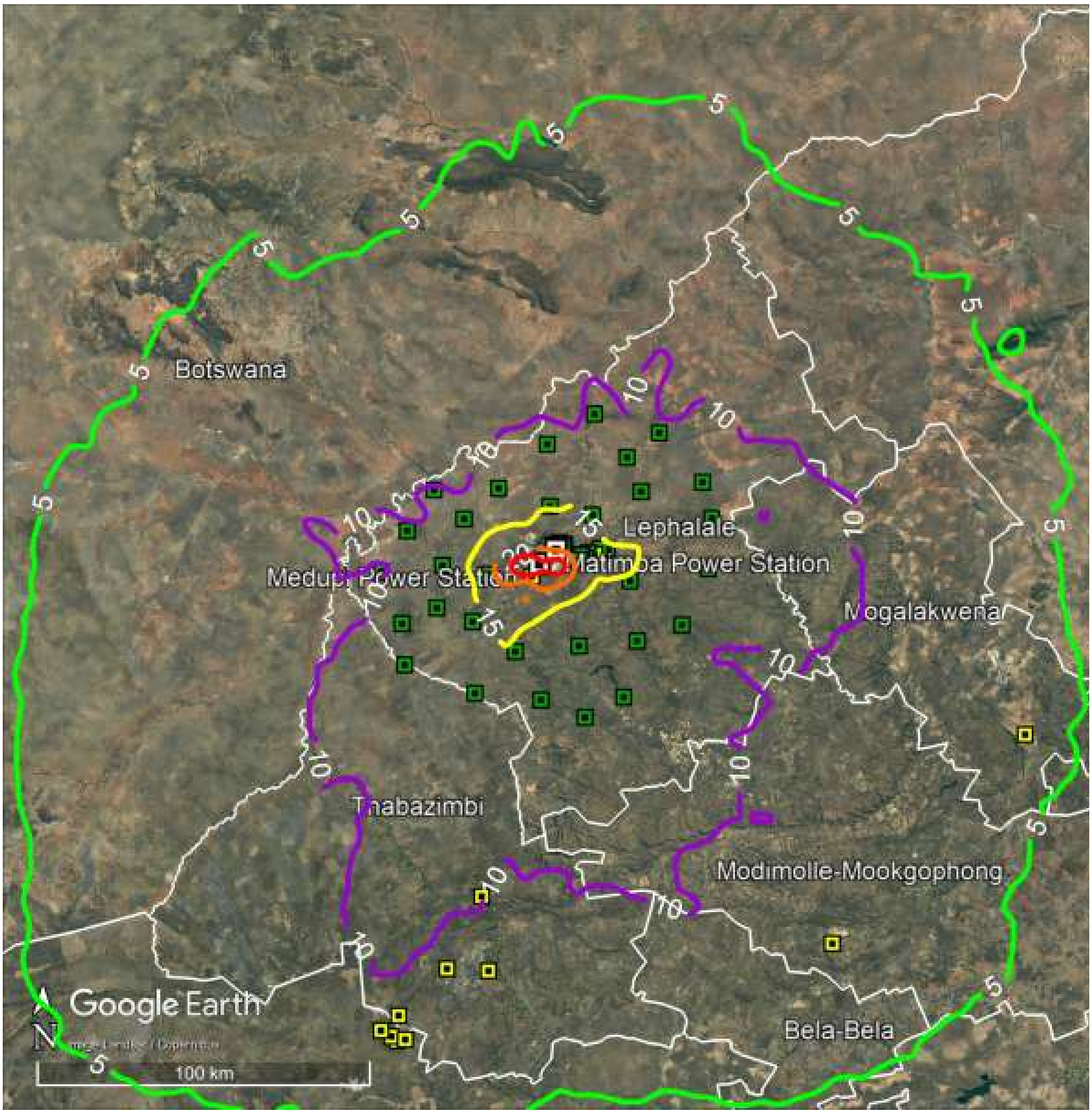

Figure 7-31: Predicted 99th percentile of the 24-hour $PM_{2.5}$ concentrations in µg/m³ for Scenario C (NAAQS Limit is 25 µg/m³)

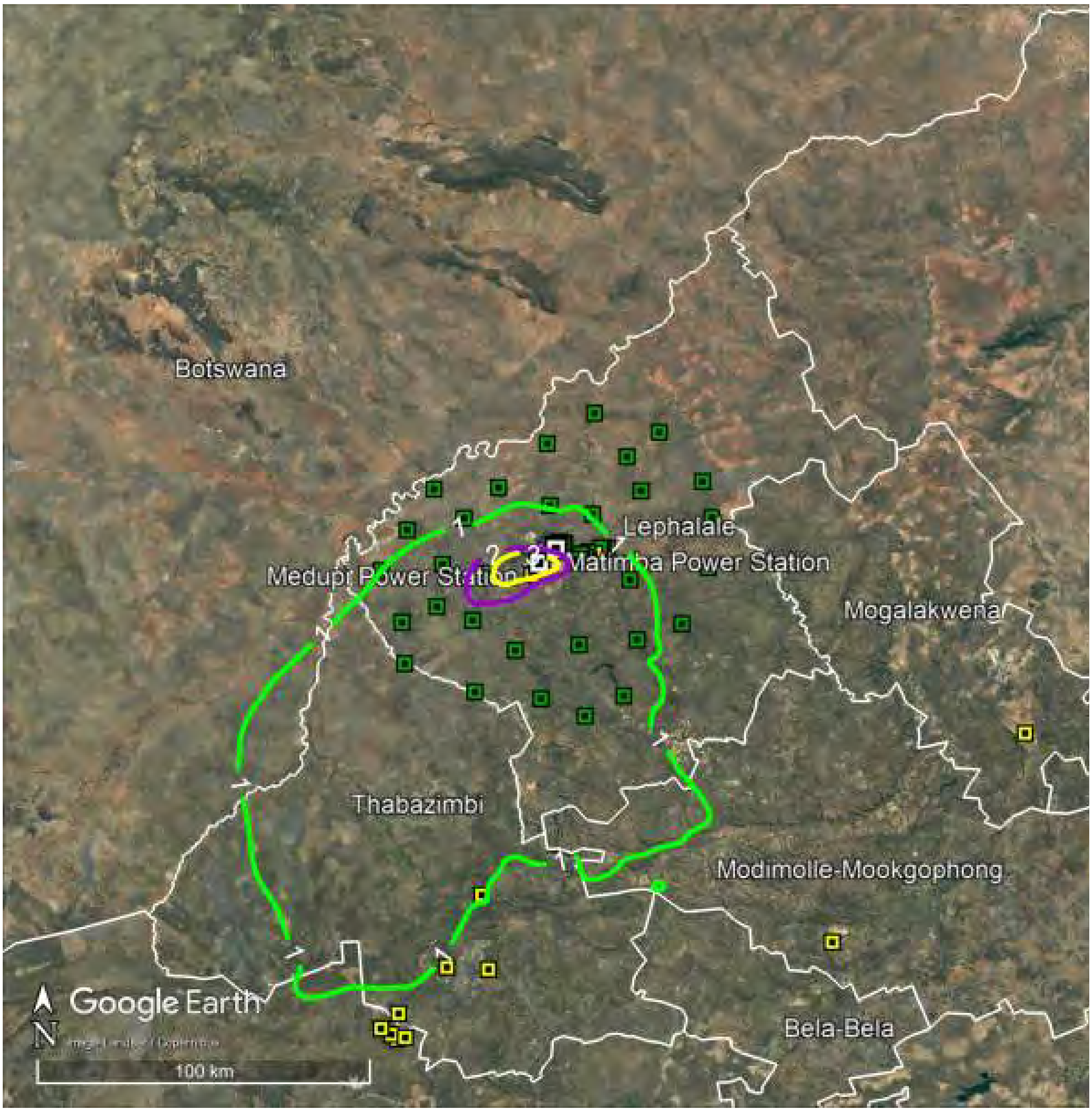

Figure 7-32: Predicted annual average $PM_{2.5}$ concentrations in µg/m³ for Scenario D (NAAQS Limit is 15 µg/m³)

