MODELLING OF WIND ERODED DUST TRANSPORT IN THE ERONGO REGION, NAMIBIA

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Episodic dust storms over Namibia, associated with strong easterly winds, are a common phenomenon during the winter months, with the dust generated off primarily natural surfaces (observable in SeaWifs and MODIS images). These plumes are readily observed against the darker background of the Atlantic Ocean as they pass over the coastline. The sources are intermittent, giving rise to dust emissions only under conditions of high wind speeds. In contrast, anthropogenic sources such as unpaved roads and mining operations contribute continuously to the atmospheric dust load. With the opening of several new uranium mines in the region, there is a need to understand the generation and transport pathways of dust from natural sources, against which to evaluate the additional contributions from anthropogenic activities.

This study set out to determine the contribution of wind eroded particulates in the Erongo Region, through the application of a standard dispersion model. The modelling domain covered ~78,000 km². Local meteorological records for 2007 and 2008 were sourced as model input. Meteorological monitoring sites in Namibia are sparse, resulting in long-range interpolation between stations by the three-dimensional wind-field model. Vertical profiles of wind velocity and mass flux were calculated using literature-derived equations [Marticorena and Bergametti, *Journal of Geophysical Research*, 100 (1995) 16 415; and Alfaro and Gomes, *Journal of Geophysical Research*, 106D (2001) 18 075]. Soil samples were collected at several sites across the region and analysed for particle size distribution, moisture content and particle density. The effect of soil crusting was determined following reported field tests [Goossens, *Journal of Geomorphology*, 58 (2004) 145]. Model simulation results were evaluated for selected dust episodes against values from a limited number of ambient monitoring sites, and from remote sensing retrievals. Discrepancies between predicted and measured data were primarily a result of unknown roughness lengths and interpolated meteorological data.

Key words: wind erosion, arid areas, dispersion modelling, Namibia, uranium mining

1. Introduction

Prospecting for uranium within the central Namib was at a relative low intensity in the past. This has changed recently with renewed interest in uranium sources to supply projected nuclear reactor requirements (SEA, 2010). The scramble for prospecting and subsequent mining licences has triggered the term “Central Namib Uranium Rush”. A Strategic Environmental Assessment (SEA) was undertaken to consider likely sector development scenarios and their implications (economical, social and environmental) for the region. One of the environmental criteria indentified to potentially affect human health and well-being is air quality in the form of dust generation with associated radiation.

Dust emissions giving rise to ambient pollution concentrations and deposition levels are derived from anthropogenic, natural and biogenic sources (Friedrich, 2009). Windblown dust from natural mineral sources is estimated to account for 89% of the global aerosol load (Satheesh and Moorthy, 2005) whilst mining operations and aggregate extraction sites are significant sources of fugitive dust emissions (Neuman *et al*., 2009). Evaporation of sea spray can produce particles, while pollen grains, mould spores and plant and insect parts all contribute to the particulate load (WHO, 2000).

The Erongo region falls within the west coast arid zone of Southern Africa and is characterised by low rainfall with extreme temperature ranges and unique climatic factors influencing the natural environment and biodiversity (Goudie, 1972). Episodic dust storms associated with strong easterly winds are a common phenomenon during the winter months. The natural surfaces give rise to dust emissions only under extreme conditions of high wind speeds, whereas anthropogenic sources such as unpaved roads and mining operations continuously contribute to the atmospheric dust load in the Erongo region. Even though the dust storm incidences are sporadic, the public perception is that these are significant sources of dust and associated nuclear radiation from the uranium and thorium content. Proposed and current mining developments in the region will add to the existing dust load. In assessing the significance of the additional contributions, it is critical that the natural baseline is well understood. Figure 1 provides the geographical setting of the Erongo region.

