Project done for

Zitholele Consulting

Continuous Disposal of Ash at Kendal Power Station

Air Quality Basic Evaluation

Report No.: APP/12/ZIT04 Rev 0.4 Final

DATE: 2014/08/06

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REPORT DETAILS

Reference	APP/12/ZIT04
Status	Revision 0.4 Final
Report Title	Continuous Disposal of Ash at Kendal Power Station
Date	2014/08/06
Client	Zitholele Consulting
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Notice	Airshed Planning Professionals (Pty) Ltd is a consulting company located in Midrand, South Africa, specialising in all aspects of air quality, ranging from nearby neighbourhood concerns to regional air pollution impacts. The company originated in 1990 as Environmental Management Services, which amalgamated with its sister company, Matrix Environmental Consultants, in 2003.
Declaration	Airshed is an independent consulting firm with no interest in the project other than to fulfil the contract between the client and the consultant for delivery of specialised services as stipulated in the terms of reference.
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Acknowledgements	Gerhard de Beer, Eskom, for provision of the meteorological data.

EXECUTIVE SUMMARY

Airshed Planning Professionals (Pty) Ltd was appointed by Zitholele Consulting to determine the potential for dust impacts on the surrounding environment and human health from the proposed operations, with specific reference to air quality.

The proposed continuous ash disposal site is located to the north of the current disposal facility, within 2 km from the Kendal Power Station, approximately 10 km from the town of Ogies (to the north-east). Kendal Power Station and the ash disposal facility fall within the Highveld Priority Area – an area of known, or potentially poor, air quality. It is likely that the ash disposal facility influences the air quality within the Priority Area.

In modelling the projected impacts to air quality in the vicinity, meteorological data from Kendal Power Station for the period January 2009 to October 2012 was used. The dominant wind direction is west-north-west with a frequency of occurrence approaching 12%. Easterly sector winds are the next dominant with a frequency of 10%. The modelling of the impact to air quality included four scenarios, with respect to wind—blown dust emissions from the ash disposal facility: (1) unmitigated emissions; (2) mitigation through re-vegetation (to 80% of the facility area); (3) mitigation through wetting (maintaining the moisture content to 5%); and, (4) mitigation through both re-vegetation and wetting.

The impact of the proposed continuous ash disposal facility was assessed on the basis of three criteria: (a) the number of sensitive receptors at which the daily PM_{10} (particulate matter with an aerodynamic diameter of less than 10 μm) NAAQS (National Ambient Air Quality Standards) were exceeded; (b) the number of sensitive receptors at which the daily $PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) NAAQS were exceeded (for each alternative); and, (c) the number of sensitive receptors at which the monthly dust-fall rate is likely to exceed 600 $mg.m^{-2}.day^{-1}$ – the residential draft dust-fall standard.

ASSUMPTIONS AND LIMITATIONS

The following Assumptions and Limitations should be considered when interpreting the findings from the air quality assessment for the continuous ash disposal facility.

- Meteorological data was acquired from the Eskom operated monitoring station at the Kendal Power Station, for January 2009 to October 2012. Due to the proximity between the power station and its ash disposal facility, it was assumed that the meteorological data are representative of the site.
- A comprehensive list of sensitive receptors was not available. As such, individual residences and small residential complexes were identified via aerial photography (using Google Earth™) and used as identified sensitive receptors around the ash disposal facility alternatives.
- The dispersion model cannot compute real-time processes. The end-of-life, worst-case, area footprint for the maximum extent of the continuous ash disposal was used in the model. The range of uncertainty of the model predictions could to be -50% to 200%. There will always be

some error in any geophysical model, but it is desirable to structure the model in such a way to minimise the total error. A model represents the most likely outcome of an ensemble of experimental results. The total uncertainty can be thought of as the sum of three components: the uncertainty due to errors in the model physics; the uncertainty due to data errors; and the uncertainty due to stochastic processes (turbulence) in the atmosphere.

- The selection of a modelling domain takes account of the expected impacts and it is possible that the impacts, when modelled, extend beyond the modelling domain. This occurred for the projected dust-fall rates in the unmitigated scenario; however exceedance of the guideline outside of the modelling domain is not expected to cover a substantial area.
- Increased life-time cancer risk was calculated at the identified sensitive receptors for arsenic, nickel and chromium.
    - Carcinogenic trivalent arsenic (As^{3+}) was assumed to account for 10% of the total arsenic in the ash sample.
        - The US-EPA (United States Environmental Protection Agency) unit risk factor (URF), 4.3×10^{-3}, was used to calculate the increased cancer risk, due to the fact that it is more conservative than the WHO unit risk factor.
    - There is much uncertainty in the literature regarding the species and the mechanisms through which nickel is toxic. A conservative estimate of increased life-time cancer risk was calculated assuming:
        - All forms of nickel present in the ash sample are carcinogenic.
        - The US-EPA IRIS unit risk factor (URF) of cancer as a result of exposure to nickel used was 2.4×10^{-4} $(\mu g.m^{-3})^{-1}$.
    - The following important assumptions were made with regards to Cr^{6+} (hexavalent chromium) emissions and impacts:
        - All forms of Cr^{6+} were assumed to be carcinogenic. Known carcinogenic Cr^{6+} compounds include chromium trioxide, lead chromate, strontium chromate and zinc chromate. Cr^{6+} was assumed to represent only 1.1% of the total Cr in the PM_{10} fraction, as per literature.
        - Uncertainty regarding the unit risk factor (URF) for Cr^{6+} is evident in the range of 1.1×10^{-2} $(\mu g.m^{-3})^{-1}$ to 13×10^{-2} $(\mu g.m^{-3})^{-1}$ as specified by the WHO (World Health Organisation). The US-EPA URF of 1.2×10^{-3} $(\mu g.m^{-3})^{-1}$ was used in the estimation of increased life-time cancer risk compensating for conservative approach followed in the estimation of Cr^{6+} emissions and impacts.

KEY FINDINGS

The model output shows that in the unmitigated scenario annual PM_{10} concentrations exceed the NAAQS well beyond the boundary of the proposed continuous ash disposal facility; however mitigation through watering, re-vegetation, or a combination of both, can reduce the impact within acceptable levels. In relation to sensitive receptors, non-compliance with daily PM_{10} and $PM_{2.5}$ NAAQS are expected at five of the nine identified sensitive receptors, when mitigation of emissions is absent.

Dust-fall rates exceeding 600 $mg.m^{-2}.day^{-1}$ affect a large area around the ash disposal facility, again if no or limited mitigation measures were to be effectively implemented.

The life-time increased cancer risk was calculated at each of the identified sensitive receptors for exposure to inhalable arsenic, nickel and chromium. The calculations were based on the projected annual PM_{10} concentrations at each sensitive receptor, literature values for the proportion of the toxic forms of the trace metals in coal fly ash in combination with total trace metal concentrations in a sample of ash from Kendal Power station and the US-EPA IRIS Unit [cancer] Risk Factor for exposure via inhalation. These calculations showed that the increased life-time cancer risk was low to very low.

Continuous disposal of ash, from Kendal Power Station, at the northern edge of the current facility will impact the air quality by exposing the public to elevated levels of airborne particulates and the associated potential human health impacts. However, the findings from modelling the mitigation scenarios illustrate the value in effective mitigation of wind-blown dust emissions to reduce the impact of the ash disposal facility. Mitigation using re-vegetation was more effective in controlling wind-blown dust emissions than only watering; however, the combination of both re-vegetation and watering was the most effective. Using either re-vegetation or a combination of re-vegetation and watering will reduce particulate concentrations to levels, off-site, that comply with NAAQS.

TABLE OF CONTENTS

List of Figures

List of Tables

List of Acronyms and Symbols

°C	Degrees Celsius
µg.m^{-3}	Microgram per metre cubed
As^{3+}	Trivalent arsenic
CE	Control effciency
Cr^{6+}	Hexavalent chromium
m	metre
m²	Metre squared
m.s^{-1}	Metre per second
mg.m^{-2}.day^{-1}	Milligram per metre squared per day
mamsl	metres above mean sea level
NAAQS	National Ambient Air Quality Standards
Ni	Nickel
PM_{10}	Particulate Matter with an aerodynamic diameter of less than 10 µm
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter of less than 2.5 µm
SA	South Africa
tpa	Tonnes per annum
TSP	Total Suspended Particles
URF	Unit risk factor (life-time exposure)
US	United States
US-EPA	United States Environmental Protection Agency
WHO	World Health Organisation

Glossary

"**air pollution**" means any change in the composition of the air caused by smoke, soot, dust (including coal), cinders, solid particles of any kind, gases, fumes, aerosols and odorous substances.

"**ambient air**" is defined as any area not regulated by Occupational Health and Safety regulations.

"atmospheric emission" or **"emission"** means any emission or entrainment process emanating from a point, non-point or mobile source that results in air pollution.

"particulates" comprises a mixture of organic and inorganic substances, ranging in size and shape. These can be divided into coarse and fine particulate matter. The former is called Total Suspended Particulates (TSP), whilst thoracic particles or PM_{10} (particulate matter with an aerodynamic diameter of less than 10 µm) fall in the finer fraction. PM_{10} is associated with health impacts for it represents particles of a size that would be deposited in, and damaging to, the lower airways and gas-exchanging portions of the lung. TSP, on the other hand, is usually of interest in terms of dust deposition (nuisance).

1 INTRODUCTION

Kendal Power Station is a coal-fired power generation facility on which construction started in mid-1982 and the last unit came online in 1993. The power station is located in the Nkangala District of Mpumalanga, approximately 10 km south-west of the town of Ogies. Kendal Power Station disposes of boiler- and fly-ash in a dry (8 to 15% moisture content conditioning) format, which is transported by means of conveyors. The ash will be distributed onto the ash disposal facility by means of a stacker at a rate of approximately 4.6 million tons per year for all six generating units. The 10-year ash disposal facility will, at full extent, cover approximately of 310 ha, including associated infrastructure.

Airshed Planning Professionals (Pty) Ltd was appointed by Zitholele Consulting to determine the potential for dust impacts on the surrounding environment and human health from the proposed operations, with specific reference to air quality. Practical mitigation measures were considered for the operational phase of the project, including the initiation of re-vegetation of the ash disposal facility and a watering programme for dust suppression.

1.1 Site Description

The proposed 10–year ash disposal facility will be located to the north-west of the current ash disposal facility. The current disposal facility is primarily surrounded by coal-mining operations, the Kendal Power Station and agricultural activities. Residential areas in the region include Ogies (~10 km north-east), Delmas (~30 km south-west), Phola (~11 km north-east), and Kendal town (~3 km north). Individual residences (i.e. farm houses) are also in the immediate vicinity of the proposed operations and are considered to be sensitive receptors with respect to air quality.

1.2 Assumptions and limitations

The following Assumptions and Limitations should be considered when interpreting the findings from the air quality assessment for the continuous ash disposal facility.

- Meteorological data was acquired from the Eskom operated monitoring station at the Kendal Power Station, for January 2009 to October 2012. Due to the proximity between the power station and its ash disposal facility, it was assumed that the meteorological data are representative of the site.
- A comprehensive list of sensitive receptors was not available. As such, individual residences and small residential complexes were identified via aerial photography (using Google Earth™) and used as identified sensitive receptors around the ash disposal facility alternatives.
- The dispersion model cannot compute real-time processes. The end-of-life, worst-case, area footprint for the maximum extent of the continuous ash disposal was used in the model. The range of uncertainty of the model predictions could to be -50% to 200%. There will always be some error in any geophysical model, but it is desirable to structure the model in such a way to minimise the total error. A model represents the most likely outcome of an ensemble of experimental results. The total uncertainty can be thought of as the sum of three components: the uncertainty due to errors in the model physics; the uncertainty due to data errors; and the uncertainty due to stochastic processes (turbulence) in the atmosphere.
- The selection of a modelling domain takes account of the expected impacts and it is possible that the impacts, when modelled, extend beyond the modelling domain. This occurred for the projected dust-fall rates in the unmitigated scenario; however exceedance of the guideline outside of the modelling domain is not expected to cover a substantial area.
- Increased life-time cancer risk was calculated at the identified sensitive receptors for arsenic, nickel and chromium.
    - Carcinogenic trivalent arsenic (As^{3+}) was assumed to account for 10% of the total arsenic in the ash sample.
        - The US-EPA (United States Environmental Protection Agency) unit risk factor (URF), 4.3×10^{-3}, was used to calculate the increased cancer risk, due to the fact that it is more conservative than the WHO unit risk factor.
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    - The following important assumptions were made with regards to Cr^{6+} (hexavalent chromium) emissions and impacts:
        - All forms of Cr^{6+} were assumed to be carcinogenic. Known carcinogenic Cr^{6+} compounds include chromium trioxide, lead chromate, strontium chromate and

zinc chromate. Cr^{6+} was assumed to represent only 1.1% of the total Cr in the PM_{10} fraction, as per literature.

- Uncertainty regarding the URF for Cr^{6+} is evident in the range of 1.1×10^{-2} $(\mu g.m^{-3})^{-1}$ to 13×10^{-2} $(\mu g.m^{-3})^{-1}$ as specified by the WHO (World Health Organisation). The US-EPA URF of 1.2×10^{-3} $(\mu g.m^{-3})^{-1}$ was used in the estimation of increased life-time cancer risk compensating for conservative approach followed in the estimation of Cr^{6+} emissions and impacts.