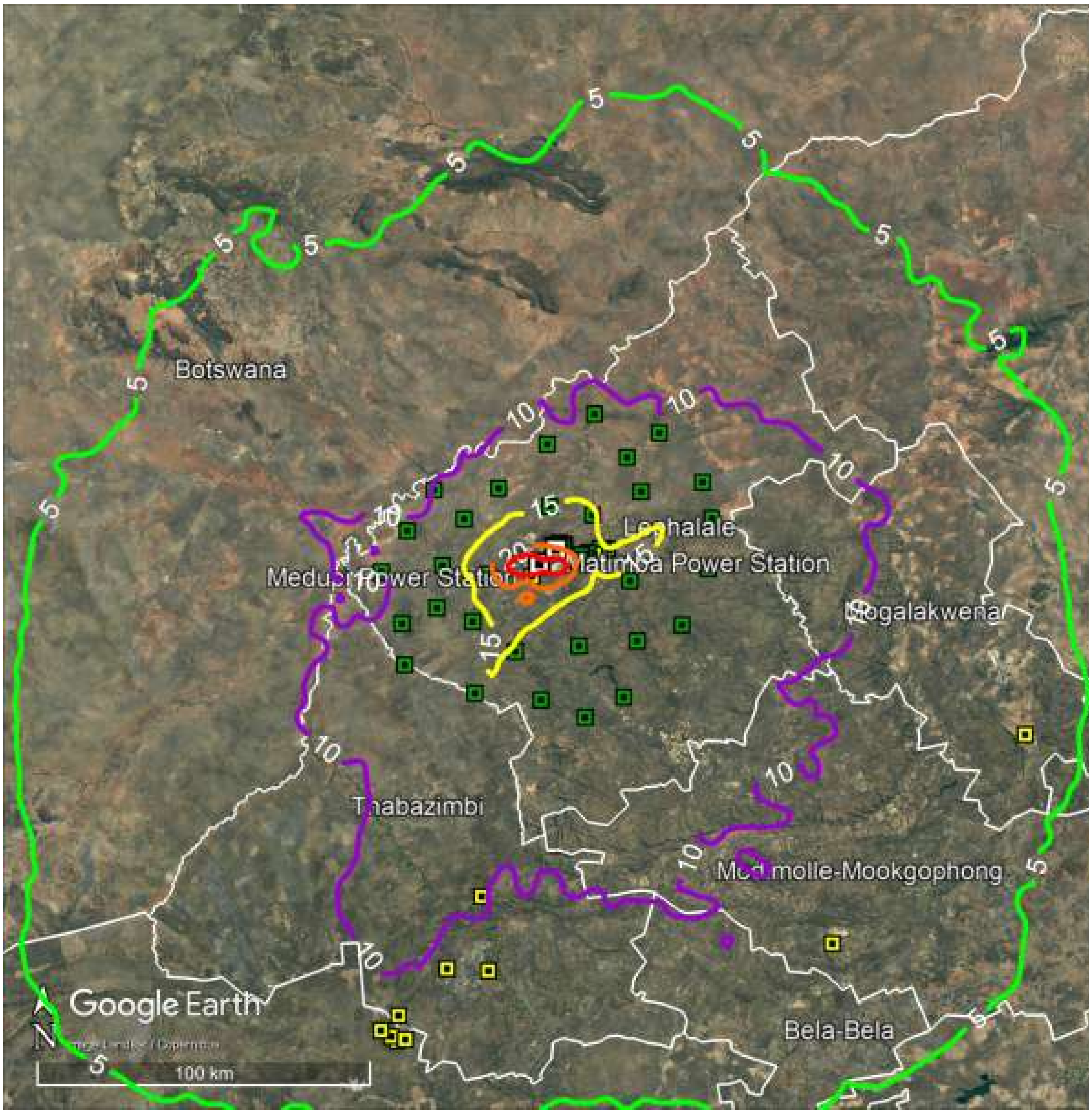

Figure 7-33: Predicted 99th percentile of the 24-hour $PM_{2.5}$ concentrations in µg/m³ for Scenario D (NAAQS Limit is 25 µg/m³)

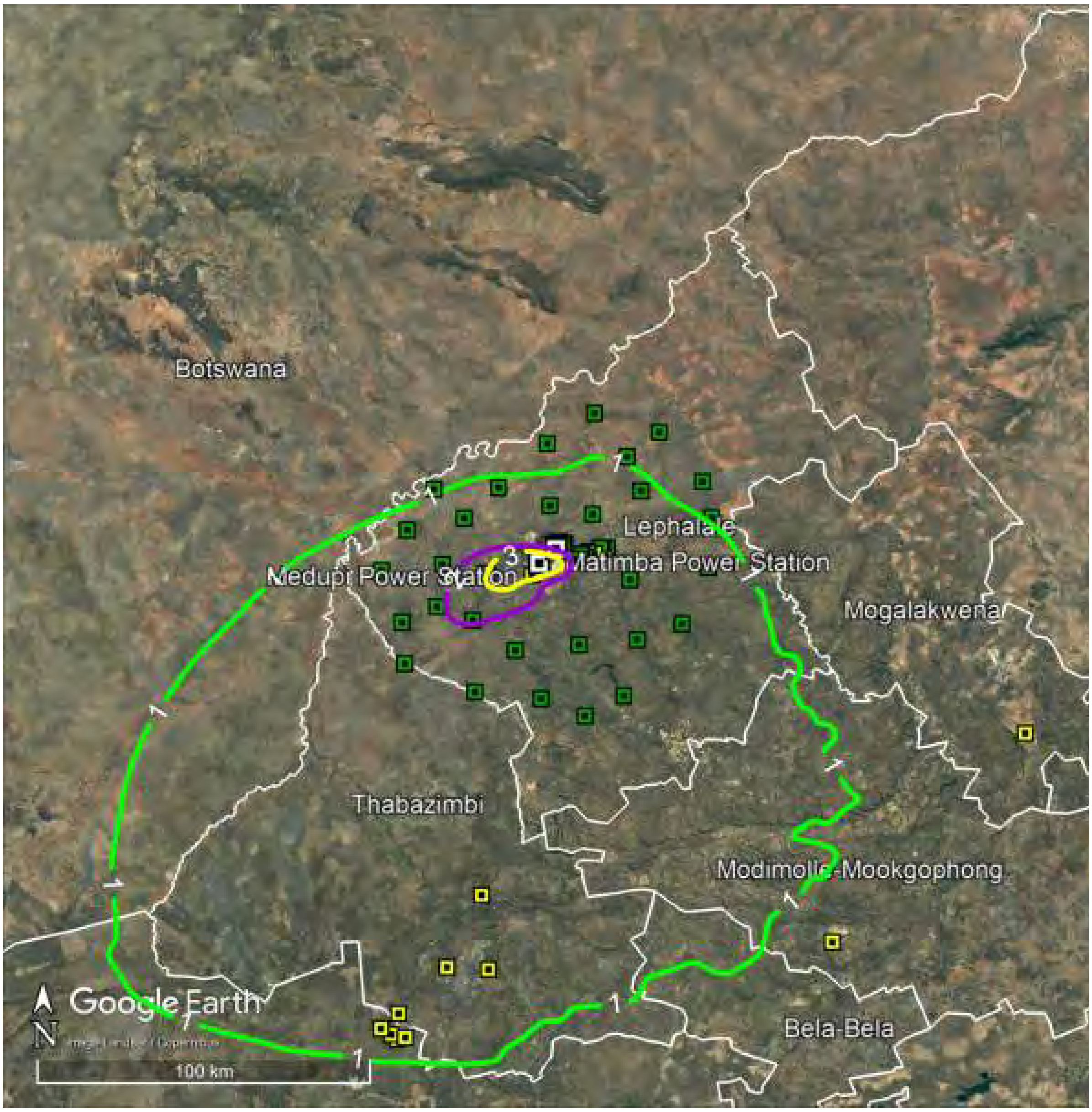

Figure 7-34: Predicted annual average $PM_{2.5}$ concentrations in µg/m³ for Scenario E (NAAQS Limit is 15 µg/m³)