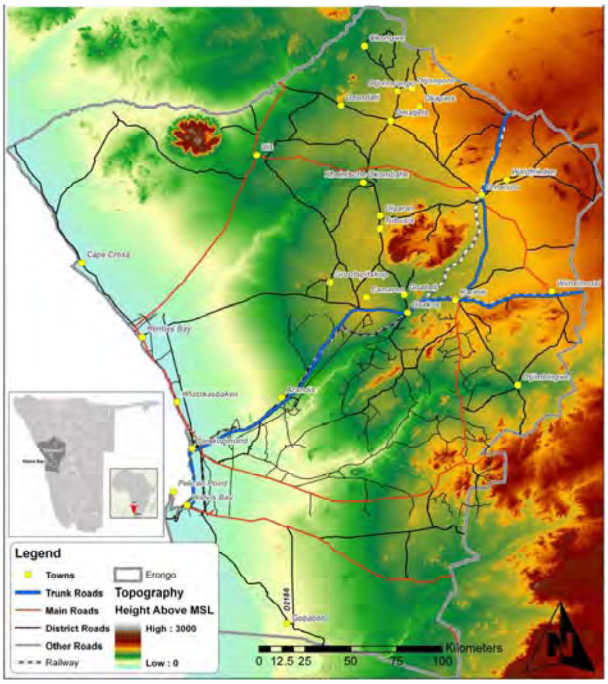

Figure 1: Location of the Erongo region, Namibia

Knowing the complex physics pertaining to wind erosion (and even this is not yet fully understood) (Shao, 2008), the focus of this paper is on the methodology followed in predicting background atmospheric particulate concentrations within the Erongo region, and providing a critical review thereof.

1.1. Study Scope

Various factors influence the dispersion, transformation and eventual removal of pollutants from the atmosphere. The main influencing factors are local meteorological conditions, topography, land-use, source features (e.g. point, area, volume, line or pit source, and source dimensions) and source strengths (i.e. amount of emissions deriving from the source).

Baseline characterisation typically includes the assessment of measured ambient air quality data, or dispersion modelling results, or preferably both. Whereas ambient monitoring data provide an indicator of the current state of the air at a given geographical location, dispersion modelling provides the freedom of assessing air pollution at a number of locations within a defined area. It is also a useful tool to determine the main contributing sources to air pollution. Dispersion modelling in turn is directly related to the emission data and source parameters included into the model and the meteorological data used.

Emissions were quantified for current mining operations and roads within the region as well as windblown dust deriving from natural background sources. The US EPA CALPUFF/CALMET suite of models were used for the dispersion simulation with meteorological data obtained from government and privately owned surface weather stations and the South African Weather Services Unified Model upper air data.

A monitoring network comprising dust fallout buckets and PM10 samplers were established as part of the SEA project (SEA, 2010). These data and data from mining monitoring networks were used to provide an indication of the range of accuracy of model predictions.

2. Ambient Monitoring data

A monitoring network, comprising 20 single dust fallout buckets, was established during the period 10 to 16 August 2009, using the ASTM Standard D1739 method for the collection of dustfall (ASTM Standard D1739-70, 1970). Background dust fallout data were collected over a period of eleven months. Dust fallout data from existing mining monitoring networks were also made available for inclusion in this study. Figure 2 indicates the locations of the dust fallout buckets as part of the Erongo SEA network and the existing mining networks.

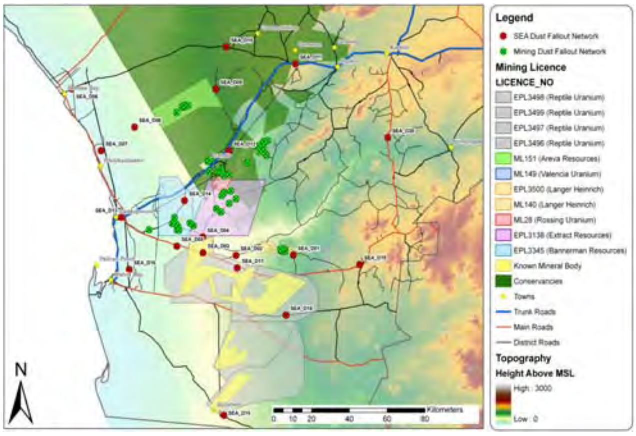

Figure 2: Location of dust fallout buckets

Dust fallout was assessed against the maximum monthly dust fallout limits as provided by the South African SANS 1929 dustfall standards (Standards South Africa, 2005: 13-14). The results are presented in Figure 3 and the main findings are summarised as follows:

- In general, dust deposition throughout the Erongo region is slight (< 250 mg/m²/day) with a few isolated incidences of higher dust fallout. Dust fallout collected at the SEA dust fallout sites vary due to spatial location (as is shown in Figure 2) and localised activities and sources. A

- general trend throughout the monitoring network indicates higher dust fallout during the monitoring months of September 2009 and June 2010. This is more prominent at the sites located on the western side of the monitoring network and in open gravel plains (i.e. SEAD03, SEAD05, SEAD07, SEAD08, SEAD13 and SEAD16). These months are characterised with higher incidences of high wind speed (NWN, 2010). For the 11 months reported on, dust fallout levels are below the SANS residential limit of 600 mg/m²/day for all 20 sites.
- Results from the mine dust fallout networks reflect similar low dust fallout rates to that of the SEA network, i.e. the results are primarily below 150 mg/m²/day. Incidences of higher dust fallout rates could be attributed to construction activities near the buckets or where located near a busy unpaved road. A dust fallout bucket located at a residence next to the Swakop River also has higher dust fallout rates. Similar to the SEA network results, a decrease in dust fallout was noted for the period November to January.

2.2 Ambient PM10 Observations

Two PM10 samplers were deployed, one at Swakopmund and one at Gobabeb. Additional PM10 data were made available for this study: Etango project (March to November 2009) and Trekkopje (September to October 2009). Available results are shown in Figure 3. The World Health Organisation (WHO) Interim Targets 3 (IT-3) were used as screening criteria. These are 75 µg/m³ for 24-hour averages (allowed to be exceeded for 1% over a year) and 50 µg/m³ for annual averages. The WHO IT-3 guidelines were selected for its similarity to the South African standards for 2015, and South Africa is regarded to be similar to Namibia (i.e. environmentally and social-economically).

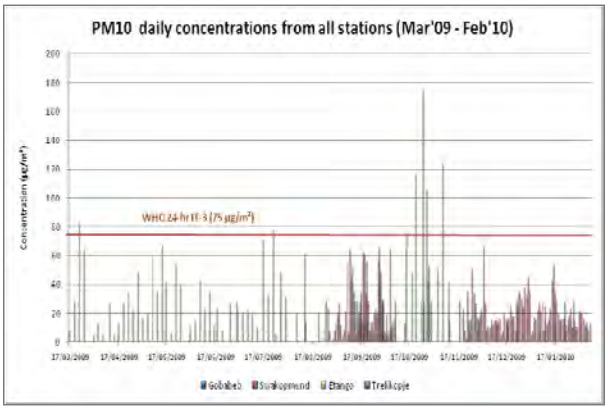

Figure 3: Ambient monitored PM10 concentrations from Gobabeb, Swakopmund, Etango and Trekkopje for the period March 2009 to February 2010

The main findings from the PM10 campaigns are as follows:

- At Swakopmund, the maximum PM10 concentration recorded is 283 µg/m³ with an average of 21 µg/m³ over the 129 days. The WHO AQG IT-3 was exceeded 28% of the time.
- Analysis of the measurements taken at the Etango site, located approximately 35 km east-southeast of Swakopmund, resulted in a period average PM10 concentration of 40 µg/m³ for the nine-months. The highest daily concentration recorded is 329 µg/m³ and the WHO IT-3 of 75 µg/m³ was exceeded 11% of the time.
- A maximum of 56 µg/m³, with no exceedances of the WHO AQG IT-3 daily concentrations, was recorded at Trekkopje's PM10 sampler during September/October 2009.
- The aim of locating a PM10 sampler at Gobabeb was to record background PM10 concentrations. The highest daily average PM10 concentration is 57 µg/m³ with a period (6-month) average of 23 µg/m³. The WHO AQG was exceeded for only one day over the six-month period.