1.3 Report Outline

Section 2 describes the legislative context applicable to the process. Section 3 of the report provides a description of the site specific dispersion potential through the discussion of near-site surface meteorology. Section 4 describes the approach taken to assess the impact of the ash disposal facility on the air quality in the vicinity. The main findings are outlined in Section 5. A short conclusion and way forward are presented in Section 6. The references are provided in Section 7, followed by Appendix A in which the calculation of fugitive dust emissions is described.

2 LEGISLATIVE CONTEXT

The environmental regulations and guidelines governing the emissions and impact of the ash disposal operations need to be considered prior to potential impacts and sensitive receptors are identified.

Air quality guidelines and standards are fundamental to effective air quality management, providing the link between the source of atmospheric emissions and the user of that air at the downstream receptor site. The ambient air quality limits are intended to indicate safe daily exposure levels for the majority of the population, including the very young and the elderly, throughout an individual's life-time. Air quality guidelines and standards are normally given for specific averaging periods. These averaging periods refer to the time-span over which the air concentration of the pollutant was monitored at a location. Generally, five averaging periods are applicable, namely an instantaneous peak, 1-hour average, 24-hour average, 1-month average, and annual average. The application of these standards varies, with some countries allowing a certain number of exceedances of each of the standards per year.

2.1 National Ambient Air Quality Standards

The South African Bureau of Standards (SABS) assisted the Department of Environmental Affairs (DEA) in the development of ambient air quality standards. National Ambient Air Quality Standards (NAAQS) were determined based on international best practice for PM_{10}, SO_2, NO_2, ozone (O_3), CO, lead (Pb) and benzene. The NAAQS were published in the Government Gazette (no. 32816) on 24 December 2009 (Table 1). The $PM_{2.5}$ national ambient air quality standards were finalised and gazetted (Government Gazette no. 35463, #486) on the 29th June 2012 with lowering concentration limits over three commitment periods.

Table 1: South African national ambient air quality standards (Government Gazette 32816, 2009)

Substance	Molecular formula / notation	Averaging period	Concentration limit (µg/m^3)	Frequency of exceedance[1]	Compliance date[2]
Sulphur dioxide	SO_2	10 minutes	500	526	Immediate
		1 hour	350	88	Immediate
		24 hours	125	4	Immediate
		1 year	50	0	Immediate
Nitrogen dioxide	NO_2	1 hour	200	88	Immediate
		1 year	40	0	Immediate
Particulate matter	PM_{10}	24 hour	120	4	Immediate – 31 Dec 2014
			75	4	1 Jan 2015
		1 year	50	0	Immediate – 31 Dec 2014
			40	0	1 Jan 2015
Particulate matter	$PM_{2.5}$	24 hour	65	4	Immediate – 31 Dec 2015
			40	4	1 Jan 2016 – 31 Dec 2029
			25	4	1 Jan 2030
		1 year	25	0	Immediate – 31 Dec 2015
			20	0	1 Jan 2016 – 31 Dec 2029
			15	0	1 Jan 2030
Ozone	O_3	8 hours (running)	120	11	Immediate
Benzene	C_6H_6	1 year	10	0	Immediate – 31 Dec 2014
			5	0	1 Jan 2015
Lead	Pb	1 year	0.5	0	Immediate
Carbon monoxide	CO	1 hour	30 000	88	Immediate
		8 hour (calculated on 1 hour averages)	10 000	11	Immediate

[1]The number of averaging periods where exceedance of limit is acceptable. [2]Date after which concentration limits become enforceable.

2.2 National Regulations for Dust Deposition

Dust deposition may be gauged according to the criteria published by the South African Department of Environmental Affairs (DEA). In terms of these criteria dust deposition is classified as follows:

SLIGHT	-	less than 250 mg.m^{-1}.day^{-1}
MODERATE	-	250 to 500 mg.m^{-1}.day^{-1}
HEAVY	-	500 to 1 200 mg.m^{-1}.day^{-1}
VERY HEAVY	-	more than 1 200 mg.m^{-1}.day^{-1}y

The South African Department of Mineral Resources (DMR) use the 1 200 mg.m^{-2}.day^{-1} threshold level as an action level. In the event that on-site dust-fall exceeds this threshold, the specific causes of high dust-fall should be investigated and remedial steps taken.

A perceived weakness in the current dust-fall guidelines is that they are purely descriptive, without giving any guidance for action or remediation (SLIGHT, MEDIUM, HEAVY, and VERY HEAVY). On the basis of the cumulative South African experience of dust-fall measurements, a modified set of dust-fall standards is proposed, within the overall framework of the new Clean Air Legislation. Dust-fall will be evaluated against a four-band scale as presented in Table 2 and Table 3.

A draft copy of the National Dust Regulation was published for comment on the 27 May 2011 which states no person may conduct any activity in such a way as to give rise to dust in such quantities and concentrations that:

- The dust or dust fall, has a detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage, or has contributed to the degradation of ambient air quality beyond the premises where it originates; or
- The dust remains visible in the ambient air beyond the premises where it originates; or
- The dust fall at the boundary or beyond the boundary of the premises where it originates exceeds:
    - 600 mg/m^2/day averaged over 30 days in residential and light commercial areas measured using reference method ASTM 01739; or
    - 1 200 mg/m^2/day averaged over 30 days in areas other than residential and light commercial areas measured using reference method ASTM 01739.

Table 2: Bands of dust-fall rates proposed for adoption

Band number	Band description label	Dust-fall rate (D) (mg.m^{-2}.day^{-1}, 30-day average)	Comment
1	Residential	D < 600	Permissible for residential and light commercial
2	Industrial	600 < D < 1 200	Permissible for heavy commercial and industrial
3	Action	1 200 < D < 2 400	Requires investigation and remediation if two sequential months lie in this band, or more than three occur in a year.
4	Alert	2 400 < D	Immediate action and remediation required following the first exceedance. Incident report to be submitted to relevant authority.

Table 3: Target, action and alert thresholds for ambient dust-fall

Level	Dust-fall rate (D) ($mg.m^{-2}.day^{-1}$, 30-day average)	Averaging period	Permitted frequency of exceedances
Target	300	Annual	
Action residential	600	30 days	Three within any year, no two sequential months.
Action industrial	1 200	30 days	Three within any year, not sequential months.
Alert threshold	2 400	30 days	None. First exceedance requires remediation and compulsory report to authorities.

2.3 Increased life-time cancer risk

Trace metals, some of which are potentially carcinogenic, occur in coal ash. The increased life-time cancer risk was calculated at the identified sensitive receptors in order to assist in the identification of the preferred ash disposal facility location. The South African National Cancer Registry life-time cancer risk for South African men and women (Table 4), based on histologically diagnosed cancers in 2004, provide context for the increased risk as a result of exposure to the coal ash from the Kendal Power Station. The risks contextualised in Table 4 are for the types of cancer that may develop as a result of long-term exposure to the coal ash. After metal analysis of an ash sample, increased life-time cancer risk was calculated for the three most abundant metals likely to result in increased risk of cancer.

Table 4: Life-time risk of three types of cancer for South African men and women (NHLS-NCR, 2004)

Cancer type	All men	All women
Lung cancer	1 in 79	1 in 219
Naso-oropharynx	1 in 358	1 in 1355
Oesophogeal	1 in 107	1 in 206

2.3.1 Trivalent Arsenic

Arsenic and its compounds are ubiquitous in nature, exhibiting both metallic and non-metallic properties. Arsenic is most commonly found in nature with sulfides of ores of lead, copper, nickel, antimony, cobalt and iron. The most prevalent oxidation states of arsenic include the trivalent (As^{3+}) and pentavalent (As^{5+}) forms. The more toxic trivalent arsenic form, i.e. arsenic trioxide, is introduced into nature mainly as a result form industrial activities including the smelting of ores. Pentavalent arsenic compounds are generally considered to be less toxic and are most frequently found naturally.

Arsenic is released to the atmosphere from both natural and anthropogenic sources. The principal natural source is volcanic activity, with man-made emissions mainly arising from the smelting of metals, the combustion of fuels (especially low-grade brown coal) and the use of pesticides. Historically, pesticides have constituted the largest use (~50%) of arsenic compounds. The use of arsenic compounds in agriculture has been reduced in recent years.

Mean levels of ambient arsenic air concentration in the United States range from less than 1 $ng.m^{-3}$ to 3 $ng.m^{-3}$ in remote areas, whereas the background levels in urban area have been found to be an order of magnitude higher, i.e. 20 to 30 $ng.m^{-3}$. Concentrations can reach several hundred nanograms per cubic metre in some cities and exceed 1000 $ng.m^{-3}$ (1 $\mu g.m^{-3}$) near nonferrous metal smelters (WHO, 1981) and some power plants, depending on the arsenic content of the coal.

Arsenic is toxic to human health and is considered a carcinogen. The exposure of humans to arsenic affects several organs and may interfere in the immune system (Duker *et al.*, 2005). Inorganic arsenic can have acute, sub-acute and chronic affects which may be either local or systemic. Lung cancer is considered to be the critical effect following inhalation. An increased incidence in lung cancer has been seen in several occupational groups exposed to inorganic arsenic. Some studies show that populations near emissions sources of inorganic arsenic, such as smelters, have a moderately elevated risk of lung cancer (Blot *et al.*, 1975). Other studies have failed to detect an effect in such situations (Greaves *et al.,* 1981*;* Rom *et al.*, 1982). The main pathway of arsenic exposure to the general population is through ingestion and inhalation.

The inhalation reference concentration (RfC) of a substance is based on the assumption that thresholds exist for certain toxic effects such as cellular necrosis. This is similar to the treatment of, for example, sulphur dioxide. The inhalation RfC considers toxic effects for both the respiratory system (portal-of-entry) and for effects peripheral to the respiratory system (extra-respiratory effects).In general, the RfC is an estimate of a daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without an appreciable risk of harmful effects during a life-time, with uncertainty potentially spanning an order of magnitude. Present risk estimates have been derived from studies in exposed human populations in the United States and Sweden. When assuming a linear dose–response relation, a safe level for inhalation exposure cannot be recommended. At an air concentration of 1 $\mu g.m^{-3}$, an estimate of life-time risk is 1.5×10^{-3} (or 1 500 in 1 million). This means that the excess life-time risk level is 1:10 000, 1:100 000 or 1:1 000 000 at an atmospheric concentration of about 66 $ng.m^{-3}$, 6.6 $ng.m^{-3}$ or 0.66 $ng.m^{-3}$, respectively. Arsenic in particulate matter (PM) is considered a pollutant of major concern in the EU and ambient air concentrations have been regulated. WHO (2000) Air Quality Guidelines state that no safe inhalation level could be established and recommended a unit risk factor of 1.5×10^{-3} $(\mu g.m^3)^{-1}$. The US-EPA Integrated Risk Information System (IRIS) recommends a more conservative 4.3×10^{-3} $(\mu g.m^3)^{-1}$ URF for arsenic. It was decided to use the more conservative URF to estimate increased cancer risk through exposure to ash from the Kendal Power Station.

A coal fly-ash sample from an Australian Power Station was found to contain 10% of the total arsenic as the toxic As^{3+} species (Shah *et al.*, 2008). Increased life-time cancer risk as a result of long-term exposure to As in ash from the Kendal Power Station was calculated from the annual PM_{10} concentrations at the identified sensitive receptors, assuming 10% of total As being carcinogenic.

2.3.2 Nickel

Nickel (Ni) is used in many industrial and commercial applications including: in stainless steel, nickel alloys, catalysts, batteries, pigments and ceramics. According to the US-National Toxicology Program of the Department of Health and Human Services, nickel compounds are classed as known human carcinogens, while metallic nickel is classed as '*reasonably anticipated to be a human carcinogen*'. Evidence suggests that the genotoxic agent, and probable carcinogenic agent, is the Ni^{2+} ion although the potency of nickel compounds is highly variable, based on solubility and chemical speciation. The US-EPA IRIS (Integrated Risk Information System) therefore defines risk profiles for nickel carbonyl, nickel subsulfide and soluble nickel salts. Inhalation, ingestion and dermal contact are the mechanisms via which exposure to Ni occurs. Most people are exposed to low levels of environmental Ni, in air (with ambient concentrations generally less than 2.5 $ng.m^{-3}$ – Sivulka, 2005), water, food and consumer products. Occupational exposure through inhalation of dust particles and fumes has the greatest cancer risk (Sivulka, 2005), potentially results in the development of cancers of the lung and / or nasal passages, with a possibility of extra-pulmonary tumours. The unit risk (URF) for lung cancer based on life-time exposure to 1 $\mu g.m^{-3}$ of Ni compounds ranges between 2.1×10^{-4} $(\mu g.m^{-3})^{-1}$ and 37×10^{-4} $(\mu g.m^{-3})^{-1}$. The recommended inhalation URF for exposure to Ni refinery dust is 2.4×10^{-4} $(\mu g.m^{-3})^{-1}$ and for exposure to Ni subsulfide is 4.8×10^{-4} $(\mu g.m^{-3})^{-1}$. Haney *et al.* (2012) recently presented a weighted URF of 1.74×10^{-4} $(\mu g.m^{-3})^{-1}$, translating into an ambient Ni concentration of 0.059 $\mu g.m^{-3}$ for the increased lung cancer risk of 1 in 100 000. The revised URF presented by Haney *et al.* (2012) is, however, most appropriate for the low sulfidic nickel emissions from Texas (USA) refineries.