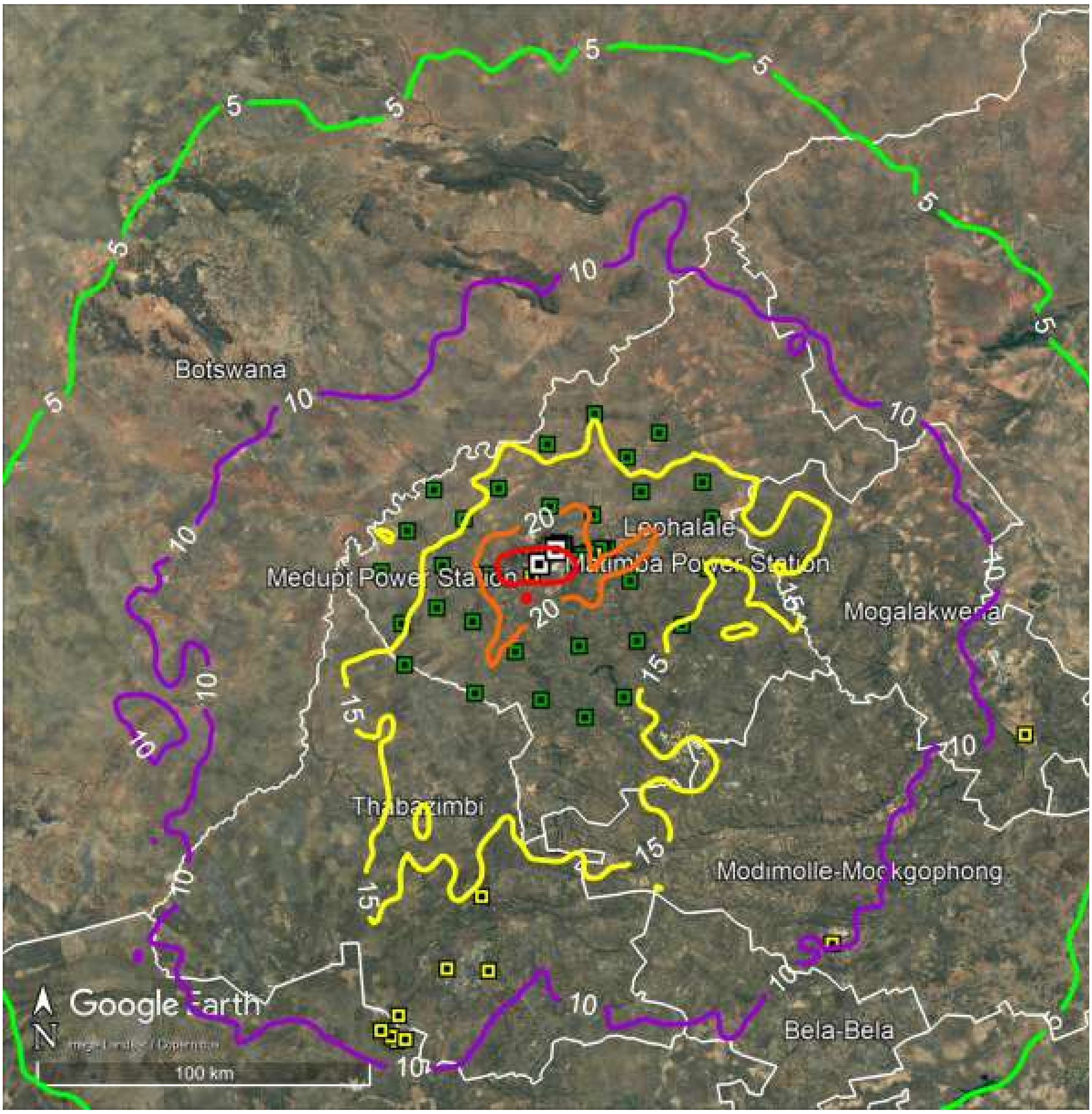

Figure 7-35: Predicted 99th percentile of the 24-hour $PM_{2.5}$ concentrations in µg/m³ for Scenario E (NAAQS Limit is 25 µg/m³)

8. MODEL PREDICTIONS VS MONITORED DATA

8.1 Model predictions vs monitored data

Dispersion modelling outputs are a fundamental input to the Health BCA model, making it essential to evaluate the confidence in these results. This is typically done by comparing modelled ambient concentrations with measured ambient data. The following sections first discuss the accuracy of the dispersion modelling, then examine the quality and representativeness of the measured ambient data, and finally compare the model predictions with the ambient air quality monitoring station (AQMS) observations.

8.2 Model accuracy

Air quality models attempt to predict ambient concentrations based on "known" or measured parameters, such as wind speed, temperature profiles, solar radiation and emissions. There are however, variations in the parameters that are not measured, the so-called "unknown" parameters as well as unresolved details of atmospheric turbulent flow. Variations in these "unknown" parameters can result in deviations of the predicted concentrations of the same event, even though the "known" parameters are fixed.

There are also "reducible" uncertainties that result from inaccuracies in the model, errors in input values and errors in the measured concentrations. These might include poor quality or unrepresentative meteorological, geophysical and source emission data, errors in the measured concentrations that are used to compare with model predictions and inadequate model physics and formulation used to predict the concentrations. "Reducible" uncertainties can be controlled or minimised. This is done by using accurate input data, preparing input files correctly, checking and re-checking for errors, correcting for odd model behaviour, ensuring that the errors in the measured data are minimised and applying appropriate model physics.

Models recommended in the DEA dispersion modelling guideline (DEA, 2014a) have been evaluated using a range of modelling test kits (http://www.epa.gov./scram001). CALPUFF is one of the models that have been evaluated and it is therefore not mandatory to perform any modelling evaluations. Rather the accuracy of the modelling in this assessment is enhanced by every effort to minimise the "reducible" uncertainties in input data and model parameterisation.

When comparing CALPUFF model outputs with ambient SO_2 measurements, the focus is on the cumulative scenario that includes stack emissions from both the Matimba and Medupi Power Stations. The model incorporates actual monthly average emission rates for the full three-year assessment period. It is important to note that the modelled ambient concentrations reflect only these stack emissions; no other SO_2 sources are included.

8.3 Ambient data

Three AQMSs are located in close proximity to the Matimba and Medupi Power Stations. These include the South African Weather Service (SAWS) Lephalale-NAQI AQMS and two Eskom monitoring stations: the Marapong AQMS and the Medupi AQMS. Each of these stations is exposed to multiple SO_2 sources, both nearby and more distant. Depending on their location and proximity to emission sources, they are influenced to varying degrees by power station emissions, residential and domestic fuel burning and motor vehicle emissions (Table 8-1).

The relative locations of the three AQMSs are shown in Figure 8-1 and summarised in Table 8-1. The Lephalale and Marapong AQMSs are generally upwind of the Matimba and Medupi Power Stations, whereas the Medupi AQMS is generally downwind of these sources. Table 8-1 also presents the data capture rates for the three AQMSs, expressed as the percentage of valid hourly SO_2 measurements obtained over the three-year assessment period (i.e. 26 304 hours). The South African Air Quality Information System (SAAQIS) adheres to a guideline, derived from the South African National Accreditation System (SANAS) requirements, which mandates a minimum data capture/collection efficiency of 90% for data to be considered acceptable and valid. Data recovery at all three AQMSs is below the minimum requirement of 90% as stipulated by the SANAS TR 07-03 (SANAS, 2012).