3. Emissions quantification

Based on existing sources of atmospheric emissions identified within the Erongo region, the following sources were included:

- Current mining activities at Rössing Uranium Limited (RUL) and Langer Heinrich Uranium (LHU);
- Current traffic on all trunk, main and district roads; and
- Windblown dust resulting from natural background sources.

3.1 Mining Sources

Features associated with uranium mining and processing operations likely to emit particulate matter into the atmosphere include the following:

- Excavation, crushing and screening, materials transfer, drilling and blasting;
- Vehicle (equipment) movement on paved and unpaved roads;
- Wind erosion from tailings storage facilities, waste dumps and other stock piles; and
- Stacks from processing operations (e.g. acid plant, bag house, scrubber).

Emission rates for the mines were extracted from Environmental Impact Assessment (EIA) reports conduction for RUL in 2010 and LHU in 2009. These reported using US EPA emission factors in the quantification of emissions. Both mines indicated trucks and vehicle movement on unpaved roads to be the main contributing sources to PM10 and TSP emissions. Material handling operations were the second highest dust generating source at RUL with windblown dust third. Windblown dust was the second most significant source at LHU but the wind erosion model did not account for crusting at the time of the EIA, hence resulting in an overestimation.

3.2 Roads

In the quantification of emissions from paved and unpaved roads within the Erongo region, use was made of the US EPA road size-specific emission factor equations. Estimated annual average daily traffic (EAADT) per district as provided by the Namibian Roads Authority for the year 2008 were used in addition to information provided by the Directorate of Parks and Wildlife.

For unpaved roads, a silt content of 4.8% and a moisture content of 0.16% were applied as derived from a soil sample taken from the D1991 and assumed representative of all public unpaved roads. A generic silt content of 0.6 g/m^2 was applied on all paved roads (MPCA, 2006). The road width was taken to be 20 m with a speed limit of 80 km/hr on unpaved roads and 120 km/hr on paved roads.

The main contributing unpaved roads to PM10 and TSP emissions are the M0036 from Walvis Bay and the M0052 from Swakopmund. The M0044, between Swakopmund and Henties Bay, is a salt road and a control efficiency of 90%[1] was applied ranking this road ninth.

3.3 Windblown dust from natural sources

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).

The in-house Airshed wind erosion model (ADDAS) was used for the windblown dust quantification (Burger et al., 1997; Burger, 2010). This model is based on the dust emission model proposed by Marticorena and Bergametti (1995). The model attempts 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. The model has recently been updated to account for the reduction in wind erosion caused by surface soil crusting. This is based on the research conducted by Gillette et al. (1982) and Goossens (2004). Gillette related friction velocity to specific soil crust thickness and modulus of rupture, and Goossens investigated the physical crust strength relationship to the horizontal and vertical sediment fluxes.

A large part of the Erongo Region comprises of gravel plains with little to no vegetation cover. The challenge was to quantify wind erosion from these natural background sources. This was attempted by taking 10 random soil samples and having these analysed for particle size distribution, moisture content, clay fraction, and bulk density. Table 1 provides the various parameters used in the calculation of wind erosion. A soil map of the Erongo region was used to match soil sample locations with soil classes, assuming the properties to be uniform throughout the soil class. In addition, a topographical map was used to identify all large rocky outcrops and vegetated areas. These were regarded to be non-erodible and excluded. This approach fitted well with the methodology proposed by Callot et al. (2000). Figure 5 shows the selected wind erosion areas with associated soil samples. A total of seven wind erodible areas were included, divided into blocks of 5 km by 5 km for dispersion modelling purposes.