The increased life-time cancer risk as a result of long-term exposure to Ni in ash from the Kendal Power Station was calculated from the annual PM_{10} concentrations at the identified sensitive receptors using the URF of 2.4×10^{-4} $(\mu g.m^{-3})^{-1}$, recommended for nickel refinery dust. Due to the uncertainty in the literature of the carcinogenic Ni species and the proportion of carcinogenic species in relation to total Ni, it was conservatively assumed that 100% of Ni present in the ash from the Kendal Power Station would be carcinogenic.

2.3.3 Hexavalent Chromium

In the hexavalent state, chromium exists as oxo-species such as CrO_3 and CrO_4^{2-} that are strongly oxidizing (Cotton & Wilkinson, 1980). In a solution, hexavalent chromium exists as hydrochromate ($HCrO^{4-}$), chromate (CrO_4^{2-}), and dichromate ($Cr_2O_7^{2-}$) ionic species. The proportion of each ion in a

solution is pH dependent. In basic and neutral pH, the chromate form predominates. As the pH is lowered (6.0 to 6.2), the hydrochromate concentration increases. At very low pH, the dichromate species predominate (US EPA, 1984).

The primary sources of hexavalent chromium in the atmosphere are chromate chemicals used as rust inhibitors in cooling towers and emitted as mists, particulate matter emitted during manufacture and use of metal chromates, and chromic acid mist from the plating industry. Hexavalent chromium in air eventually reacts with dust particles or other pollutants to form trivalent chromium (National Academy of Sciences, 1974); however, the exact nature of such atmospheric reactions has not been extensively studied. Both hexavalent (Cr^{6+}) and trivalent (Cr^{3+}) chromium are removed from air by atmospheric fallout and precipitation (Fishbein, 1981). The atmospheric half-life for the physical removal mechanism is dependent on the particle size and particle density. Chromium particles of small aerodynamic diameter (<10 µm) will remain airborne for a longer period.

Hexavalent chromium may exist in aquatic media as water-soluble complex anions and may persist in water. Hexavalent chromium is a strong oxidizing agent and may react with organic matter or other reducing agents to form trivalent chromium. The trivalent chromium will eventually be precipitated as $Cr_2O_3 \cdot xH_2O$. Therefore, in surface water rich in organic content, hexavalent chromium will exhibit a much shorter life-time (Callahan, Slimak, & Bagel, 1979). Any hexavalent chromium in soil is expected to be reduced to trivalent chromium by organic matter. The primary processes by which the converted trivalent chromium is lost from soil are aerial transport through aerosol formation and surface water transport through runoff (US EPA, 1984). The insolubility of Cr_2O_3 restricts the extent to which chromium is leached from soil (Fishbein, 1981). Chemical *in situ* treatment with ferrous sulfate has been found to stabilize trace metals in coal fly-ash to limit impacts as a result of leaching, especially for unlined disposal facilities (Bhattacharyya *et al.*, 2009).

A number of factors can influence the absorption of chromium following inhalation, including the size, oxidation state, and solubility of the chromium particles; the activity of alveolar macrophages; and the interaction of chromium with bio-molecules following deposition in the lung. A very detailed review on the toxicology of hexavalent chrome was compiled by the US-EPA (US EPA, 1998).

2.3.3.1 Chronic Exposure and Dose-Response Relationships for Hexavalent Chrome

There are many epidemiologic studies demonstrating that hexavalent chromium (Cr^{6+}) is a potential human carcinogen, but few provide adequate exposure data for use in risk estimation. Mancuso (1975) provides limited but adequate information for this purpose, and Mancuso's data are used as the main database for estimating the carcinogenic potency of hexavalent chromium.

Results of occupational epidemiological studies of chromium-exposed workers are consistent across investigators and study populations. Dose-response relationships have been established for chromium exposure and lung cancer. Chromium-exposed workers were exposed to both Cr^{3+} and

Cr^{6+} compounds. Because only Cr^{6+} has been found to be carcinogenic in animal studies, however, it was concluded that only Cr^{6+} should be classified as a human carcinogen consistent with the human carcinogenicity data on hexavalent chromium, confirmed by many tumour types in animal bioassays.

In assessing the impacts of constituents a distinction need be made between carcinogenic and non-carcinogenic pollutants. It is plausible that for any dose of a carcinogen there could be some finite increase in cancer risk (i.e. there is no safe dose). In most countries, as is the case in South Africa, non-carcinogens are, however, considered to act via a threshold mechanism, which allows for the identification of a safe dose. Unit Risk Factors (i.e. life-time exposure) were used in the current study to determine the potential for human health impacts associated with Cr^{6+}. Unit risk factors are applied in the calculation of carcinogenic risks. These factors are defined as the estimated probability of a person (60-70 kg) contracting cancer as a result of constant exposure to an ambient concentration of 1 $\mu g.m^{-3}$ over a 70-year life-time. In the generic health risk assessment undertaken as part of the current study, maximum possible exposures (24-hours a day over a 70-year life-time) are assumed for all areas beyond the boundary of the ash disposal facility.

Cr^{6+} is classified as a Group A, human carcinogen of high carcinogenic hazard by the US-EPA. The US-EPA has calculated the inhalation unit risk factor (US EPA, 1998) to be 1.2×10^{-2} $(\mu g.m^{-3})^{-1}$. Using the US-EPA cancer unit risk factor, a concentration of 0.0008 µg $Cr^{6+}.m^{-3}$ in air would be associated with an excess cancer risk of one in a hundred thousand. The WHO cancer unit risk factor for hexavalent chromium is stated in the range 1.1 to 13×10^{-2} $(\mu g.m^{3})^{-1}$. Using the lower factor, a concentration of 0.000091 µg $Cr^{6+}.m^{-3}$ in air would be associated with an excess cancer risk of one in a million.

The risk calculations above are generic and simplified, based on assumptions that are not always applicable. For example, the estimates have not considered the greater vulnerability of children to such exposures. Furthermore, it is assumed that individuals would be exposed to all the hexavalent chromium in the particulates. This may be conservative, as particulates with aerodynamic diameter above 10 µm are largely trapped in the nasopharyngeal region of the respiratory system, from where they may be washed out for ingestion through mucociliary action. This is an important consideration in assessing exposure and risk, because carcinogenicity of hexavalent chromium by the oral route of exposure has not been shown.

Since not all combustion processes result in release of Cr^{6+} it is valuable, in assessing the increased life-time cancer risk as a result of inhalation, to understand the contribution of Cr^{6+} to total Cr in ash, and especially in the PM_{10} (inhalable) fraction. In two recent studies of Cr in ash from Australian coal-fired power stations, it was found that a small proportion of total Cr occurs as Cr^{6+} (Shah *et al.*, 2008; 2012). The focus of the earlier study (Shah *et al.*, 2008) was on the speciation of trace metals (As, Cr and selenium) in the coal ash from a single power station in New South Wales using bituminous rank coal. The authors found that Cr^{6+} accounted for only 2.7% of the total Cr in coal fly-ash. The later investigation (Shah *et al.*, 2012) focussed on the Cr speciation in bituminous rank coal and ash by-product from four coal-fired power stations across Australia. The range of contribution of Cr^{6+} to total

Cr in ash products ranged between 0.9 and 1.6%. Further analyses showed that in the PM_{10} fraction, only 1.1% of total Cr was in the toxic Cr^{6+} form (Shah *et al.*, 2012).

Increased life-time cancer risk as a result of long-term exposure to Cr in ash from Kendal Power Station was calculated from the annual PM_{10} concentrations assuming 1.1% of total Cr as carcinogenic.

2.3.4 Acceptable Cancer Risk

The identification of an acceptable cancer risk level has been debated for many years and it possibly will still continue as societal norms and values change. Some people would easily accept higher risks than others, even if it were not within their own control; others prefer to take very low risks. An acceptable risk is a question of societal acceptance and will therefore vary from society to society.

In spite of the difficulty to provide a definitive “acceptable risk level”, the estimation of a risk associated with an activity provides the means for a comparison of the activity to other everyday hazards, and therefore allowing risk-management policy decisions. Technical risk assessments seldom set the regulatory agenda because of the different ways in which the non-technical public perceives risks. Consequently, science does not directly provide an answer to the question.

Risk assessment, as an organized activity of the US Food and Drug Administration (FDA) and the EPA, began in the 1970s. During the middle 1970s, the EPA and FDA issued guidance for estimating risks associated with small exposures to potentially carcinogenic chemicals. Their guidance made estimated risks of one extra cancer over the life-time of 100 000 people (EPA) or 1 million people (FDA) action levels for regulatory attention. Estimated risks below those levels are considered negligible because they add individually so little to the background rate of about 250 000 cancer deaths out of every 1 million people who die every year in the United States, i.e. 25%. Accepting 1 in 100 000 or 1 in 1 million risk translates to 0.004% or 0.0004% increase in the existing cancer risk level, respectively.

The European Parliament and the European Council, when considering the proposal for a Directive on Drinking Water, agreed that an excess life-time risk of 1 in 1 million should be taken as the starting point for developing limit values. In South Africa, the Department of Environmental Affairs (DEA) has only been noted to give an indication of cancer risk acceptability in the case of dioxin and furan exposures. According to the DEA, emissions of dioxins and furans from a hazardous waste incineration may not result in an excess life-time cancer risk of greater than 1 in 100 000 on the basis of annual average exposure (DEAT, 1994). Excess cancer risks of less than 1 in 100 000 appear therefore to be viewed as acceptable to the DEA.

Whilst it is perhaps inappropriate to make a judgment about how much risk should be acceptable, through reviewing acceptable risk levels selected by other well-known organizations, it would appear that the US-EPA's application is the most suitable, i.e.

"If the risk to the maximally exposed individual (MEI) is no more than $1x10^{-6}$, then no further action is required. If not, the MEI risk must be reduced to no more than $1x10^{-4}$, regardless of feasibility and cost, while protecting as many individuals as possible in the general population against risks exceeding $1x10^{-6}$".

Some authorities tend to avoid the specification of a single acceptable risk level. Instead a "risk-ranking system" is preferred. For example, the New York Department of Health produced a qualitative ranking of cancer risk estimates, from very low to very high (Table 5). Therefore if the qualitative descriptor was "low", then the excess life-time cancer risk from that exposure is in the range between one per ten thousand and one per million.

Table 5: Excess life-time cancer risk (as applied by the New York Department of Health)

Risk Ratio	Qualitative Descriptor
Equal to or less than one in a million	*Very low*
Greater than one in a million to less than one in ten thousand	*Low*
One in ten thousand to less than one in a thousand	*Moderate*
One in a thousand to less than one in ten	*High*
Equal to or greater than one in ten	*Very high*

3 AIR QUALITY BASELINE EVALUATION

The baseline evaluation primarily comprises the assessment of near-site surface meteorology and current ambient air quality. Recent ambient monitoring data from the Witbank (owned by Emalahleni Municipality) and Greendale monitoring stations (owned by Mpumalanga Government) are presented as an indication of the background air pollution in the region (Section 3.2).

3.1 Regional Climate and Atmospheric Dispersion Potential

The meteorological characteristics of a site govern the dispersion, transformation and eventual removal of pollutants from the atmosphere (Pasquill and Smith, 1983; Godish, 1990). The extent to which pollution will accumulate or disperse in the atmosphere is dependent on the degree of thermal and mechanical turbulence within the earth's boundary layer. Dispersion comprises vertical and horizontal components of motion. The vertical component is defined by the stability of the atmosphere and the depth of the surface mixing layer. The horizontal dispersion of pollution in the boundary layer is primarily a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution as a result of plume 'stretching'. The generation of mechanical turbulence is similarly a function of the wind speed, in combination with the surface roughness. The wind direction and the variability in wind direction, determine the general path pollutants will follow, and the extent of cross-wind spreading (Shaw and Munn, 1971; Pasquill and Smith, 1983; Oke, 1990).

Pollution concentration levels therefore fluctuate in response to changes in atmospheric stability, to concurrent variations in the mixing depth, and to shifts in the wind field. Spatial variations, and diurnal and seasonal changes in the wind field and stability regime are functions of atmospheric processes operating at various temporal and spatial scales (Goldreich and Tyson, 1988). Atmospheric processes at macro- and meso-scales must be accounted for to accurately parameterise the atmospheric dispersion potential of a particular area. A qualitative description of the synoptic climatology of the study region is provided based on a review of the pertinent literature. The analysis of meteorological data observed for the proposed site, where available, and data for neighbouring sites will provide the basis for the parameterisation of the meso-scale ventilation potential of the site.

The analysis of at least one year of hourly average meteorological data for the study site is required to facilitate a reasonable understanding of the ventilation potential of the site. The most important meteorological parameters to be considered are: wind speed, wind direction, ambient temperature, atmospheric stability and mixing depth. Atmospheric stability and mixing depths are not routinely recorded and frequently need to be calculated from diagnostic approaches and prognostic equations, using as a basis routinely measured data, e.g. temperature, predicted solar radiation and wind speed.

Meteorological data for the Kendal monitoring station were available for the period January 2009 – October 2012.