Table 8-1: Relative location of the Lephalale, Marapong and Medupi AQMSs relative to major SO_2 sources, with corresponding SO_2 data capture rates for the three-year assessment period

AQMS	Relative location	SO_2 sources	SO_2 Data recovery
SAWS Lephalale	11 km E of Matimba 16 km E of Medupi	Nearby: Residential and domestic fuel burning; vehicle emissions Distant: Both power stations	68.5%
Eskom Marapong	2 km NE of Matimba 8 km NE of Medupi	Nearby: Residential and domestic fuel burning; vehicle emissions and Matimba Power Station Distant: Medupi Power Station	24.5%
Eskom Medupi	11 km SW of Matimba 4 km SSW of Medupi	Nearby: Medupi Power Station Distant: Matimba Power Station	59.6%

Figure 8-1: Relative location of the three AQMS with an annual windrose from Meteoblue.com

8.4 Comparison between modelled and monitored data

Several important considerations must be taken into account when comparing dispersion model predictions with ambient monitoring data:

- Continuous measurements at an AQMS using analysers are fundamentally different from concentrations estimated by a dispersion model; differences in results are therefore expected.
- A monitoring station represents a single point, whereas a dispersion model generates an average concentration for an entire grid cell.
- A monitoring station is influenced by multiple emission sources, while the model only reflects the sources explicitly included in the modelling exercise.
- The model uses hourly average meteorological inputs for predictions, while actual ambient conditions at the station can fluctuate over much shorter timescales.
- The 99th percentile modelled concentrations are used, i.e. the highest 1% of the predictions are excluded, while in the ambient data short-term peaks are included.

Given these factors, it is expected that dispersion modelling results will be conservative and that predicted concentrations may be lower than those measured. This is consistent with the findings: at all three AQMS locations, the average measured SO_2 concentrations exceed the corresponding modelled values (Table 8-2). At Lephalale, the model underpredicts by approximately 25%, while underprediction is more pronounced at Marapong (70% lower) and Medupi (44% lower).

Table 8-2: Comparison of average and maximum measured (AQMS) and predicted (CALPUFF) concentrations in µg/m^3 at the three AQMS locations

Station		AQMS	CALPUFF
SAWS Lephalale-NAQI	Average	6.7	5.9
	Maximum	464.4	200.2
Eskom Marapong	Average	15.2	4.4
	Maximum	1 693.3	216.0
Eskom Medupi	Average	22.8	12.7
	Maximum	1 892.4	414.8

The difference between measured and modelled maximum concentrations is also notable, with measured values substantially higher at all stations. However, these maximums do not necessarily occur at the same time for the model and the monitoring stations. At Lephalale, the four highest measured SO_2 concentrations occurred between 13:00 and 15:00. Similarly, the highest concentrations at Marapong and Medupi occurred between 13:00 and 16:00. This timing suggests that these elevated concentrations are most likely due to power station plumes being mixed down to ground level by afternoon atmospheric convection, rather than emissions from residential fuel-burning, which typically peaks later in the day.

The following conclusions are drawn:

- The dispersion modelling was conducted in accordance with the DFFE Regulations for Dispersion Modelling.
- All reasonable steps were taken to minimise uncertainties in both input data and model parameterisation. This included using representative and accurate input

data, preparing input files correctly, cross-checking for errors, and performing iterative corrections and model reruns.

- Data recovery at all three AQMS are poor relative to SAAQIS guidelines and the SANAS minimum requirement of 90% for acceptable data quality assurance and valid data capture.
- As might be expected, the dispersion modelling results are conservative, with predicted concentrations generally lower than measured concentrations at all three AQMSs.
- Based on these findings, the modelling team has a high level of confidence in the reliability of the modelled results.

9. ASSUMPTIONS

The following assumptions are relevant to this AIR:

a) No ambient monitoring is done in this assessment, rather available ambient air quality data is used.
b) The assessment of potential human health impacts is based on predicted (modelled) ambient concentrations of SO_2, PM_{10} and $PM_{2.5}$ and the health-based National Ambient Air Quality Standards (NAAQS).
c) Emissions data used in this study have been provided by Eskom and are deemed to be accurate and representative of operating conditions in the respective scenarios.
d) All PM emitted from stacks is assumed to be PM_{10}, which represents a worse-case emission scenario for PM_{10}.
e) In the case where PM from stacks are modelled, it is assumed that $PM_{2.5}$ can be reliably estimated as a fixed fraction of PM_{10} (or total PM) using US EPA AP-42 dry-bottom boiler emission factor ratios, rather than being directly measured. This represents a more realistic emission scenario for $PM_{2.5}$ stack emissions. A detailed methodology for the calculations is provided in Section 5.3.
f) Assumptions regarding emissions from the coal yards, ash dumps and gypsum disposal facilities are included in Section 5.5.

10. SUMMARY

Atmospheric Emissions and Dispersion Modelling [Methodology Note]

1. Emission Scenarios

Five emission scenarios were assessed to support the Minimum Emission Standard (MES) Health Benefit–Cost Analysis for Medupi Power Station, with Matimba Power Station included to account for cumulative regional impacts.

- Scenario A – Actual historical emissions (2022–2024): Based on measured monthly emissions per stack. This represents the baseline ("as-is") condition and reflects operations with five Medupi units, as Unit 4 was offline for the period.
- Scenario B – Future baseline: Assumes all six Medupi units operating at the forecasted upper load factor (70%), without flue gas desulphurisation (FGD). Emissions reflect actual SO_2 levels, which are lower than MES limits.
- Scenario C wet FGD: Emissions modelled assuming wet FGD retrofitting, complying with a 1 000 mg/Nm³ SO_2 ELV and modelled conservatively at 80% of the limit (800 mg/Nm³).
- Scenario D semi-dry FGD: Emissions modelled assuming semi-dry FGD, complying with the same ELV and modelled at 800 mg/Nm³.
- Scenario E dry FGD: Emissions modelled assuming dry FGD, complying with an alternative SO_2 ELV of 2 500 mg/Nm³ and modelled at 2 000 mg/Nm³.

For all scenarios, NO_X, PM and other pollutants were held constant in accordance with the Minister's Decision (Condition 7.32). Modelled emissions represent a conservative, worst-case scenario relative to measured emissions.

2. Point Source Characterisation

Medupi and Matimba were modelled as elevated point sources with two stacks per station. Stack heights, diameters, locations, exit velocities, gas temperatures and volumetric flow rates were defined using plant-specific operational data. Adjustments were made for Medupi Stack 2 to account for reduced operation during the historical period.

Emission rates were derived as follows:

- Scenario A used averaged measured monthly emissions.
- Scenarios B–E assumed continuous (24-hour) operation at maximum anticipated emission rates.

All emission concentrations were normalised to 10% O_2, standard temperature and pressure.

3. $PM_{2.5}$ Estimation

Fine particulate matter ($PM_{2.5}$) emissions were derived from measured total PM using Tier 3 Continuous Emission Monitoring System (CEMS) data combined with US EPA AP-42 dry bottom boiler emission ratios.

- Medupi (Fabric Filter Plants): $PM_{2.5}$:PM_{10} ratio = 0.50
- Matimba (Electrostatic Precipitators): $PM_{2.5}$:PM_{10} ratio = 0.44

This approach provides a site-specific and conservative estimate of $PM_{2.5}$ emissions.

4. Fugitive Emissions

Fugitive particulate emissions from coal stockpiles, ash dumps and gypsum disposal facilities were estimated using the US EPA AP-42 methodology. Worst-case (dry, drought) conditions were assumed, with conservative estimates of exposed surface area and moisture content. Facility-specific characteristics (material throughput, surface area, silt content, moisture content and abatement practices) were applied for Medupi and Matimba. Gypsum emission estimates were differentiated by FGD technology (wet, semi-dry, dry) using in-house laboratory and literature-based silt content values.

5. Dispersion Modelling Framework

Air dispersion modelling was conducted using the CALPUFF modelling system, approved by the USEPA and DEA for Level 3 assessments. Meteorological fields were generated using the TAPM model, producing hourly, three-dimensional meteorology for 2022−2024.

- TAPM configuration: Two nested domains (24 km and 12 km resolution) with 27 vertical layers.
- CALPUFF domain: 330 km × 330 km with 1.25 km grid spacing.
- Terrain and land use: CSIRO TAPM datasets based on USGS data.

Key CALMET and CALPUFF parameters were set to reflect rural dispersion conditions, transitional plume rise, partial plume-terrain interaction and calm wind handling.

6. Secondary Particulate Formation

Secondary PM formation was simulated using the MESOPUFF II chemical transformation scheme within CALPUFF. The model accounts for:

- Oxidation of SO_2 to sulphate (SO_4^{2-}),
- Conversion of NO_X to nitric acid and particulate nitrate (NO_3^-),
- Temperature and humidity-dependent equilibrium between gaseous and particulate nitrate.