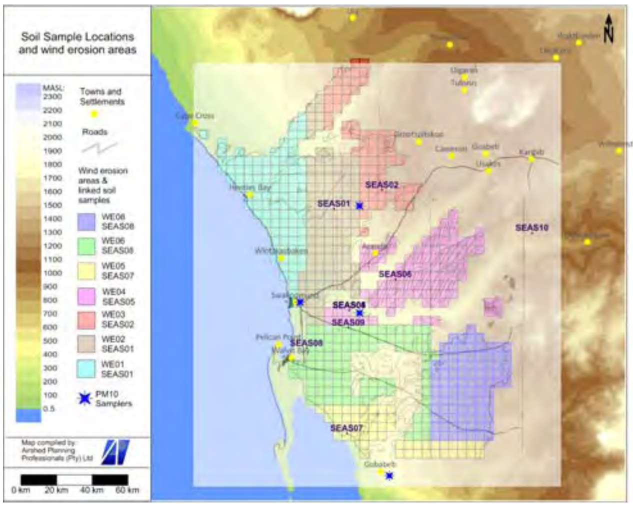

Figure 4: **Soil sample locations and associated soil classes used in the wind erosion calculations**

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[1] The control efficiency was based on dust reduction achievable through the application of chemical suppressants (Stevenson, 2004)

Table 1: Soil sample particle size distribution including moisture content, clay content and bulk density

Location	Bulk Density material <425 µm	Clay Content	Moisture	<425 µm	1.06 µm	2.65 µm	5.7 µm	10.5 µm	19.3 µm	30.5 µm	48.3 µm	76.3 µm	222.3 µm
	g/m^2	%	%	%	%	%	%	%	%	%	%	%	%
SEAS01	1.7	2	0.3	59	7	2	3	4	4	5	7	31	40
SEAS02	1.7	2	0.4	55	8	3	3	5	6	8	12	28	28
SEAS03	1.16	3	1.2	99	5	2	2	3	5	8	16	43	17
SEAS04	1.51	5	0.6	65	16	5	6	8	7	9	12	17	20
SEAS05	1.64	3	0.3	66	9	3	3	5	6	10	17	29	18
SEAS06[a]	1.67	1	0.2	39	7	2	2	2	2	3	6	30	47
SEAS07	1.61	2	0.2	72	4	1	0	1	1	2	8	63	18
SEAS08	1.55	5	0.2	66	9	0	0	2	3	6	17	48	15
SEAS09	1.51	6	0.8	73	16	4	4	5	5	6	10	25	27
SEAS10	1.64	2	0.1	55	5	2	3	4	4	6	10	34	33

Notes: (a) Taken on the D1991 road surface to be representative of unpaved roads.

4. Dispersion Modelling

The modelling area covered the entire Erongo region with residential areas and small-scale farming locations included as sensitive receptors. The modelled simulations included the mines identified, current traffic on all trunk, main and district roads and windblown dust resulting from natural background sources.

4.1 Meteorological data

Meteorological data as obtained from surface weather stations operated by the Namibian Weather Services and the private sector were used to determine the atmospheric dispersion potential of the region. Data were available only from the mining and exploration areas, Walvis Bay and Gobabeb. No data were available for Swakopmund or the region north of Swakopmund. This is regarded a limitation of the study likely to influence the predicted PM10 concentrations and dust fallout rates in the north-western part of the study area. Since this was the best data available at the time, reliance was placed on the ability of the wind field model to simulate the conditions in this region without local observations nudging the predictions. Simulated wind data extracted for Swakopmund did however reflect expected patterns that are characteristic of the coastal environment.

The US EPA recommends three-years of meteorological data as model input. Although three years of surface station data were available (2006 to 2008), the upper air MM5 prognostic model data for 2006 displayed inexplicable wind patterns and as a result was excluded from the study.

4.2 Simulation results

Predicted PM10 annual average ground level concentrations and daily dust deposition at selected communities are provided in Table 2.

Table 2: Predicted PM10 ground level concentrations and dust deposition at selected communities for the Baseline situation.