3.1.1 Local wind field

The dominant wind direction (Figure 1), during the period under investigation, is west-north-west with a frequency of occurrence approaching 12%. Easterly sector winds are the next dominant with a frequency of 10%. Winds from the southern and south-western sectors occur relatively infrequently (<4% of the total period). Calm conditions (wind speeds <1 m/s) occur 6.66% of the time.

A frequent north-westerly flow dominates day-time conditions with >12% frequency of occurrence. At night, an increase in easterly flow is observed (~11% frequency).

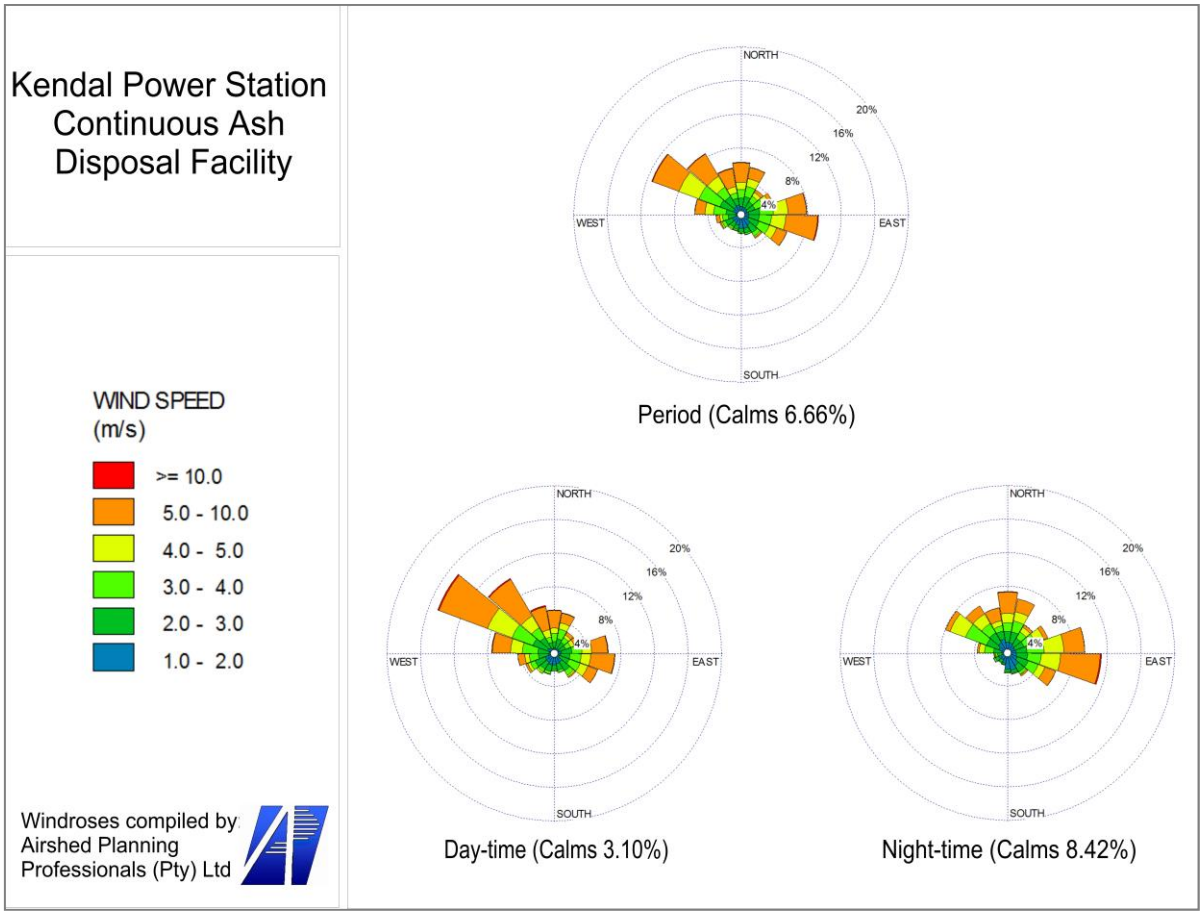

Figure 1: Period, day-time and night-time wind roses for Kendal monitoring station (January 2009 – October 2012)

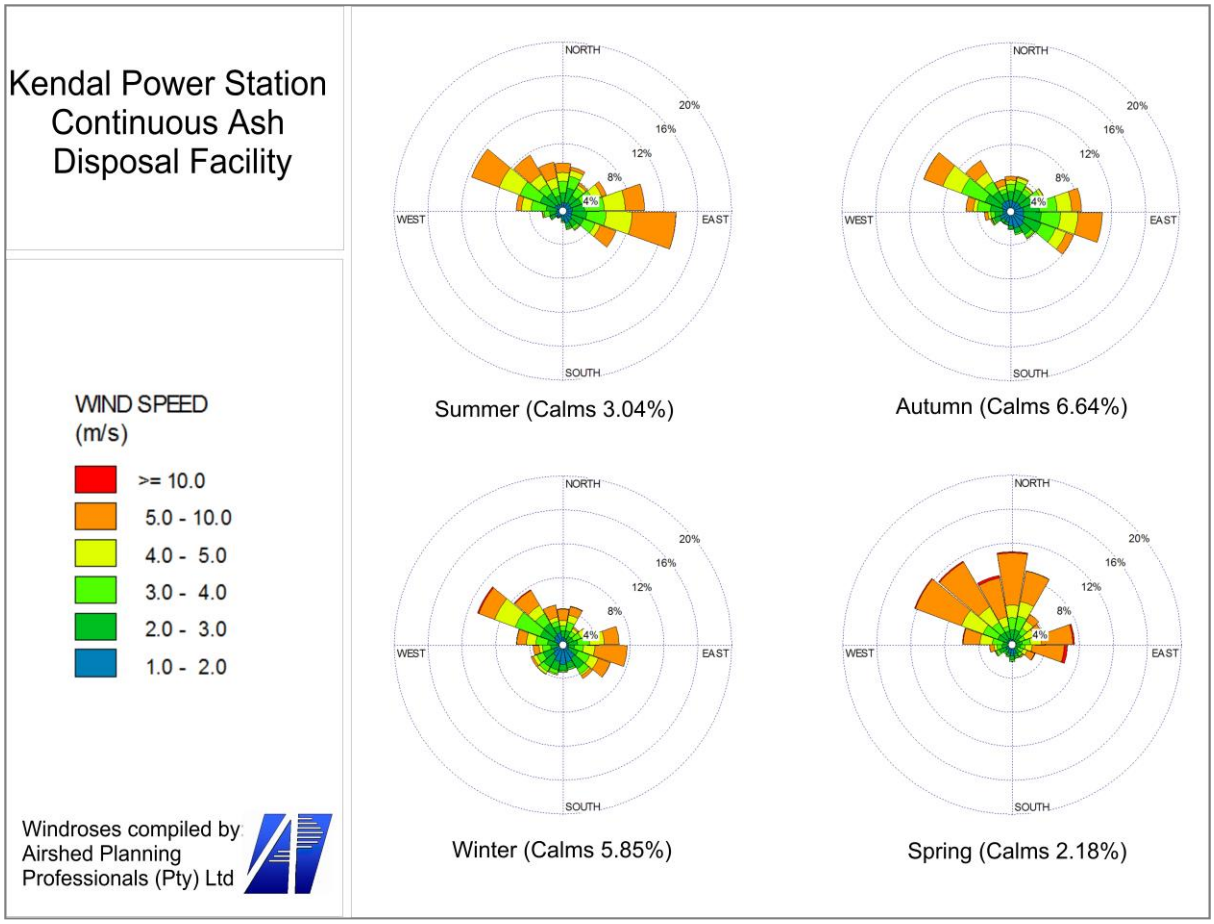

Figure 2: Seasonal wind roses for Kendal monitoring station (January 2009 – October 2012)

During summer months (Figure 2), winds from the east become slightly more frequent. There is an increase in the frequency of calm periods (i.e. wind speeds <1 m/s) during the autumn (6.64%) and winter months (5.85%) with an increase in the westerly flow. During spring-time, winds from the north-westerly sector dominate, frequently in the range of 5.0 to 10.0 m/s, with calm conditions only 2.18% of the time.

3.1.2 Surface Temperature

Air temperature has important implications for the buoyancy of plumes; the larger the temperature difference between the plume and the ambient air, the higher the plume is able to rise. Temperature also provides an indication of the extent of insolation, and therefore of the rate of development and dissipation of the mixing layer.

The monthly temperature profile for the area is given in Figure 3. Annual average maximum, minimum and mean temperatures for the site are given as 26.5°C, 9.6°C and 16.2°C, respectively, based on the measured data at Eskom's Kendal Power station for the period 2009 - October 2012. Average

daily maximum temperatures range from 31.5°C in December to 19.9°C in June, with daily minima ranging from 14.5°C in December to 2.1°C in July (Figure 3).

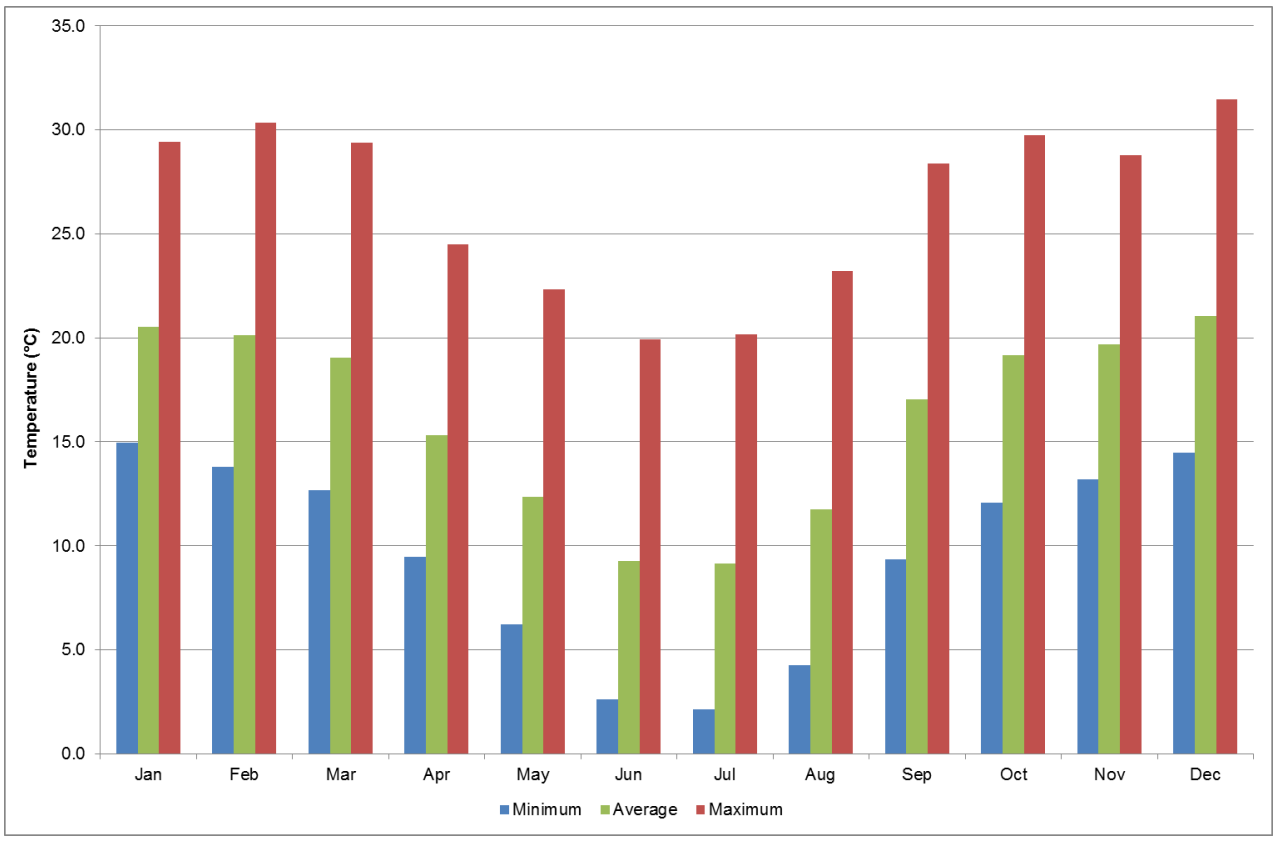

Figure 3: Minimum, average, and maximum monthly temperatures near Kendal Power Station during the period January 2009 – October 2012

3.1.3 Precipitation

Rainfall represents an effective removal mechanism of atmospheric pollutants and is therefore frequently considered during air pollution studies. Precipitation records for Kendal were not available; long-term precipitation records for Middleburg and Bethal are presented below in the absence of these records.

Long-term total annual rainfall figures for various stations within the Emalahleni region is in the range of 730 mm to 750 mm (Table 6). Rain falls mainly in summer from October to April, with the peak for the region being in January.