Total PM_{10} and $PM_{2.5}$ concentrations were calculated as the sum of primary particulate emissions and secondary ammonium sulphate and ammonium nitrate formed in the atmosphere. Model outputs were compared against applicable National Ambient Air Quality Standards (NAAQS).

Dispersion Modelling Results

In this study, CALPUFF dispersion modelling is used to predict ambient concentrations of SO_2, PM_{10} and $PM_{2.5}$ for five emission scenarios at Medupi and Matimba Power Stations. Predicted particulate concentrations include both primary emissions and secondary particulates formed in the atmosphere from SO_2 and NO_X. Short-term impacts were assessed using the 99th percentile of predicted concentrations, in line with the DEA Code of Practice, and compared against the South African National Ambient Air Quality Standards (NAAQS), including permitted exceedance frequencies.

Across the modelling domain, predicted annual average concentrations of SO_2, PM_{10} and $PM_{2.5}$ are generally low and below applicable NAAQS limit values for all scenarios. For SO_2, exceedances of the 24-hour and 1-hour standards are predicted in the domain under the historical (Scenario A), future baseline (Scenario B) and dry FGD scenario (Scenario E); however, the number of exceedances remains within allowable limits, and compliance with the NAAQS is maintained in all scenarios.

For PM_{10}, both annual and short-term (24-hour) predicted concentrations remain below the NAAQS in all scenarios. Ambient PM_{10} levels are influenced by a combination of stack emissions, low-level fugitive sources (coal stockyards, ash dumps and gypsum disposal facilities) and secondary particulate formation. Fugitive emissions dominate concentrations close to the sources, while stack emissions influence concentrations further downwind.

For $PM_{2.5}$, predicted annual average concentrations comply with both current and future NAAQS in all scenarios. Short-term (24-hour) $PM_{2.5}$ concentrations exceed the applicable limit values in parts of the modelling domain; however, the predicted frequency of exceedances remains below the permitted thresholds, and compliance is therefore maintained. Contributions from gypsum disposal facilities in the FGD scenarios are relatively small compared to coal and ash handling sources.

At all identified sensitive receptors, predicted annual and short-term concentrations of SO_2, PM_{10} and $PM_{2.5}$ remain below the respective NAAQS for all scenarios.

Isopleth maps show that dispersion is strongly influenced by prevailing northeasterly winds, with maximum impacts occurring predominantly southwest of the power stations. Variations in affected areas between scenarios reflect changes in emission rates, stack exit velocities and temperatures, and the formation of secondary particulates. As a result, changes in emission rates do not translate linearly into changes in ambient particulate concentrations.

11. REFERENCES

Auer, A.H. (1978): Correlation of Land Use and Cover with Meteorological Anomalies, Journal of Applied Meteorology, 17:636-643.

CARB (2024): https://ww2.arb.ca.gov/capp-resource-center/community-assessment/sensitive-receptor-assessment.

CSIRO (2008): TAPM V4. User Manual. Prepared by Peter Hurley, CSIRO Marine and Atmospheric Research Internal Report No. 5, October 2008, ISBN: 978-1-921424-73-1.

DEA (2009): National Ambient Air Quality Standards, Government Gazette, 32861, Vol. 1210, 24 December 2009.

DEA (2012): National Ambient Air Quality Standard for Particulate Matter of Aerodynamic Diameter less than 2.5 micrometers, Notice 486, 29 June 2012, Government Gazette, 35463.

DEA (2014a): Code of Practice for Air Dispersion Modelling in Air Quality Management in South Africa, Government Notice R.533, Government Gazette, no. 37804, 11 July 2014.

DEA (2014b): Environmental Assessment Regulations, 2014 identified in terms of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), Government Gazette 38282, Notice No. R 982 of 4 December 2014.

DEA (2020): Listed Activities and Associated Minimum Emission Standards identified in terms of Section 21 of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), Government Gazette 43174, Notice No. 421 of 27 March 2020.

Fungaro, D. A., Grosche, L. C., & Silva, P. C. S. (2023). Physicochemical and radiological characterization of flue gas desulfuration waste samples from Brazilian coal-fired power plants. Brazilian Journal of Radiation Sciences, 11(2), e2275. DOI: 10.15392/2319-0612.2023.2275

Hurley, P. (2000): Verification of TAPM meteorological predictions in the Melbourne region for a winter and summer month. Australian Meteorological Magazine, 49, 97-107.

Hurley, P.J., Blockley, A. and Rayner, K. (2001): Verification of a prognostic meteorological and air pollution model for year-long predictions in the Kwinana industrial region of Western Australia. Atmospheric Environment, 35(10), 1871-1880.

Hurley, P.J., Physick, W.L. and Ashok, K.L. (2002): The Air Pollution Model (TAPM) Version 2, Part 21: summary of some verification studies, CSIRO Atmospheric Research Technical Paper No. 57, 46 p.

Prime Africa Consult (2025): The Minimum Emission Standard (MES) Health Benefit Cost Analysis (BCA) Study at Medupi Power Station, Prepared for Eskom Holdings SOC Ltd.

SANAS (2012): Tr 07-03 Supplementary Requirements for the Accreditation of Continuous Ambient Air Quality Monitoring Stations (pp. 112).

Scire, J. S., Strimaitis, D. G., & Yamartino, R. J. (2000a): A User's Guide for the CALPUFF Dispersion Model (Version 5). Earth Tech, Inc.

Scire, J. S., Strimaitis, D. G., & Yamartino, R. J. (2000b): A User's Guide for the CALMET Meteorological Model. Earth Tech, Inc.

Su, Q., Jiang, Y., Lu, M., Chen, Y., & Wu, M. M. (2013). Development of Dry FGD By-Product Utilization as Building Materials in China. In Proceedings of the World of Coal Ash (WOCA) Conference, Lexington, Kentucky, USA.

uMoya-NILU (2024a): Atmospheric Impact Report in Support of the Application for Exemption from the Minimum Emission Standards for Eskom's Coal-Fired Power Stations in the Waterberg (A Cumulative Assessment), Report No.: uMN219-24, November 2024.

uMoya-NILU (2024b): Addendum to: Atmospheric Impact Report in Support of the Application for Exemption from the Minimum Emission Standards for Eskom's Coal-Fired Power Stations in the Waterberg (A Cumulative Assessment), Report No.: uMN296-24, December 2024.

USEPA (1995): A user's guide for the CALPUFF dispersion model (version 5). Prepared by Scire, J., Strimaitis, D. and Yamartino, Robert.

USEPA (2003): CALPUFF Modeling System: Technical Review and Evaluation of Model Performance. EPA-454/R-03-005.

USEPA (2005): Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions, 40 CFR Part 51, US Environmental Protection Agency 40 CFR Part 51.

USEPA (2024a): https://www.epa.gov/newenglandhc/environmental-issues-concern-urban- communities-resources.

USEPA (2024b): Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources. Chapter 13: Miscellaneous Sources. http://www.epa.gov/ttn/chief/ap42/ch13/index.html.

USEPA (2008): Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5, and Regional Haze. EPA-454/B-07-002.