Settlements	Predicted PM10 annual average CONCENTRATION (µg/m^3)(a)	Predicted dust deposition levels (mg/m^2/day)(b)
Swakopmund	46	1 883
Walvis Bay	16	145
Henties Bay	72	5 916
Wlotzkasbaken	95	7 306
Arandis	65	1 421
Goanikontes	50	552
Gobabeb	20	75

Notes: (a) WHO IT-3 guideline for annual averages of 30 µg/m^3
(b) SANS limit of 600 mg/m^2/day

Figure 5 shows the contribution from each source group to the predicted impacts at each of the communities. Spatial plots are provided in Figures 7 and 8 for annual average PM10 and dust fallout, respectively.

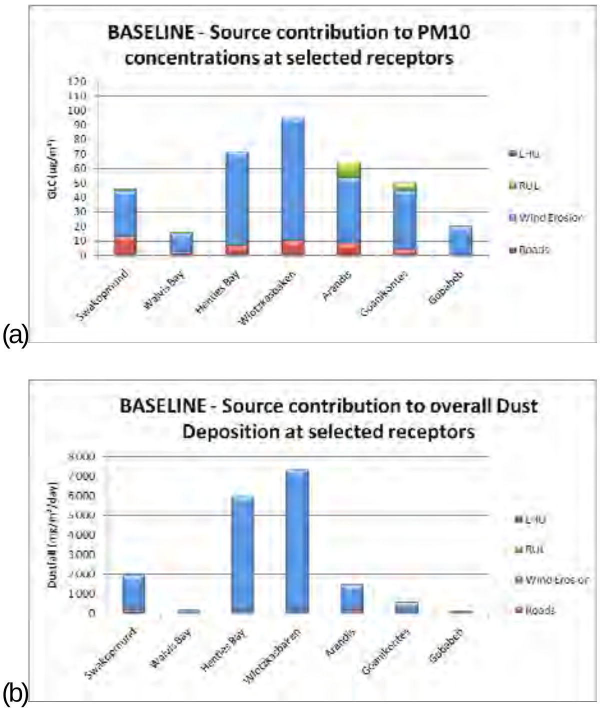

Figure 5: Source contribution to the predicted impacts for the Baseline situation at the selected communities for: (a) PM10 annual average ground level concentrations; and (b) dust deposition