Table 6: Long-term mean monthly rainfall figures (mm) for various stations within the Emalahleni region.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Middelburg (1904 – 1950)	132	103	88	42	19	7	9	8	22	63	124	118	735
Bethal (1904 – 1984)	134	94	78	46	19	7	8	10	25	78	128	120	747

3.1.4 Atmospheric Stability

The vertical component of dispersion is a function of the extent of thermal turbulence and the depth of the surface mixing layer. Unfortunately, the mixing layer is not easily measured, and must therefore often be estimated using prognostic models that derive the depth from some of the other parameters that are routinely measured, e.g. solar radiation and temperature. During the daytime, the atmospheric boundary layer is characterised by thermal turbulence due to the heating of the earth's surface and the extension of the *mixing layer* to the lowest elevated inversion. Radiative flux divergence during the night usually results in the establishment of ground based inversions and the erosion of the mixing layer. The mixing layer ranges in depth from ground level (i.e. only a stable or neutral layer exists) during night-times to the base of the lowest-level elevated inversion during unstable, day-time conditions.

Atmospheric stability is frequently categorised into one of six stability classes. These are briefly described in Table 7.

Table 7: Atmospheric Stability Classes

A	very unstable	calm wind, clear skies, hot daytime conditions
B	moderately unstable	clear skies, daytime conditions
C	unstable	moderate wind, slightly overcast daytime conditions
D	neutral	high winds or cloudy days and nights
E	stable	moderate wind, slightly overcast night-time conditions
F	very stable	low winds, clear skies, cold night-time conditions

The atmospheric boundary layer is normally unstable during the day as a result of the turbulence due to the sun's heating effect on the earth's surface. The thickness of this mixing layer depends predominantly on the extent of solar radiation, growing gradually from sunrise to reach a maximum at about 5-6 hours after sunrise. This situation is more pronounced during the winter months due to strong night-time inversions and a slower developing mixing layer. During the night a stable layer, with limited vertical mixing, exists. During windy and/or cloudy conditions, the atmosphere is normally neutral.

For low level releases, such as due to vehicle entrainment from unpaved roads, the highest ground level concentrations will occur during weak wind speeds and stable (night-time) atmospheric conditions. Wind erosion, on the other hand, requires strong winds together with fairly stable conditions to result in high ground level concentrations i.e. neutral conditions.

3.2 Ambient Air Quality near Kendal Continuous Ash Disposal Facility

3.2.1 Highveld Priority Area

The Highveld Airshed Priority Area (HPA) was declared the second national air quality priority area (after the Vaal Triangle Airshed Priority Area) by the Minister of Environmental Affairs at the end of 2007 (HPA, 2011). This required that an Air Quality Management Plan for the area be developed. The plan includes the establishment of emissions reduction strategies and intervention programmes based on the findings of a baseline characterisation of the area. The implication of this is that all contributing sources in the area will be assessed to determine the emission reduction targets to be achieved over the following few years.

The DEA published the management plan for the Highveld Priority Area in September 2011. Included in this management plan are 7 goals, each of which has a further list of objectives that has to be met. The 7 goals for the Highveld Priority area are as follows:

- **Goal 1:** By 2015, organisational capacity in government is optimised to efficiently and effectively maintain, monitor and enforce compliance with ambient air quality standards.
- **Goal 2:** By 2020, industrial emissions are equitably reduced to achieve compliance with ambient air quality standards and dust fallout limit values.
- **Goal 3:** By 2020, air quality in all low-income settlements is in full compliance with ambient air quality standards.
- **Goal 4:** By 2020, all vehicles comply with the requirements of the National Vehicle Emission Strategy.
- **Goal 5:** By 2020, a measurable increase in awareness and knowledge of air quality exists.

- **Goal 6:** By 2020, biomass burning and agricultural emissions will be 30% less than current.
- **Goal 7:** By 2020, emissions from waste management are 40% less than current.

The Kendal Ash Disposal Facility, current and the expanded footprint, fall within the HPA. Therefore the particulate emissions from the facility are likely to contribute to the air quality of the HPA. The ash disposal facility is located in the vicinity of the Emahaleni Hot Spot (HPA, 2011) and the ambient air quality, with particular reference to particulates, is outlined below.

3.2.1.1 Emahaleni Hot Spot

The poor ambient air quality in the Emahaleni Hot Spot is a result of emissions from power generation, metallurgical manufacturing processes, open-cast coal mining and residential fuel burning; where industrial processes dominate the source contribution (HPA, 2011). Dispersion modelling projected exceedances of the daily PM_{10} limit for more than 12 days across the Emahaleni Hot Spot (HPA. 2011). Monitored daily PM_{10} concentrations within the Hot Spot, at Witbank and Greendale High School show regular exceedances of the daily limit, between 2008 and 2012 (Figure 4). The HPA Air Quality Management Plan (2011) reported exceedance of the annual limit, for 2008 / 2009, at one of the two monitoring stations in Witbank with an annual averages ~83 $\mu g.m^{-3}$ for Witbank 2.

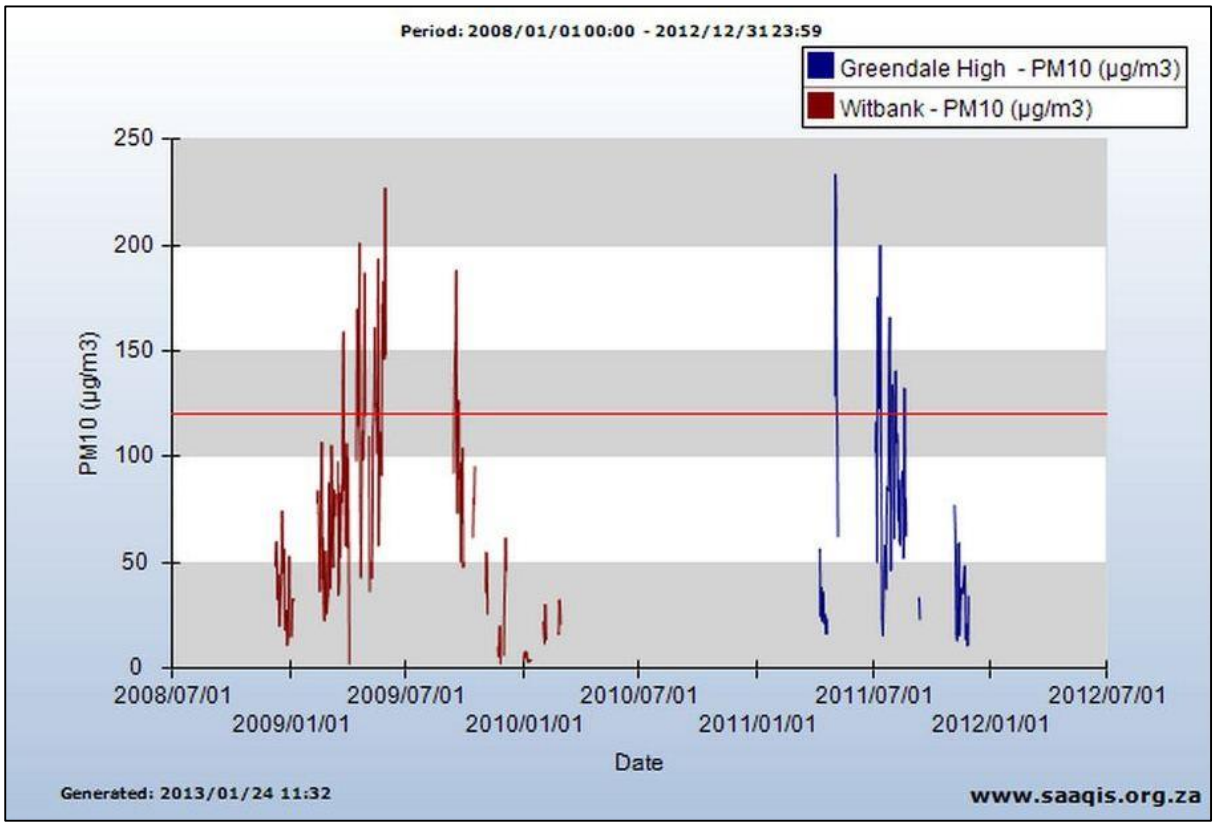

Figure 4: Daily PM_{10} concentrations monitored at two stations in the Emahaleni Hot Spot between 2008 and 2012 (from www.saaqis.org.za). The horizontal red line indicates the current daily limit of 120 $\mu g.m^{-3}$.

4 METHODOLOGY

4.1 Source Identification

The project includes the continuous disposal of ash from the Kendal Power Station at the northern edge of the current disposal facility (less than 2 km from the power station). The main pollutant of concern associated with the proposed operations is particulate matter. Particulates are divided into different particle size categories with Total Suspended Particulates (TSP) associated with nuisance impacts and the finer fractions of PM_{10} (particulates with a diameter less than 10 µm) and $PM_{2.5}$ (diameter less than 2.5 µm) linked with potential health impacts. PM_{10} is primarily associated with mechanically generated dust whereas $PM_{2.5}$ is associated with combustion sources. Gaseous pollutants (such as sulphur dioxide, oxides of nitrogen, carbon monoxide, etc.) derive from vehicle exhausts and other combustion sources. These are however insignificant in relation to the particulate emissions and are not discussed in detail.

The establishment of the ash disposal facility will result in particulate emissions (listed in Table 8) during the following operations:

- land preparation during establishment and progression of the ash disposal facility;
- freshly exposed topsoil, as a step in rehabilitation of the ash disposal facility, that will be prone to wind erosion before establishment of vegetation; and,
- movement of vehicles across exposed soil or ash, will also be a source of pollution.

The subsequent sections provide a generic description of the parameters influencing dust generation from the various aspects identified.

Table 8: Activities and aspects identified for the construction, operational and closure phases of the proposed operations

Pollutant(s)	Aspect	Activity
Construction		
Particulates	Construction of progressing ash disposal facility site	Clearing of groundcover
		Levelling of area
		Wind erosion from topsoil storage piles
		Tipping of topsoil to storage pile
	Vehicle activity on-site	Vehicle and construction equipment activity during construction operations
Gases and particles	Vehicle and construction equipment activity	Tailpipe emissions from vehicles and construction equipment such as graders, scrapers and dozers
Continuous ash disposal		
Particulates	Wind erosion from ash disposal facility	Exposed dried out portions of the ash disposal facility
	Vehicle activity on-site	Vehicle activity at the ash disposal facility
Gases and particles	Vehicle activity	Tailpipe emissions from vehicle activity at the ash disposal facility
Rehabilitation		
Particulates	Rehabilitation of ash disposal facility	Topsoil recovered from stockpiles
		Tipping of topsoil onto ash disposal facility
	Wind erosion	Exposed cleared areas and exposed topsoil during rehabilitation
	Vehicle activity on unpaved roads and on-site	Truck activity at site during rehabilitation
Gases and particles	Vehicle activity	Tailpipe emissions from trucks and equipment used for rehabilitation

4.1.1 Construction phase

The construction phase is relevant as the ash disposal facility is established and during continuous ash disposal, as this would normally comprise a series of different operations including land clearing, topsoil removal, road grading, material loading and hauling, stockpiling, compaction, etc. Each of these operations has a distinct duration and potential for dust generation. It is anticipated that the extent of dust emissions would vary substantially from day to day depending on the level of activity, the specific operations, and the prevailing meteorological conditions.

It is not anticipated that the various construction activities will result in higher off-site impacts than the operational activities. The temporary nature of the construction activities, and the likelihood that these activities will be localised and for small areas at a time, will reduce the potential for significant off-site impacts. The Australian Environmental Protection Agency recommends a buffer zone of 300 m from the nearest sensitive receptor when extractive-type materials handling activities occur (AEPA, 2007).

4.1.2 Continuous ash disposal

Wind erosion is a complex process, including three different phases of particle entrainment, transport and deposition. It is primarily influenced by atmospheric conditions (e.g. wind, precipitation and temperature), soil properties (e.g. soil texture, composition and aggregation), land-surface characteristics (e.g. topography, moisture, aerodynamic roughness length, vegetation and non-erodible elements) and land-use practice (e.g. farming, grazing and mining) (Shao, 2008).

Windblown dust generates from natural and anthropogenic sources. For wind erosion to occur, the wind speed needs to exceed a certain threshold, called the threshold velocity. This relates to gravity and the inter-particle cohesion that resists removal. Surface properties such as soil texture, soil moisture and vegetation cover influence the removal potential. Conversely, the friction velocity or wind shear at the surface is related to atmospheric flow conditions and surface aerodynamic properties. Thus, for particles to become airborne the wind shear at the surface must exceed the gravitational and cohesive forces acting upon them, called the threshold friction velocity (Shao, 2008).

Estimating the amount of windblown particles to be generated from the proposed ash disposal facility is not a trivial task and requires detailed information on the particle size distribution, moisture content, silt content and bulk density (as discussed in Appendix A). Dust will only be generated under conditions of high wind speeds and from areas where the material is exposed and has dried out (US-EPA, 1995a). Annual emissions were quantified for four scenarios (Section 4.3.3) where mitigation practices were calculated to have control efficiencies (CE) greater than 70% (Table 9), based on a facility area of 334 ha..