ANNEXURE 1: PREDICTED CONCENTRATIONS AT SENSITIVE RECEPTORS

Predicted concentrations in µg/m[3] at the sensitive receptors for Scenario A, together with the limit value of the NAAQS

	SO_2			PM_{10} Total		$PM_{2.5}$ Total	
	1-hr	24-hr	Ann	24-hr	Ann	24-hr	Ann
Receptor	350	125	50	75	40	40	20
Phegelelo Senior Secondary	181.8	118.1	8.6	28.9	2.2	22.2	1.6
Contractors Village	169.9	82.1	7.8	29.0	2.4	22.1	1.6
Ditheku Primary School	181.0	114.5	8.4	28.9	2.2	22.2	1.6
Ditheko Primary School	226.8	110.6	9.0	28.0	2.2	22.2	1.6
Marapong Training Centre	194.2	119.9	8.9	28.3	2.3	22.1	1.6
Marapong Clinic	223.0	116.0	9.1	28.2	2.3	22.2	1.6
Tielelo Secondary School	178.8	116.9	8.6	29.0	2.3	22.3	1.6
Grootegeluk Medical Centre - Community Center	200.8	117.9	9.1	29.1	2.3	22.4	1.6
Lephalale College	229.8	105.3	9.7	28.9	2.0	23.0	1.6
Nelsonskop Primary School	221.6	113.1	9.1	29.0	2.3	22.5	1.6
Hansie en Grietjie Pre-Primary School	231.3	105.8	9.8	29.1	2.0	23.1	1.6
Sedibeng Special School for the Deaf and Disabilities	219.3	99.2	9.4	27.7	1.9	22.8	1.5
Kings College	233.0	109.7	10.2	29.9	2.1	23.6	1.6
Bosveld Primary School	223.8	101.5	9.9	29.3	2.0	23.4	1.6
Lephalale Medical Hospital	189.2	112.7	8.8	29.2	2.3	22.4	1.6
Ellisras Hospital	220.4	101.5	9.1	27.1	1.8	22.3	1.5
Laerskool Ellisras Primary School	186.9	88.2	8.0	21.5	1.6	18.7	1.4
Hoerskool Ellisras Secondary School	194.8	88.2	8.1	22.7	1.7	19.6	1.4
Marlothii Learning Academy	193.3	91.3	8.1	21.8	1.7	19.2	1.4
Hardekool Akademie vir C.V.O	177.0	86.5	7.7	22.0	1.6	19.3	1.4
Lephalale Clinic	186.1	89.5	8.0	21.4	1.6	18.7	1.4
Ons Hoop	154.4	88.7	6.8	21.8	1.5	18.8	1.3
Woudend	68.1	52.2	3.1	15.5	0.9	14.4	0.9

Ramabara's	151.4	72.6	7.2	20.8	1.5	19.3	1.4
Ga-Shongoane	76.9	47.8	3.9	15.1	1.0	14.4	1.0
Bulge River	118.6	43.5	6.7	15.5	1.5	14.8	1.4
Kaingo Mountain Lodge	108.7	44.8	6.0	15.7	1.5	15.0	1.4
Community	142.8	48.1	8.5	17.7	1.7	16.6	1.6
Kiesel	165.9	69.2	8.7	17.5	2.2	16.0	1.7
Kremetartpan	270.2	93.3	13.3	21.3	3.1	17.4	2.2
Mbala Private Camp	227.0	86.9	12.9	20.3	2.1	18.7	1.8
Steenbokpan	210.2	84.5	9.2	33.2	6.0	21.5	3.1
Receptor	97.6	44.8	4.2	19.1	1.5	15.9	1.2
Sandbult	127.6	59.2	5.7	21.1	2.6	16.3	1.7
Hardekraaltjie	76.4	41.3	3.4	15.7	1.2	14.3	1.0
Receptor	103.9	72.9	4.8	22.3	1.5	18.2	1.2
Receptor	83.5	59.9	4.0	19.1	1.3	17.0	1.1
Receptor	65.5	54.0	3.1	14.8	1.0	13.4	0.9
Receptor	86.8	55.2	4.0	15.0	1.1	13.4	1.0
Receptor	102.3	55.5	4.7	16.7	1.2	15.2	1.1
Ditaung	69.5	38.3	3.3	15.8	1.0	15.1	0.9
Letlora	78.1	49.2	3.4	13.6	1.0	12.6	0.9
Receptor	178.6	74.4	8.6	19.2	3.0	15.6	2.0
Glenover	142.0	61.5	7.2	17.7	2.3	15.4	1.7
Oxford Safaris	95.7	42.7	4.5	16.4	1.7	14.5	1.3
Receptor	84.1	41.9	3.8	13.9	1.4	11.9	1.2
Tholo Bush Estate	123.3	53.6	6.2	15.8	1.5	14.9	1.4
Receptor	184.7	65.6	9.3	18.7	1.8	16.9	1.6
Receptor	93.7	47.0	5.0	15.0	1.3	14.3	1.2
Cheetah Safaris	169.1	68.5	10.2	19.8	2.0	18.5	1.7
Rhinoland Safaris	84.0	45.3	4.4	15.3	1.2	14.5	1.1

Predicted concentrations in µg/m^3 at the sensitive receptors for Scenario B, together with the limit value of the NAAQS

	SO_2			PM_{10} Total		$PM_{2.5}$ Total	
	1-hr	24-hr	Ann	24-hr	Ann	24-hr	Ann
Receptor	350	125	50	75	40	40	20
Phegelelo Senior Secondary	155.1	107.6	7.9	33.5	2.3	26.9	1.7
Contractors Village	151.8	90.5	7.1	33.2	2.5	26.0	1.8
Ditheku Primary School	150.0	107.6	7.8	33.6	2.3	26.9	1.7
Ditheko Primary School	186.2	111.8	8.2	31.9	2.3	26.2	1.7
Marapong Training Centre	169.2	113.4	8.2	32.7	2.4	26.5	1.8
Marapong Clinic	186.0	121.2	8.4	32.4	2.4	26.5	1.7
Tielelo Secondary School	154.5	114.8	8.0	33.4	2.4	26.8	1.7
Grootegeluk Medical Centre - Community Center	174.7	112.0	8.3	32.6	2.4	26.5	1.8
Lephalale College	213.9	116.2	9.4	31.1	2.1	25.3	1.7
Nelsonskop Primary School	186.0	111.7	8.3	33.2	2.4	26.7	1.7
Hansie en Grietjie Pre-Primary School	213.6	119.8	9.5	31.5	2.1	25.6	1.7
Sedibeng Special School for the Deaf and Disabilities	209.5	107.8	9.3	30.3	2.0	25.4	1.7
Kings College	211.6	114.7	9.9	32.3	2.2	26.0	1.7
Bosveld Primary School	204.7	109.0	9.7	31.6	2.1	25.7	1.7
Lephalale Medical Hospital	159.9	103.7	8.1	33.4	2.4	26.8	1.7
Ellisras Hospital	205.8	107.1	8.9	29.0	1.9	24.3	1.6
Laerskool Ellisras Primary School	180.6	95.7	8.1	23.3	1.8	20.7	1.5
Hoerskool Ellisras Secondary School	187.4	96.6	8.2	23.8	1.8	20.9	1.6
Marlothii Learning Academy	184.9	95.1	8.2	23.5	1.8	20.9	1.6
Hardekool Akademie vir C.V.O	175.5	96.1	7.9	23.4	1.7	20.7	1.5
Lephalale Clinic	182.6	93.8	8.1	23.4	1.8	20.8	1.5
Ons Hoop	142.0	95.2	6.7	24.9	1.6	22.2	1.4
Woudend	77.6	55.3	3.5	17.9	1.1	16.9	1.0
Ramabara's	164.3	73.3	7.9	21.1	1.7	20.1	1.6
Ga-Shongoane	86.6	52.2	4.3	21.2	1.2	20.6	1.1
Bulge River	142.0	51.5	7.6	19.9	1.7	19.4	1.6