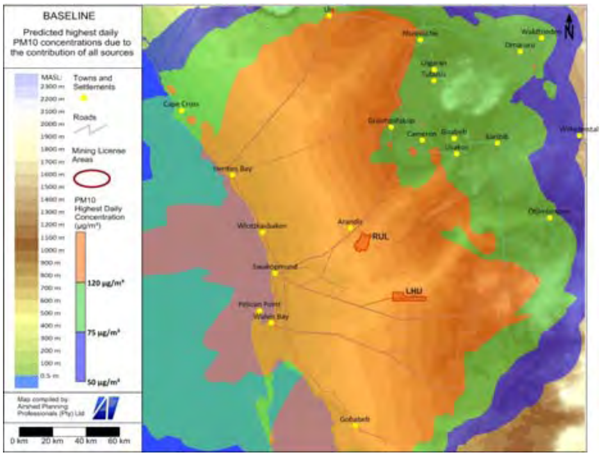

Figure 6: Predicted PM10 daily concentrations

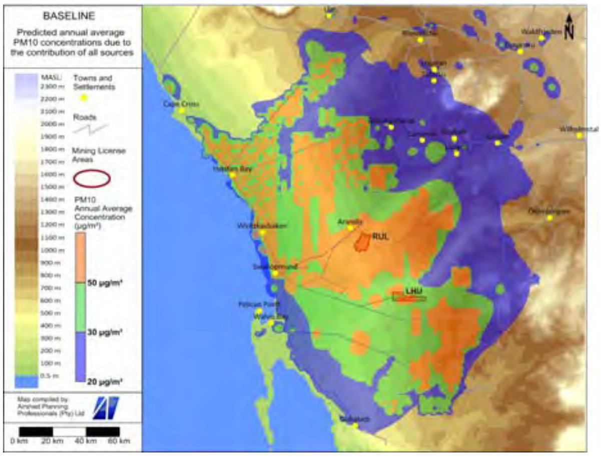

Figure 7: Predicted PM10 annual average concentrations

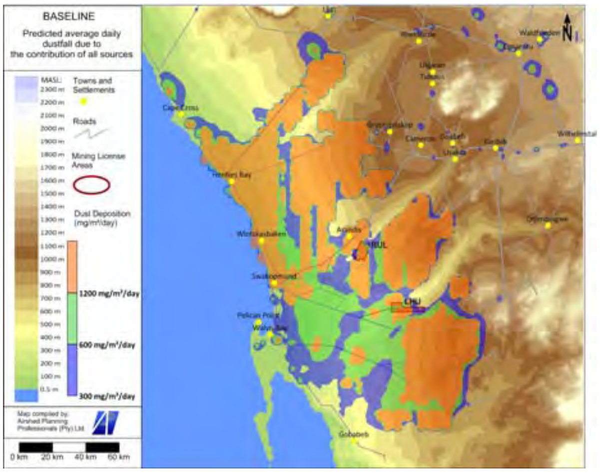

Figure 8: Predicted dust deposition

The main findings are as follows:

- Predicted PM10 concentrations over a daily average exceed the selected WHO IT-3 limit of 75 µg/m³ at all settlements (Figure 6). The WHO allows for 4 exceedances in a year, with 38 exceedances predicted at Swakopmund over the year (as averaged over 2007 and 2008). Arandis and Goanikontes have 81 and 50 exceedances, respectively, with the highest number of exceedances predicted for Wlotzkasbaken of 106. Walvis Bay has the least number of exceedances (i.e. 8 days). The predicted PM10 annual average concentration ranges between 20 µg/m³ (Gobabeb) and 95 µg/m³ (Wlotzkasbaken) (Table 2). The WHO IT-3 limit is 30 µg/m³ indicating non-compliance at all settlements except Gobabeb and Walvis Bay.
- The main contributing source is background wind erosion (82% on average) with dust emanating from traffic on roads being the second largest source (contributing 13%). Roads in the vicinity of Swakopmund contribute more to the overall concentrations at the town (28%) with contributions from the mining operations noticeable at communities located near the source. For example Arandis, Swakopmund, Walvis Bay and Goanikontes show impacts from Rössing Uranium whereas at Gobabeb a slight contribution from Langer Heinrich Uranium is shown (Figure 8a).
- Dust deposition is primarily caused by background wind erosion and to a lesser extent traffic on the roads (Figure 8b). Predicted dust fallout at Gobabeb is low with the highest levels predicted for Henties Bay and Wlotzkasbaken.

4.3 Impacts from windblown dust

Wind erosion is an intermittent source of emissions occurring when the wind speed exceeds a certain threshold. The threshold friction velocity is influenced by the various soil properties linked to the wind erosion sources, whereas the friction velocity is dependent on the varying atmospheric conditions (Burger, 2010). Thus, the predicted daily average PM10 concentration due to wind erosion should be a result of a few isolated occurrences of high wind speeds, occurring for less than 5% of the time (Figure 6).

Further investigation of the monthly PM10 plots due to windblown dust alone shows a clear correlation with the prevailing monthly wind fields. For example, January is characterized by low wind speeds (below 10 m/s) on average and reflects the lowest concentrations (Figure 9a). During July when the highest incidences of high wind speeds were recorded, the predicted concentration exceeds 120 µg/m³ over Swakopmund and Wlotzkasbaken and stretches as far as 80 km over the Atlantic (Figure 9b).