Table 9: Annual emissions for each site alternative for each of the modelled scenarios (facility area: 334 ha)

Scenario	Particulate fraction	Annual emissions (tpa)
Unmitigated	TSP	44 607
	PM_{10}	17 735
	$PM_{2.5}$	5 111
Re-vegetation CE = 97%	TSP	1 342
	PM_{10}	533
	$PM_{2.5}$	154
Wetting CE = 74%	TSP	11 601
	PM_{10}	4 588
	$PM_{2.5}$	1 322
Both (re-vegetation & wetting) CE = 99%	TSP	349
	PM_{10}	138
	$PM_{2.5}$	40

4.1.3 Rehabilitation

Rehabilitation is planned to occur continuously throughout the disposal of ash and will include the removal and tipping of topsoil onto the completed ash disposal facility surface areas. Dust may be generated from the dried out exposed ash surfaces before it is covered with topsoil. Once vegetation is established the potential for dust generation will reduce significantly. The tipping of topsoil and vehicle entrainment on associated unpaved roads will also result in dust generation.

It is assumed that all ash disposal activities will have ceased during closure phase, when the power station has reached end of life. Because most of the rehabilitation is undertaken during the operations, the ash disposal facility should be almost completely rehabilitated by the closure phase. The potential for impacts after closure will depend on the extent of continuous rehabilitation efforts on the ash disposal facility.

The significance of the rehabilitation activities is likely to be linked to impacts from windblown dust from the exposed dried out ash, topsoil and vehicle entrainment during the rehabilitation process. Windblown dust is likely to only impact off-site under conditions of high wind speed with no mitigation in place. If rehabilitation as indicated takes place, i.e. vegetation cover, the impacts should be limited to be within the site boundary. As vegetation cover increases, the potential for wind erosion will decrease.

4.2 Identification of Sensitive Receptors

The National Ambient Air Quality Standards (NAAQS) (Section 2.1) are based on human exposure to specific criteria pollutants and as such, possible sensitive receptors were identified where the public is likely to be unwittingly exposed. NAAQS are enforceable outside of power station and ash disposal facility boundaries and therefore a number of sensitive receptors have been identified (Figure 5; Table 10). These sensitive receptors are individual residences and small residential areas in the vicinity of the proposed ash disposal facility. The modelled ground-level concentrations of PM_{10} and $PM_{2.5}$ will were compared to National Standards and dust-fall draft standards at these sensitive receptors (Section 5).

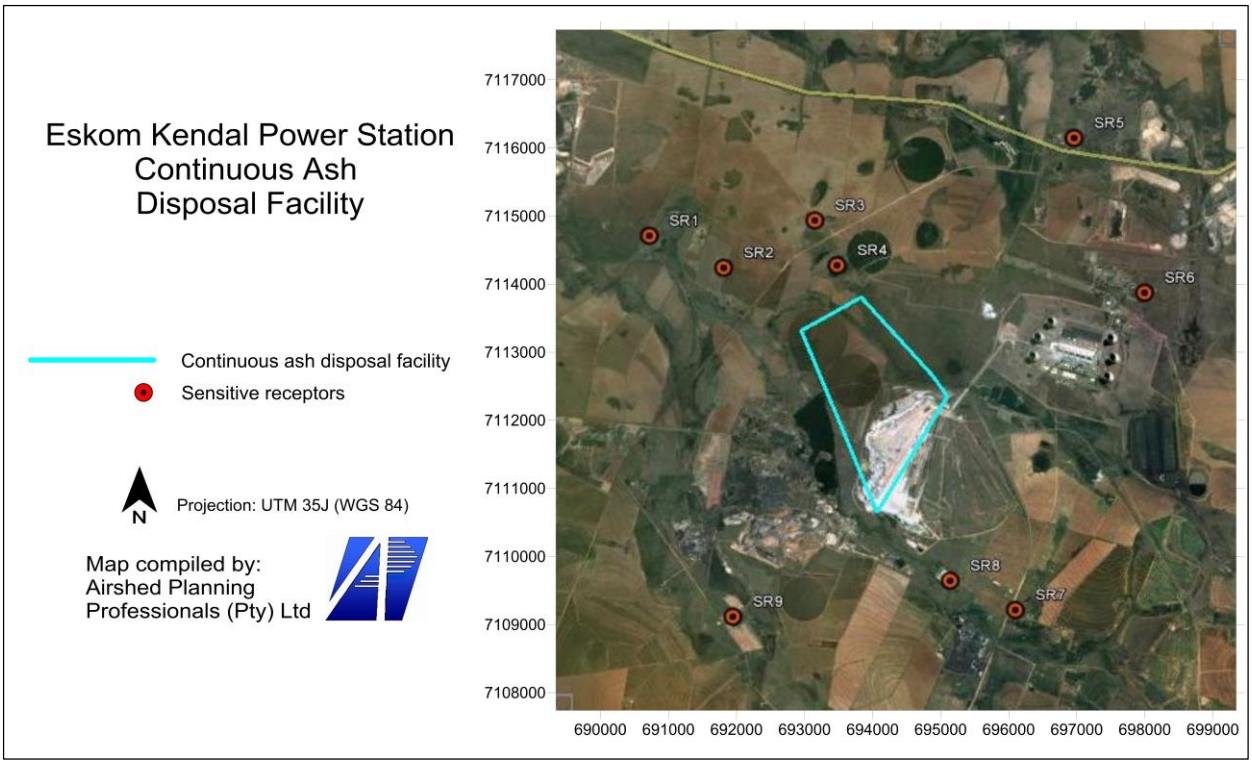

Figure 5: Aerial map (from Google Earth™ - image date 2012) of the Kendal Power Station, the proposed continuous ash disposal facility and the potential sensitive receptors (red markers).

Table 10: Location of the sensitive receptors (Projection: WGS 84, UTM 35J, units are in meters (m))

Receptor name	Easting	Northing
SR1	690808.44	7114832
SR2	691890.19	7114332
SR3	693236.25	7115012
SR4	693549	7114340
SR5	697023.5	7116190
SR6	697989.31	7113856
SR7	696062.5	7109158
SR8	695123.19	7109603
SR9	691949	7109106

4.3 Compliance analysis and impact assessment

The current air quality near the proposed site is discussed in Section 2.2. The ash disposal facility will continue to give rise to dust generation as the ash disposal operations are initiated and continue through the life of the power station (10 years for the proposed site and at another site until power station decommissioning in 2053). These operations, as discussed under Section 3.1.2, are low level release sources meaning that the dust gets generated at heights of between 0.5 and 1 m from the ash disposal facility surface.

The assessment of impact of the continuous ash disposal facility, specifically on air quality, is based on longer-term predictions and pollutants with human health risk. Therefore although some dust-fall simulation results are presented, the assessment is based on annual PM_{10} and $PM_{2.5}$ ground-level concentrations over the modelling domain and at the specific sensitive receptors.

Wind erosion, will occur during strong wind conditions when wind speeds exceed the critical threshold required to lift and suspend the ash particles. This threshold is determined by the parameters that resist removal such as the particle size distribution of the bed material, moisture content and vegetation. A typical wind speed threshold is given as 5.4 $m.s^{-1}$ for storage piles (US.EPA, 1995). Wind data for the proposed ash disposal facility site (2009 to 2012) indicate an average wind speed of 3.42 $m.s^{-1}$ and a maximum of 15.2 $m.s^{-1}$, where the wind speed threshold is exceeded 15.1% of the time.

4.3.1 Dispersion Model Selection and Data Requirements

Dispersion models compute ambient concentrations as a function of source configurations, emission strengths and meteorological characteristics, thus providing a useful tool to ascertain the spatial and temporal patterns in the ground level concentrations arising from the emissions of various sources. Increasing reliance has been placed on concentration estimates from models as the primary basis for environmental and health impact assessments, risk assessments and emission control requirements. It is therefore important to carefully select a dispersion model for the purpose.

For the purpose of the current study, it was decided to use the Atmospheric Dispersion Modelling System (ADMS) developed by the Cambridge Environmental Research Consultants (CERC). CERC was established in 1986 and developed a number of computer models for pollutant dispersion, including ADMS 5. This model simulates a wide range of buoyant and passive releases to the atmosphere either individually or in combination. It has been the subject of a number of inter-model comparisons (CERC, 2004); one conclusion of which is that it tends provide conservative values under unstable atmospheric conditions in that it predicts higher concentrations than the older models close to the source.

ADMS 5 is a new generation air dispersion model which differs from the regulatory models traditionally used in a number of aspects. The most important of which are the description of atmospheric stability as a continuum rather than discrete classes (the atmospheric boundary layer properties are described by two parameters; the boundary layer depth and the Monin-Obukhov length, rather than in terms of the single parameter Pasquill Class) and in allowing more realistic asymmetric plume behaviour under unstable atmospheric conditions. Dispersion under convective meteorological conditions uses a skewed Gaussian concentration distribution (shown by validation studies to be a better representation than a symmetric Gaussian expression).

ADMS is used in many countries worldwide and users of the model include Environmental Agencies in the UK and Wales, the Scottish Environmental Protection Agency (SEPA) and regulatory authorities including the UK Health and Safety Executive (HSE).

Concentration and deposition distributions for various averaging periods can be calculated by ADMS 5. It has generally been found that the accuracy of off-the-shelf dispersion models improve with increased averaging periods. The accurate prediction of instantaneous peaks are the most difficult and are normally performed with more complicated dispersion models specifically fine-tuned and validated for the location. For the purposes of this report, the shortest time period modelled is one hour.

There will always be some error in any geophysical model, but it is desirable to structure the model in such a way to minimise the total error. The total uncertainty can be thought of as the sum of three components: the uncertainty due to errors in the model description of atmospheric physics; the uncertainty due to data errors; and the uncertainty due to stochastic processes (turbulence) in the atmosphere. Nevertheless, dispersion modelling is generally accepted as a valid tool to quantify and analyse the atmospheric impact of existing installations and for determination of the impact of future installations.

4.3.2 Meteorological Data Requirements

Hourly average wind speed, wind direction and temperature data from the Eskom meteorological station at Kendal Power Station were used. Given the proximity and the nature of the terrain, the data is considered to be suitably representative of the conditions at the proposed continuous ash disposal facility.

4.3.3 Source Data Requirements

The ash disposal facility, as the focus of this report, was the only source considered during model simulations; however, the impact of all six alternatives was simulated. Due to the fact that high ambient PM_{10} concentrations (compared to SA NAAQS) were expected, generic mitigation measures were also modelled. These included wetting of the ash by water sprays and re-vegetation. A total of four scenarios were simulated:

- unmitigated (disposal of conditioned ash but allowed to dry out);
- mitigation by means of re-vegetation covering 80% of the ash disposal facility (control efficiency of: 97%);
- mitigation by means of water sprays to maintain ash moisture content at 5% (about half of the moisture content when ash deposited at disposal facility – control efficiency of: 74%); and,
- mitigation by means of re-vegetation of 80% of ash disposal facility and watering to maintain ash moisture content at 5% (control efficiency of: 99%).

The proposed continuous ash disposal facility was modelled at full size as ADMS 5 is not capable to model real-time changes in ash disposal facility size. An ash sample from the Kendal Power Station ash disposal facility was obtained for analysis of the particle size distribution (Table 11) and elemental content (Table 12).

Table 11: Particle size distribution for the ash material at the Kendal Power Station

Size (µm)	Fraction
477.01	0.0018
258.95	0.0503
103.58	0.1950
76.32	0.0895
30.53	0.2783
22.49	0.0761
10.48	0.1388
5.69	0.0708
2.65	0.0511
1.06	0.0295

.

Table 12: Elemental analysis of the ash material at the Kendal Power Station

Element	ppm
Silver	<0.2
Aluminium	17861
Arsenic	6.1
Boron	70
Barium	326
Beryllium	0.8
Calcium	31375
Cadmium	<0.2
Cobalt	3.0
Chromium	21
Copper	9.3
Iron	7935
Mercury	<1.0
Potassium	659
Lithium	24
Magnesium	5496
Manganese	78
Molybdenum	2.2
Sodium	3261
Nickel	5.2
Phosphorous	1288
Lead	4.7
Antimony	<2.0
Selenium	<4.0
Tin	<4.0
Strontium	475
Titanium	562
Vanadium	31
Zinc	8.6

4.3.4 Modelling Domain

The dispersion of pollutants expected to arise from the proposed operations was modelled for an area covering approximately 10 km (east-west) by 10 km (north-south). The area was divided into a grid matrix with a resolution of 100 m by 100 m. ADMS 5 simulates ground-level concentrations for each of the receptor grid points. Sensitive receptors were included in the model as additional receptors points

5 DISPERSION MODELLING RESULTS AND COMPLIANCE ASSESSMENT

Dispersion modelling was undertaken to determine: maximum monthly dust-fall rates as well as second highest daily and annual average incremental ground-level concentrations for PM_{10} and $PM_{2.5}$. These averaging periods were selected to facilitate the comparison of predicted pollutant concentrations with relevant dust-fall guideline and national ambient air quality standards. It has, however, generally been found that the accuracy of dispersion models improves with increased averaging periods. The accurate prediction of instantaneous peaks are the most difficult and are normally performed with more complicated dispersion models specifically fine-tuned and validated for the location. For the purposes of this basic evaluation, the averaging period presented in this report is annual. It should be noted that the ground-level concentration isopleths depicted present interpolated values from the concentrations predicted by ADMS 5 for each of the receptor grid points specified.

5.1 Dust-fall

Dust-fall in the unmitigated scenario is likely to exceed the residential draft dust-fall regulations over a large area surrounding the continuous ash disposal facility locations (Figure 6). Although reduced in area exceedances of the residential draft dust-fall regulations are also expected if mitigation is limited to water sprays. However, dust-fall under the re-vegetation and combination mitigation strategies are within the residential draft dust-fall regulations (Figure 6). Exceedances of the dust-fall regulations at identified sensitive receptors are likely to be limited to SR 7 and 8 under the unmitigated scenario only (Table 13).