Kaingo Mountain Lodge	129.1	55.0	6.9	19.2	1.7	18.6	1.6
Community	172.5	59.2	9.3	19.7	1.9	19.0	1.8
Kiesel	183.9	78.1	9.2	19.3	2.3	17.8	1.9
Kremetartpan	294.0	103.9	13.1	24.4	3.2	20.6	2.3
Mbala Private Camp	256.8	106.3	13.1	22.5	2.2	21.1	1.9
Steenbokpan	189.4	89.2	8.8	35.9	6.1	24.2	3.3
Receptor	97.8	52.8	4.6	21.1	1.6	17.9	1.3
Sandbult	128.5	64.4	6.0	22.5	2.7	17.9	1.8
Hardekraaltjie	79.3	49.6	3.7	17.1	1.3	15.6	1.1
Receptor	101.1	70.1	4.9	25.0	1.7	21.0	1.4
Receptor	92.2	68.1	4.3	20.8	1.4	18.7	1.2
Receptor	72.6	52.2	3.4	17.5	1.1	16.2	1.0
Receptor	92.5	67.5	4.4	18.2	1.2	16.7	1.1
Receptor	104.1	62.5	5.0	19.3	1.3	17.9	1.2
Ditaung	77.7	44.5	3.7	20.0	1.1	19.4	1.0
Letlora	84.9	56.3	3.7	17.0	1.1	16.0	1.0
Receptor	178.7	70.0	8.7	21.8	3.1	18.2	2.1
Glenover	148.2	63.7	7.4	19.1	2.4	17.0	1.8
Oxford Safaris	98.8	51.1	4.8	16.8	1.8	14.9	1.4
Receptor	91.9	47.8	4.2	16.8	1.6	15.0	1.3
Tholo Bush Estate	145.8	62.0	7.1	19.0	1.6	18.3	1.6
Receptor	214.4	78.9	10.1	20.9	1.9	19.7	1.8
Receptor	109.9	51.6	5.7	17.3	1.4	16.7	1.4
Cheetah Safaris	192.9	83.6	10.7	22.0	2.1	21.0	1.9
Rhinoland Safaris	95.6	48.7	4.9	17.7	1.3	17.2	1.2

Predicted concentrations in µg/m³ at the sensitive receptors for Scenario C, together with the limit value of the NAAQS

	SO_2			PM_{10} Total		$PM_{2.5}$ Total	
	1-hr	24-hr	Ann	24-hr	Ann	24-hr	Ann
Receptor	350	125	50	75	40	25	15
Phegelelo Senior Secondary	134.5	85.3	6.3	24.7	2.0	18.2	1.3
Contractors Village	145.0	66.8	5.8	25.6	2.2	18.3	1.4
Ditheku Primary School	133.7	79.5	6.2	24.6	2.0	18.1	1.3
Ditheko Primary School	155.0	83.1	6.5	23.8	1.9	17.9	1.3
Marapong Training Centre	137.0	92.5	6.5	24.7	2.0	18.2	1.4
Marapong Clinic	151.4	89.5	6.6	24.1	2.0	18.2	1.3
Tielelo Secondary School	136.3	86.0	6.3	24.8	2.0	18.2	1.3
Grootegeluk Medical Centre - Community Center	143.5	90.0	6.6	24.9	2.0	18.2	1.4
Lephalale College	142.2	77.6	6.9	24.7	1.6	18.7	1.2
Nelsonskop Primary School	152.6	88.2	6.6	24.7	2.0	18.2	1.3
Hansie en Grietjie Pre-Primary School	140.4	77.6	6.9	24.9	1.7	18.7	1.2
Sedibeng Special School for the Deaf and Disabilities	139.9	73.2	6.6	23.0	1.5	18.1	1.2
Kings College	148.4	70.1	7.1	25.3	1.8	19.0	1.3
Bosveld Primary School	139.3	71.7	6.9	24.7	1.7	18.7	1.2
Lephalale Medical Hospital	137.1	88.0	6.4	25.3	2.0	18.3	1.3
Ellisras Hospital	146.2	69.8	6.5	22.5	1.5	17.8	1.2
Laerskool Ellisras Primary School	128.9	59.8	5.8	18.3	1.3	15.6	1.1
Hoerskool Ellisras Secondary School	132.9	63.0	5.9	18.6	1.3	15.7	1.1
Marlothii Learning Academy	131.1	61.7	5.9	18.2	1.3	15.5	1.1
Hardekool Akademie vir C.V.O	121.6	58.4	5.6	18.3	1.3	15.7	1.1
Lephalale Clinic	126.7	59.6	5.8	18.3	1.3	15.6	1.1
Ons Hoop	108.8	60.8	4.9	17.4	1.2	14.7	1.0
Woudend	49.2	33.2	2.2	11.6	0.7	10.7	0.6
Ramabara's	103.1	50.5	5.2	15.3	1.2	14.1	1.1
Ga-Shongoane	56.2	32.7	2.8	13.4	0.8	12.7	0.7
Bulge River	81.0	31.7	4.8	12.7	1.2	12.1	1.1

Kaingo Mountain Lodge	75.9	33.9	4.3	12.4	1.1	11.8	1.0
Community	95.8	35.3	6.1	13.2	1.3	12.5	1.2
Kiesel	113.0	45.3	6.2	12.9	1.8	11.4	1.4
Kremetartpan	177.7	61.3	9.4	17.7	2.7	13.9	1.8
Mbala Private Camp	149.4	62.5	9.1	15.3	1.6	13.9	1.4
Steenbokpan	153.6	55.0	6.8	29.5	5.7	17.8	2.9
Receptor	71.4	33.9	3.1	14.3	1.3	11.2	1.0
Sandbult	87.2	38.7	4.2	17.4	2.3	12.7	1.4
Hardekraaltjie	53.9	28.3	2.4	11.5	0.9	10.0	0.8
Receptor	71.5	47.9	3.5	18.8	1.3	14.6	1.0
Receptor	66.4	45.7	2.9	14.3	1.0	12.3	0.8
Receptor	48.5	37.4	2.3	11.9	0.8	10.5	0.7
Receptor	64.0	42.6	2.9	12.4	0.9	10.8	0.8
Receptor	71.3	40.2	3.4	13.3	0.9	11.9	0.8
Ditaung	51.4	27.2	2.4	12.4	0.7	11.8	0.7
Letlora	54.8	35.2	2.4	11.4	0.7	10.3	0.7
Receptor	124.0	51.7	6.1	15.8	2.6	12.3	1.6
Glenover	97.1	43.8	5.1	13.4	1.9	11.2	1.3
Oxford Safaris	64.2	30.2	3.2	11.8	1.4	10.0	1.0
Receptor	59.6	29.0	2.8	12.6	1.2	10.7	0.9
Tholo Bush Estate	87.9	38.6	4.6	12.4	1.1	11.7	1.0
Receptor	123.3	44.6	6.7	13.8	1.4	12.6	1.2
Receptor	67.2	30.6	3.7	11.6	1.0	11.0	0.9
Cheetah Safaris	110.1	47.2	7.2	14.1	1.5	13.1	1.3
Rhinoland Safaris	60.5	29.3	3.2	11.8	0.9	11.3	0.8

Predicted concentrations in µg/m³ at the sensitive receptors for Scenario D, together with the limit value of the NAAQS

	SO_2			PM_{10} Total		$PM_{2.5}$ Total	
	1-hr	24-hr	Ann	24-hr	Ann	24-hr	Ann
Receptor	350	125	50	75	40	25	15
Phegelelo Senior Secondary	84.7	83.0	5.1	25.4	1.9	18.7	1.3
Contractors Village	78.3	59.6	4.5	25.9	2.1	18.7	1.3
Ditheku Primary School	83.8	77.9	5.0	25.4	1.9	18.7	1.3
Ditheko Primary School	105.5	78.7	5.3	24.8	1.8	19.1	1.3
Marapong Training Centre	87.5	83.3	5.2	25.0	2.0	18.8	1.3
Marapong Clinic	101.6	77.9	5.4	25.2	1.9	19.2	1.3
Tielelo Secondary School	85.5	80.6	5.1	25.5	1.9	18.7	1.3
Grootegeluk Medical Centre - Community Center	91.0	82.2	5.3	25.3	2.0	19.0	1.3
Lephalale College	133.1	78.2	6.2	23.8	1.6	18.0	1.2
Nelsonskop Primary School	101.2	79.7	5.3	26.0	1.9	19.5	1.3
Hansie en Grietjie Pre-Primary School	131.9	76.3	6.2	24.0	1.6	18.1	1.2
Sedibeng Special School for the Deaf and Disabilities	137.0	70.2	6.0	22.5	1.5	17.7	1.2
Kings College	143.5	69.7	6.4	25.9	1.7	19.4	1.2
Bosveld Primary School	133.9	70.5	6.3	25.0	1.6	18.9	1.2
Lephalale Medical Hospital	83.6	85.5	5.2	25.6	1.9	18.8	1.3
Ellisras Hospital	136.8	70.8	5.9	22.2	1.5	17.4	1.1
Laerskool Ellisras Primary School	121.2	62.4	5.4	17.8	1.3	15.2	1.1
Hoerskool Ellisras Secondary School	125.4	62.8	5.5	18.3	1.3	15.4	1.1
Marlothii Learning Academy	121.8	63.1	5.4	18.0	1.3	15.4	1.1
Hardekool Akademie vir C.V.O	113.5	61.2	5.2	17.9	1.2	15.1	1.0
Lephalale Clinic	119.9	62.2	5.4	17.9	1.3	15.3	1.1
Ons Hoop	96.1	61.9	4.5	18.2	1.2	15.5	1.0
Woudend	49.1	34.6	2.2	12.2	0.7	11.2	0.6
Ramabara's	107.3	48.6	5.1	14.5	1.2	13.4	1.1
Ga-Shongoane	56.9	32.9	2.8	14.2	0.8	13.6	0.7
Bulge River	87.4	32.3	4.7	13.2	1.2	12.6	1.1
Kaingo Mountain Lodge	80.9	33.7	4.3	12.9	1.1	12.3	1.0