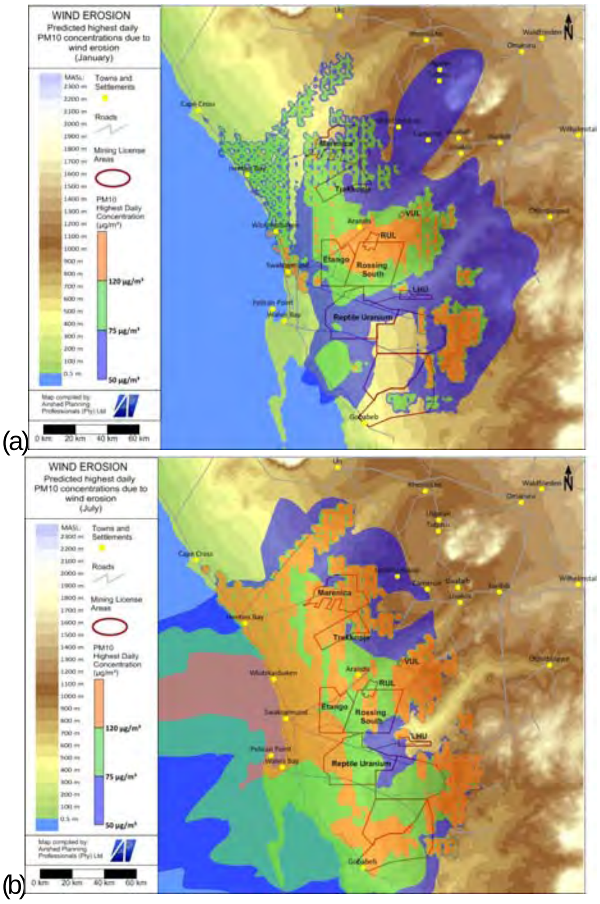

Figure 9: Predicted PM10 daily concentrations as a result of wind erosion from natural sources for (a) January and (b) July

4.3 Dispersion results verification

Limited ambient data were available and not for the same period as what was modeled for. Nonetheless, this data provide an indication of the range of accuracy. The predicted annual average PM10 concentrations were compared with the available ambient PM10 data at Etango, Swakopmund, Gobabeb and Trekkopje monitoring locations. On average, the predicted concentration over-estimated at Swakopmund by a factor of 2.8, and under-predicted slightly at Gobabeb (factor of 0.8) and Trekkopje (factor of 0.7). A close correlation was found at the Etango station (factor of 1.1). Given the uncertainties surrounding the data and the temporal difference in datasets, this was regarded an adequate correlation for all but Swakopmund which fell outside the -50% and 200% accuracy range of the CALPUFF model.

5. Conclusions

The contribution of the atmospheric pathway to a particulate exposure (health and nuisance) associated with the various background sources (natural and anthropogenic) was found to be high, exceeding the ambient air quality guidelines. When assessing the two settlements of Swakopmund (at the coast) and Goanikontes (inland), predicted annual average concentrations exceed the selected health criteria of 30 µg/m³ (WHO IT-3) by 40% and 55%, respectively. Dispersion simulations indicated wind erosion to be the main contributing source to PM10 impacts. At Swakopmund, wind erosion contributes 70% to the predicted annual average PM10 concentrations and 80% to Goanikontes. On average, PM10 concentrations as a result from natural background sources are in the order of 40 µg/m³ (average between Swakopmund, Arandis and Goanikontes). It was found that the few incidences of high wind speed, mainly associated with the east and east-northeast wind, results in the high predicted PM10 concentrations on the western side of the Erongo Region.

Dust collected over the 11 months (August 2009 to June 2010) indicated low dust fallout rates below 250 mg/m²/day most of the time. Only four collections were above 250 mg/m²/day with all below the SANS limit value for residential areas. Predicted dust fallout was high, exceeding the SANS limit at all settlements. Wind erosion contributed more than 80% at all locations. Predicted dust fallout did not show any correlation with collected dust fallout. This may be a result of the dust fallout device not trapping dust under high winds and that the dust is carried over the bucket.

Wind erosion emissions are very sensitive to source characteristics and atmospheric conditions. The study showed temporal trends corresponding with incidences of high wind speeds and provided a fair comparison with limited period average measured data (PM10 only). It is however difficult to estimate the significance of the limited input data to the wind erosion model. This initiated further research to improve data collection and dispersion simulations. Alternative methods (i.e. satellite imagery) will be employed to verify predicted results.

6. Acknowledgements

The Namibian Ministry of Mines and Energy are acknowledged for being the custodian of the project.

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