A review of European studies has shown the potential for reduced growth and photosynthetic activity in sunflower and cotton plants exposed to dust fall rates greater than 400 mg m^{-2} day^{-1}. Little direct evidence of the effects of dust-fall on South African vegetation, including crops, exists. The potential impact of dust-fall on agricultural crops near the ash disposal facility was plotted (Figure 7) at the 400 $mg.m^{-2}.day^{-1}$ guideline.

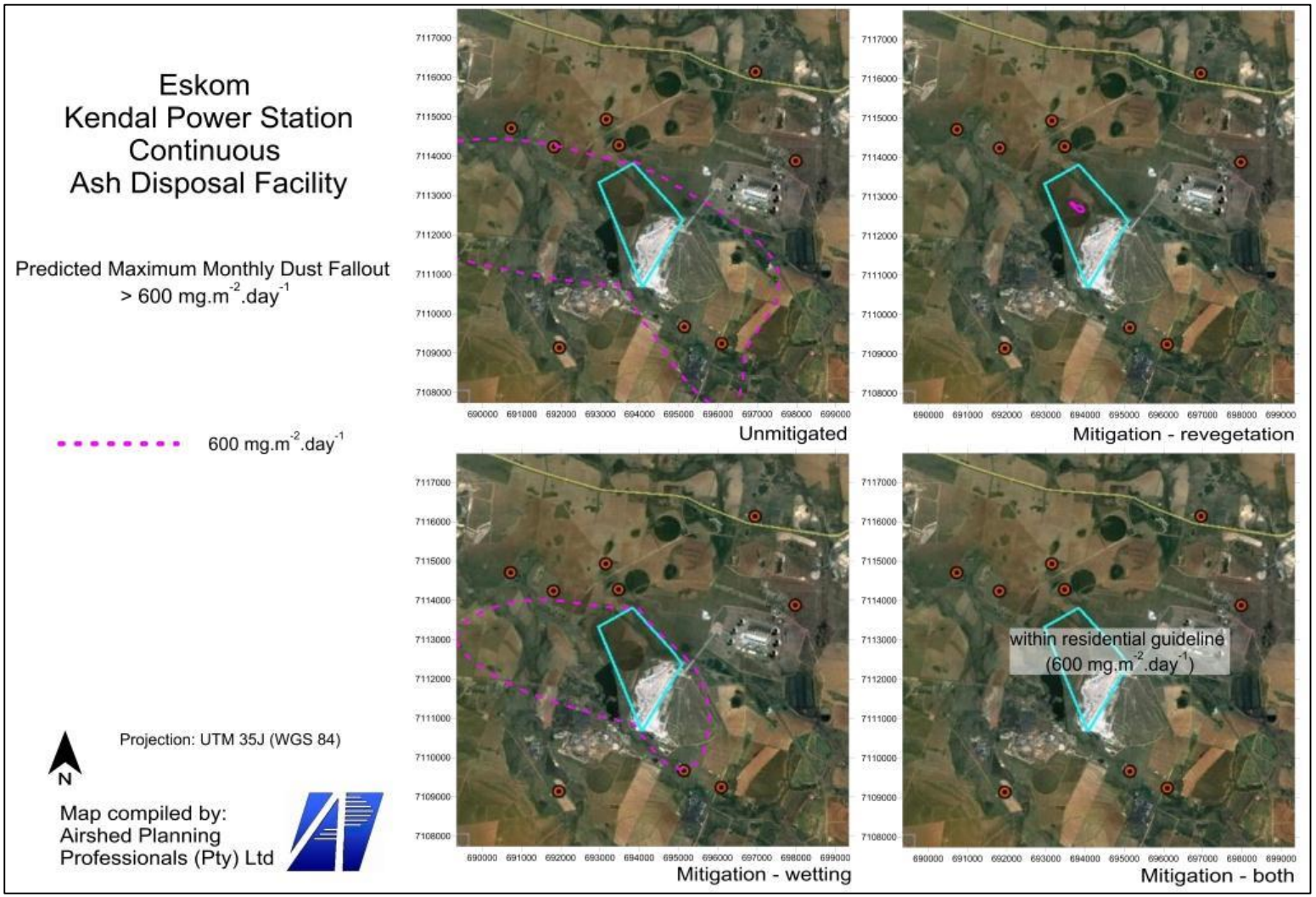

Figure 6: Predicted maximum monthly dust-fall as a result of continuous ash disposal facilities at Kendal Power Station

Figure 7: Areas impacted by dust-fall rates exceeding 400 mg.m^{-2}.day^{-1}, as a result of continuous ash disposal at Kendal Power Station

5.2 PM_{10} ground-level concentrations

Non-compliance with the annual average PM_{10} NAAQS (current NAAQS of 50 µg.m^{-3} and 2015 NAAQS of 40 µg.m^{-3}) is expected for large areas around the proposed continuous ash disposal facility in the unmitigated scenario (Figure 8). Non-compliance is limited near to the alternative ash disposal facility in the water spraying scenario. Compliance with the annual NAAQS could be achieved with mitigation by either re-vegetation or with the combination of re-vegetation and watering (Figure 8).

The number of exceedances of the daily PM_{10} limit are likely to exceed the 4 allowed days at five of the nine identified as sensitive receptors (Table 13) however improvements are likely with effective mitigation.

5.3 $PM_{2.5}$ ground-level concentrations

Despite the large proportion of Kendal ash being in the finer fraction, impact for $PM_{2.5}$ is more restricted than PM_{10}. However, exceedances of the annual NAAQS (current NAAQS of 25 µg.m^{-3}, 2016 NAAQS of 20 µg.m^{-3} and 2030 NAAQS of 15 µg.m^{-3}) are expected under the unmitigated scenario (Figure 9). The area affected by exceedances of the annual NAAQS can be reduced through mitigation via watering and controlled within the annual NAAQS via re-vegetation and a combination mitigation strategy (Figure 9).

Non-compliance with daily $PM_{2.5}$ NAAQS is expected at five of the nine sensitive receptors without mitigation of dust emissions (Table 13). Effective mitigation of dust emissions will result in compliance with daily NAAQS at sensitive receptors.

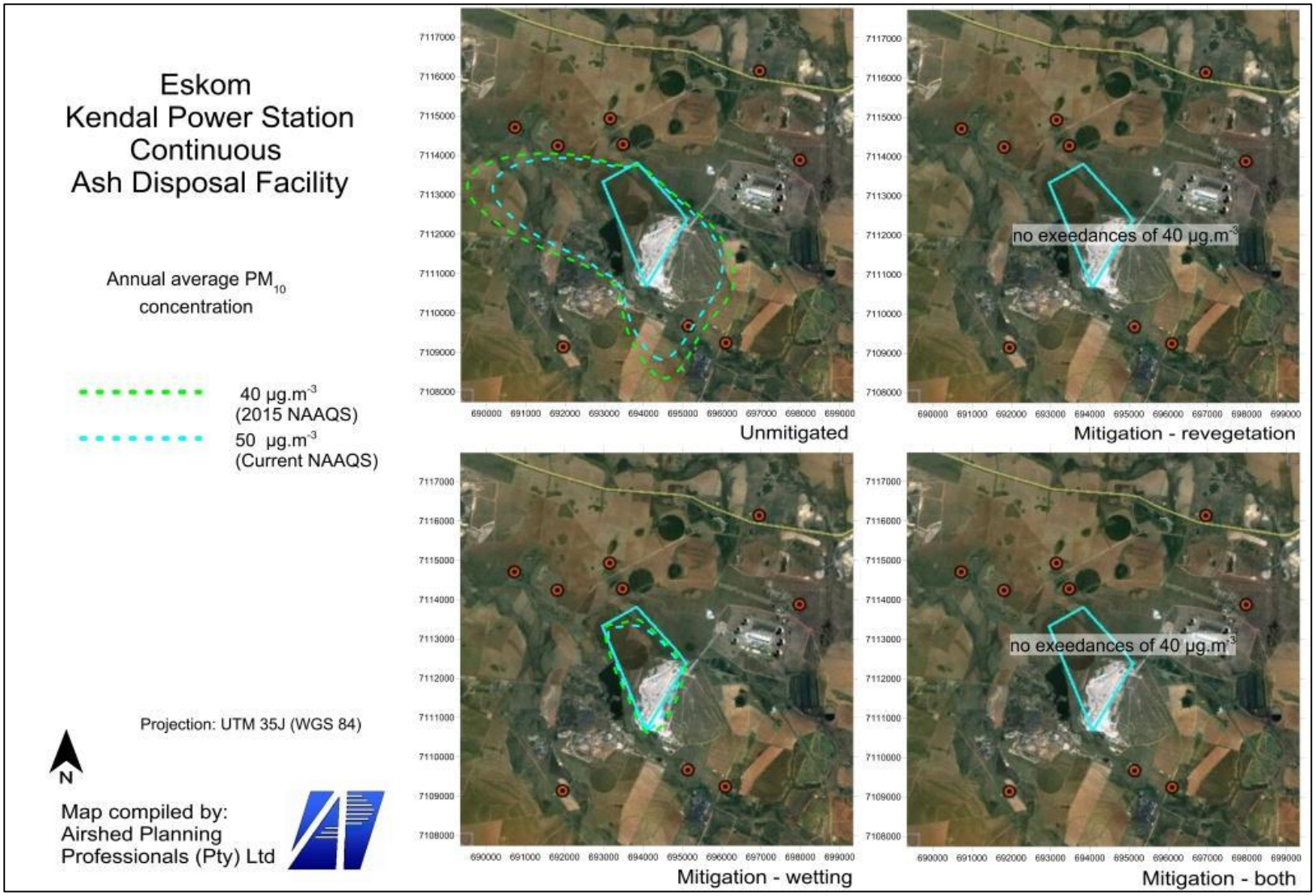

Figure 8: Predicted annual average PM_{10} concentration as a result of the continuous ash disposal at Kendal Power Station

Table 13: Monthly average dust-fall rates and frequency of exceedance of daily PM_{10} and $PM_{2.5}$ limits at sensitive receptors as a result of continuous ash disposal at Kendal Power Station.

Scenario	Receptor name	Dust-fall	PM_{10}	$PM_{2.5}$
		Monthly average ($mg.m^{-3}.day^{-1}$) (a)	Frequency of exceedance (b)	Frequency of exceedance (b)
Unmitigated	SR 1		13	12
	SR 2		20	19
	SR 3			
	SR 4			
	SR 5			
	SR 6			
	SR 7	953.17	35	31
	SR 8	1593.24	54	48
	SR 9		7	5
Re-vegetation	SR 1			
	SR 2			
	SR 3			
	SR 4			
	SR 5			
	SR 6			
	SR 7			
	SR 8			
	SR 9			
Wetting	SR 1			
	SR 2		5	5
	SR 3			
	SR 4			
	SR 5			
	SR 6			
	SR 7		8	6
	SR 8		18	15
	SR 9			
Both (re-vegetation & wetting)	SR 1			
	SR 2			
	SR 3			
	SR 4			
	SR 5			
	SR 6			
	SR 7			
	SR 8			
	SR 9			

(a) Only dust-fall rates above the residential draft standard are given.
(b) The number of days when the NAAQS 24-hour limit is exceeded. Both PM_{10} and $PM_{2.5}$ standards allow 4 daily exceedances, therefore only more than 4 daily exceedances shown (days rounded up to whole days). .