Community	105.2	37.1	5.8	13.5	1.3	12.8	1.2
Kiesel	111.7	45.6	5.7	13.6	1.7	12.1	1.3
Kremetartpan	173.3	61.6	8.2	18.1	2.6	14.2	1.7
Mbala Private Camp	153.4	67.0	8.2	15.4	1.6	14.0	1.3
Steenbokpan	126.9	52.0	5.7	30.4	5.6	18.6	2.8
Receptor	65.1	33.0	2.9	15.2	1.3	12.0	0.9
Sandbult	82.7	37.8	3.8	17.6	2.3	12.9	1.4
Hardekraaltjie	49.9	30.0	2.3	11.6	0.9	10.1	0.8
Receptor	59.9	46.4	3.1	18.9	1.3	14.8	1.0
Receptor	60.2	42.4	2.8	14.6	1.0	12.5	0.8
Receptor	46.2	35.1	2.2	12.2	0.8	10.8	0.7
Receptor	60.2	43.4	2.8	12.6	0.9	11.1	0.8
Receptor	69.1	38.7	3.3	13.4	0.9	11.9	0.8
Ditaung	50.5	28.6	2.3	13.4	0.7	12.7	0.7
Letlora	53.6	34.9	2.4	11.6	0.7	10.6	0.7
Receptor	113.8	44.6	5.5	16.2	2.6	12.6	1.6
Glenover	95.6	37.9	4.7	13.7	1.9	11.5	1.3
Oxford Safaris	62.0	31.3	3.0	12.1	1.4	10.2	1.0
Receptor	57.8	27.8	2.6	12.9	1.2	11.0	0.9
Tholo Bush Estate	93.1	39.2	4.5	13.0	1.1	12.3	1.0
Receptor	133.6	47.5	6.5	14.1	1.4	12.9	1.2
Receptor	69.0	31.6	3.6	11.9	1.0	11.4	0.9
Cheetah Safaris	116.8	48.8	6.6	14.5	1.5	13.5	1.3
Rhinoland Safaris	61.9	30.1	3.1	12.0	0.9	11.4	0.8

Predicted concentrations in µg/m[3] at the sensitive receptors for Scenario E, together with the limit value of the NAAQS

	SO_2			PM_{10} Total		$PM_{2.5}$ Total	
	1-hr	24-hr	Ann	24-hr	Ann	24-hr	Ann
Receptor	350	125	50	75	40	25	15
Phegelelo Senior Secondary	133.7	100.6	6.8	30.7	2.2	23.8	1.6
Contractors Village	124.2	78.5	6.2	31.3	2.4	23.8	1.6
Ditheku Primary School	130.3	98.0	6.7	30.7	2.2	23.8	1.6
Ditheko Primary School	160.2	99.6	7.2	29.3	2.2	23.3	1.5
Marapong Training Centre	140.7	107.5	7.0	30.1	2.3	23.8	1.6
Marapong Clinic	154.9	103.1	7.3	29.4	2.2	23.4	1.6
Tielelo Secondary School	130.8	100.6	6.9	30.9	2.2	24.0	1.6
Grootegeluk Medical Centre - Community Center	143.5	106.8	7.1	30.8	2.3	24.0	1.6
Lephalale College	184.2	101.1	8.2	28.3	1.9	22.4	1.5
Nelsonskop Primary School	161.3	100.4	7.2	30.7	2.2	24.1	1.6
Hansie en Grietjie Pre-Primary School	182.9	101.8	8.3	28.4	1.9	22.5	1.5
Sedibeng Special School for the Deaf and Disabilities	176.6	89.3	8.1	27.3	1.8	22.3	1.5
Kings College	183.5	97.0	8.6	29.9	2.0	23.4	1.6
Bosveld Primary School	177.4	95.0	8.4	29.3	1.9	23.1	1.5
Lephalale Medical Hospital	133.5	100.8	7.0	31.0	2.3	24.0	1.6
Ellisras Hospital	178.4	91.0	7.8	25.3	1.8	20.5	1.4
Laerskool Ellisras Primary School	156.8	79.7	7.0	21.3	1.6	18.7	1.4
Hoerskool Ellisras Secondary School	162.2	82.7	7.2	21.9	1.6	18.9	1.4
Marlothii Learning Academy	162.9	81.6	7.1	21.6	1.6	18.9	1.4
Hardekool Akademie vir C.V.O	152.8	79.3	6.9	21.5	1.5	18.7	1.3
Lephalale Clinic	157.9	80.4	7.0	21.5	1.6	18.8	1.4
Ons Hoop	128.7	82.1	5.9	22.3	1.5	19.5	1.2
Woudend	65.9	47.1	3.0	15.8	0.9	14.7	0.8
Ramabara's	141.3	64.4	6.8	18.4	1.5	17.3	1.4
Ga-Shongoane	75.0	44.6	3.7	18.4	1.0	17.8	1.0
Bulge River	120.2	43.5	6.5	17.2	1.5	16.6	1.4
Kaingo Mountain Lodge	111.0	46.9	5.9	16.6	1.5	15.9	1.4

Community	144.9	49.8	8.0	17.0	1.6	16.3	1.5
Kiesel	155.4	65.0	7.8	17.1	2.1	15.6	1.7
Kremetartpan	248.7	86.5	11.3	22.2	3.0	18.2	2.1
Mbala Private Camp	213.9	91.3	11.3	19.6	1.9	18.1	1.7
Steenbokpan	164.9	76.9	7.6	33.9	6.0	21.9	3.1
Receptor	85.8	44.6	3.9	19.1	1.5	15.8	1.2
Sandbult	112.1	54.2	5.1	20.8	2.6	15.9	1.7
Hardekraaltjie	68.0	41.7	3.1	15.1	1.1	13.6	1.0
Receptor	87.5	59.3	4.3	22.6	1.5	18.5	1.2
Receptor	78.1	57.9	3.7	18.3	1.3	16.2	1.1
Receptor	62.7	45.3	2.9	15.4	1.0	14.0	0.9
Receptor	79.7	58.1	3.8	16.1	1.1	14.5	1.0
Receptor	89.2	52.7	4.4	17.1	1.2	15.6	1.0
Ditaung	66.6	38.0	3.2	17.2	1.0	16.5	0.9
Letlora	72.8	47.4	3.2	14.9	0.9	13.8	0.9
Receptor	157.9	61.2	7.5	19.8	2.9	16.1	1.9
Glenover	129.0	53.9	6.4	17.1	2.2	14.9	1.6
Oxford Safaris	84.1	44.4	4.1	15.0	1.7	13.1	1.3
Receptor	78.5	40.6	3.6	15.3	1.4	13.4	1.1
Tholo Bush Estate	125.3	54.2	6.1	16.5	1.4	15.8	1.4
Receptor	186.8	67.5	8.7	18.3	1.7	17.0	1.6
Receptor	91.5	43.7	4.8	14.9	1.3	14.3	1.2
Cheetah Safaris	162.4	67.4	9.2	19.3	1.9	18.2	1.7
Rhinoland Safaris	83.5	42.4	4.2	15.4	1.1	14.8	1.1