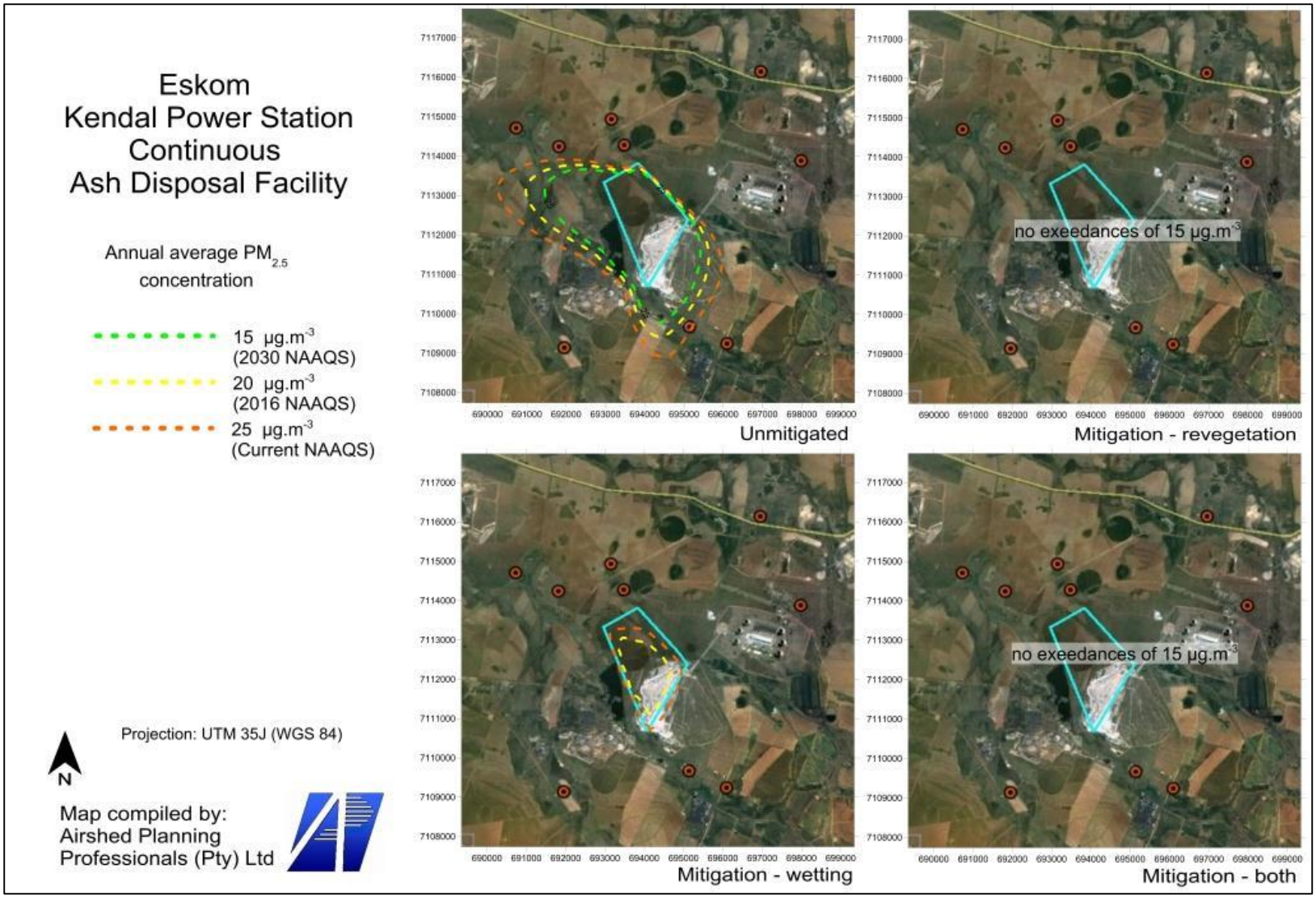

Figure 9: Predicted annual average $PM_{2.5}$ concentration as a result of the continuous ash disposal at Kendal Power Station

5.4 Increased life-time cancer risk

For all three metals (arsenic, nickel and chromium) the increased life-time cancer risk at the identified sensitive receptors is very low to low in all cases (Table 14). These estimates are based on the annual PM_{10} concentrations for the *unmitigated* scenario. Cancer risk as a result of exposure to nickel in the PM_{10} fraction of the ash shows the most variability and the highest number of 'low' cancer risk. The uncertainty with respect to the nickel compounds, and their proportion of total nickel in the ash, results in a more conservative cancer risk calculation. This conservative estimation of cancer risk adds support to the need for effective dust emission control through mitigation strategies, which will reduce the cancer risk further.

Table 14: Increased cancer risk at identified sensitive receptors, as a result of exposure to arsenic, nickel and chromium in the PM_{10} fraction of dust from the Kendal continuous ash disposal facility

Carcinogenic metal	Sensitive receptor	Annual average PM_{10}	Increased life-time cancer risk
Arsenic	SR 1	11.28	Very low
	SR 2	19.58	
	SR 3	0.14	
	SR 4	0.45	
	SR 5	0.05	
	SR 6	1.47	
	SR 7	25.42	
	SR 8	53.67	
	SR 9	4.54	
Nickel	SR 1	11.28	Low
	SR 2	19.58	Low
	SR 3	0.14	Very low
	SR 4	0.45	
	SR 5	0.05	
	SR 6	1.47	
	SR 7	25.42	Low
	SR 8	53.67	Low
	SR 9	4.54	Very low
Chromium	SR 1	11.28	Very low
	SR 2	19.58	
	SR 3	0.14	
	SR 4	0.45	
	SR 5	0.05	
	SR 6	1.47	
	SR 7	25.42	
	SR 8	53.67	Low
	SR 9	4.54	Very low

6 CONCLUSIONS

Continuous disposal of ash, from Kendal Power Station, at the northern edge of the current facility will impact the air quality by exposing the public to elevated levels of airborne particulates and the associated potential human health impacts. However, from the findings from dispersion modelling the following recommendations are proposed:

- Fugitive dust emissions from the ash disposal facility should be minimised through either re-vegetation, or a combination of re-vegetation and watering
- Due to the location of the ash disposal facility in the Highveld Priority Area (Section 3.2.1) and the already elevated concentrations of airborne particulates, it is recommended that PM_{10} concentrations be monitored near the ash disposal facility. The nearest possible, secure, location to the following point: 26° 05'27.39"S; 28°54'53.68"E. Because of the active nature of the ash disposal facility it is feasible to use a mobile unit for this additional PM_{10} monitor.
- Dust fallout monitoring should be conducted, in the direction of the prevailing winds and co-located, where possible, at sensitive receptors within the zone of highest impact.

6.1 Issues raised by I&APs at public meetings

Two issues were raised in respect of the air quality assessment at the public meeting held at Oakhouse Lodge, near Ogies on 24th July 2014. Both issues were raised by Dr James Meyer.

1. It was requested that elemental analysis be conducted on the dustfall samples to screen for potential health impacts as a result of the ash disposal facility.
    - It is important to note that it is not possible to correlate dustfall rates ($mg.m^{-2}.day^{-1}$) with inhalable particulate concentrations ($\mu g.m^{-3}$). Human health impacts are assessed based on the concentration of particulates. The value in quantifying the levels of metals contained in dustfall is in the change of these levels over time. These values will not assist screening for human health impacts. Should Eskom recognise the value in metal analysis of dustfall it is suggested that, due to the cost associated with the analysis, that only the dustfall sampling bucket with the highest dustfall rate be further analysed for metals. This suggestion can be built into the Kendal EMPr.
2. It was also suggested, by Dr Meyer, that a collaborative Environmental Management forum be established including representatives from the relevant mining houses as well as Kendal and Kusile Power stations.
    - This suggestion is a useful and, should it be practical to do so, it is suggested that the establishment of such a forum be included in the Kendal EMPr.

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8 APPENDIX A: FUGITIVE DUST EMISSIONS FROM EXPOSED AREAS

Significant emissions arise due to the mechanical disturbance of granular material from disturbed open areas and storage piles. Parameters which have the potential to impact on the rate of emission of fugitive dust include the extent of surface compaction, moisture content, ground cover, the shape of the storage pile, particle size distribution, wind speed and precipitation. Any factor that binds the erodible material, or otherwise reduces the availability of erodible material on the surface, decreases the erosion potential of the fugitive source. High moisture contents, whether due to precipitation or deliberate wetting, promote the aggregation and cementation of fines to the surfaces of larger particles, thus decreasing the potential for dust emissions. Surface compaction and ground cover similarly reduces the potential for dust generation. The shape of a storage pile or disposal dump influences the potential for dust emissions through the alteration of the airflow field. The particle size distribution of the material on the disposal site is important since it determines the rate of entrainment of material from the surface, the nature of dispersion of the dust plume, and the rate of deposition, which may be anticipated (Burger, 1994).

Wind erosion is a complex process, including three different phases of particle entrainment, transport and deposition. It is primarily influenced by atmospheric conditions (e.g. wind, precipitation and temperature), soil properties (e.g. soil texture, composition and aggregation), land-surface characteristics (e.g. topography, moisture, aerodynamic roughness length, vegetation and non-erodible elements) and land-use practice (e.g. farming, grazing and mining).

Windblown dust generates from natural and anthropogenic sources. For wind erosion to occur, the wind speed needs to exceed a certain threshold, called the threshold velocity. This relates to gravity and the inter-particle cohesion that resists removal. Surface properties such as soil texture, soil moisture and vegetation cover influence the removal potential. Conversely, the friction velocity or wind shear at the surface is related to atmospheric flow conditions and surface aerodynamic properties. Thus, for particles to become airborne the wind shear at the surface must exceed the gravitational and cohesive forces acting upon them, called the threshold friction velocity (Shao, 2008).

Estimating the amount of windblown particles to be generated from a stockpile is not a trivial task and requires detailed information on the particle size distribution, moisture content, silt content and particle density. Dust will only be generated under conditions of high wind speed which is likely to occur when winds exceed 5.4 $m.s^{-1}$ (US-EPA, 1995b).

An hourly emissions file was created for each of these source groups. The calculation of an emission rate for every hour of the simulation period was carried out using the ADDAS model. This software is based on the dust emission models proposed by Marticorena and Bergametti (1995) and Shao (2008). The models attempt to account for the variability in source erodibility through the

parameterisation of the erosion threshold (based on the particle size distribution of the source) and the roughness length of the surface.

In the quantification of wind erosion emissions, the models incorporates the calculation of two important parameters, viz. the threshold friction velocity of each particle size, and the vertically integrated horizontal dust flux, in the quantification of the vertical dust flux (i.e. the emission rate). In the Marticorena and Bergametti Model, the vertical flux is given by the following equation:

$$F(i) = G(i)10^{(0.134(\%clay)-6)}$$

for

$$Q(i) = 0.261\left[\frac{P_a}{g}\right]u^{*3}(1+R)(1-R^2)$$

and $$R = \frac{u_*^t}{u^*}$$

where,

$F_{(i)}$	=	emission rate (g/m²/s) for particle size class i
P_a	=	air density (g/cm³)
g	=	gravitational acceleration (cm.s^{-2})
u_*^t	=	threshold friction velocity (m/s) for particle size i
u^*	=	friction velocity (m.s^{-1})

With the model based on Shao (2008), the horizontal flux is as described by the equation above and the vertical flux is given by

$$F(i) = \beta(i)Q(i)u_*^{-2}$$

for

$$\beta(i) = 10^{-5}\left[1.25\ln(d_s) + 3.28\right]\exp\left(-140.7d_d + 0.37\right)$$

where,

d_s	=	the saltator particle size (mm)
d_d	=	the dust particle size (mm)

Dust mobilisation occurs only for wind velocities higher than a threshold value, and is not linearly dependent on the wind friction and velocity. The threshold friction velocity, defined as the minimum friction velocity required to initiate particle motion, is dependent on the size of the erodible particles and the effect of the wind shear stress on the surface. The threshold friction velocity decreases with a decrease in the particle diameter, for particles with diameters >60 µm. Particles with a diameter <60 µm result in increasingly high threshold friction velocities, due to the increasingly strong cohesion forces linking such particles to each other (Marticorena and Bergametti, 1995). The relationship between particle sizes ranging between 1 µm and 500 µm and threshold friction velocities (0.24 to 3.5 m.s^{-1}), estimated based on the equations proposed by Marticorena and Bergametti (1995), is illustrated in Figure.

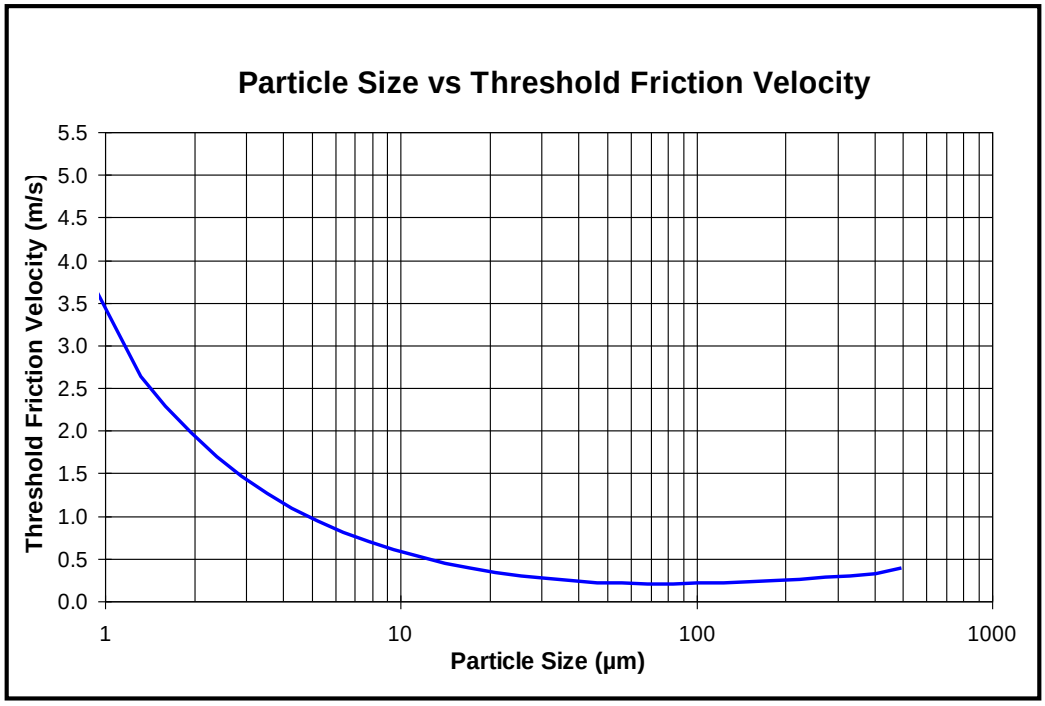

Figure A1: Relationship between particle sizes and threshold friction velocities using the calculation method proposed by Marticorena and Bergametti (1995)