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Research article

Dilution and dispersion of particulate matter from abandoned mine sites to nearby communities in Namibia

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ABSTRACT

In this study, the HYSPLIT model was used to model the dilution and dispersion of particulate matter in the surrounding of two abandoned mine sites (Klein Aub and Oamites) to the nearby communities. The simulations indicated a relationship between mass concentrations and meteorological parameters as well as their impacts on the dilution and dispersion of particulate matter. Dispersion simulations of the non-residential point indicated that the community of Klein Aub is mainly affected by tailings dust through the Easterly wind which transports tailings contaminated dust to the residential area during winter. Oamites dispersion simulations of the residential point located at 23°47′24.6 S; 016°38′46.2 E indicated that this point is not directly affected by the tailings dust. The results suggest that the influence of the wind direction and wind speed is more on the dispersion than dilution. The wind or lack of thereof can cause the particulate matter to move or accumulate around the pollution source. The dilution of particulate matter was mainly influence by the temperature, with generally low dilution observed in the cold winter months.

1. Introduction

Air pollution is one of the biggest challenges in the twenty-first century, not only at a global level but also at local and regional levels (Bodor et al., 2020). The effects of particulate matter on air quality, visibility, human health and global climate change have been widely documented (Bodor et al., 2020; Kgabi and Mokgwetsi, 2009; Wang et al., 2019; Gasparac et al., 2020). High concentrations of PM in the ambient environment are associated with respiratory and cardiovascular diseases and mortality (Wang et al., 2019) and effects on the ecosystem (acidification and eutrophication) (Gasparac et al., 2020). This also affects various meteorological processes such as radiation, cloud formation (Gasparac et al., 2020), precipitation and regional climate by altering the nucleus and energy balance (Tu et al., 2019). Thus to understand air pollution, it is important for researchers to comprehend the meteorology, dilution and dispersion of pollutants from the source (sampling point) to the receptor (Kgabi and Mokgwetsi, 2009).

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model and other numerical simulation methods have been used extensively in pollution analysis and research (Tu et al., 2019). The HYSPLIT is one of the analysis models that is capable of modelling air mass trajectories as well as particles dispersion and deposition simulations (Kgabi and Mokgwetsi, 2009) and extensively used in atmospheric sciences community with more than 800 citation (Stein et al., 2015). The historical evolution and recent improvements of the HYSPLIT are documented in Stein et al. (2015). One of the most common model application is the backward-trajectory analysis to determine the origin of air masses and establish a source-receptor relationship (Stein et al., 2015).

The backward-trajectories analysis (e.g. cluster trajectories) and concentration-weighted trajectory (CWT) simulations have been applied to identify transport pathways of air masses and the potential source areas (Bodor et al., 2020). The model calculation method is a hybrid between the lagrangian approach, using a moving frame of reference for the advection and diffusion calculations as the trajectories or air parcels move from the initial location, and Eulerian methodology which uses a fixed three-dimensional grid as a frame and reference to compute pollutant air concentration (Stein et al., 2015). Inherent constrains of simulations/models are the same as in conventional weather forecast, the accuracy may be affected when there is limited input variables (Perez et al., 2015). Atmospheric data and information on the source is always limited (Kgabi and Mokgwetsi, 2009).

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One of the most important reasons for modelling atmospheric transport and diffusion (ATD) is to predict the atmospheric concentrations of hazardous material released from various points to other locations (Kgabi and Mokgwetsi, 2009). According to Tu et al. (2019), "The atmospheric diffusion capacity is crucial in the regional transport of aerosols and greatly influenced by the meteorological conditions". The effects of wind speed on the dispersion and transport of PM is discussed in Kgabi and Mokgwetsi (2009). The problems related to particulate matter from urbanization and industrialization have steadily prompted a need for a well-elaborated and efficient long-term emission controls (Bodor et al., 2020). Hence, it is important to determine the potential pollution sources and understand the emissions to be able to maintain or improve air quality.

Past research studies on particulate matter and potential sources of particulate matter at and around Oamites and Klein Aub mine sites focused on the chemical composition analysis (Amkongo et al., 2007; Hahn et al., 2004) and remediation of heavy metals in tailings (Mbingeneeko, 2014). However, to the best of the authors' knowledge, there is no documented scientific research on the dilution and dispersion of particulate matter around Oamites and Klein Aub Mine sites. Therefore, the aim of this study was to model the dilution and dispersion of particulate matter from the two abandoned mine sites to nearby communities. The works of this study can assist policy makers in decision making as well as contribute towards the limited particulate matter portfolio of abandoned mine sites in Namibia.

2. Materials and methods

2.1. Overview of the study sites

Fallout dust samples were collected from around the two abandoned mine sites, namely, Klein Aub and Oamites. Klein Aub mine site is located on Klein Aub Farm (lat -23.80000; long 16.63300), 85 km South-West of Rehoboth (SAIEA, 2010). The mine was operated by Gencor and Metorex since 1966, mining chalcocite (Cu) until closure in 1987 (SAIEA, 2010). The mine has left concrete structures, foundations remain and volumes of scrap metals and tailings which are physically dangerous, with a potential to contaminate air via wind-blown dust from tailings and erosion (Hahn et al., 2004). According to Hahn et al. (2004), the Klein Aub Community is mainly affected by the Easterly wind which transports tailings contaminated dust from the adjacent tailing dam.

Oamites mine site is situated 50 km South of Windhoek (lat -22.90000; long 17.08300). The operations left concrete foundations and structures and tailings dumps estimated at 5.5 Mt and approximately ±450 000 tons of waste rocks (SAIEA, 2010). The mine mined bornite and chalcopyrite (Cu) and gold as a byproduct from blisters of copper in 1971–1984 (Lee and Glenister, 1976). The two tailings dams present a major pollution problem due to wind erosion, affecting mainly the Namibia Defence Force (NDF) Camp with the ENE wind direction which transports tailings contaminated dust from the two tailings dumps (Amkongo et al., 2007; Hahn et al., 2004; SAIEA, 2010). The area is characterized by semi-arid highland savannah climate, with average temperatures ranging between 6 °C in the coldest months and 31 °C in the warmest months (Green Earth Environmental Consultants, 2019).

2.2. Topography and land use densities

The topography of Klein Aub is flat with some hilly ridges and peaks flattening towards the Namib Naukluft park to the west of the settlement (Stankeviča, 2015). This can be seen in the areal image in Figure 1 and Figure 2. The most significant features that remained from the time of mining are the tailings dam and delapitated abandoned mine infrastructures that are visible from the outskirt of the settlement and underground infrustures below the settlement (Stankeviča, 2015).

A small mining settlement that was initially established to accommodate mining workers still exists with a few amenities such as a settlement office, clinic, school, police station, convenience store, water treatment plant and a restaurant and coffee shop.

The community is sparsely populated with a population of about 3000 residents (Hardap Regional Council, 2020). Majority of the residents are people that were previously employed by the mine and their families, a detailed socio-demographic profile of Klein Aub can be found in Stankeviča (2015).

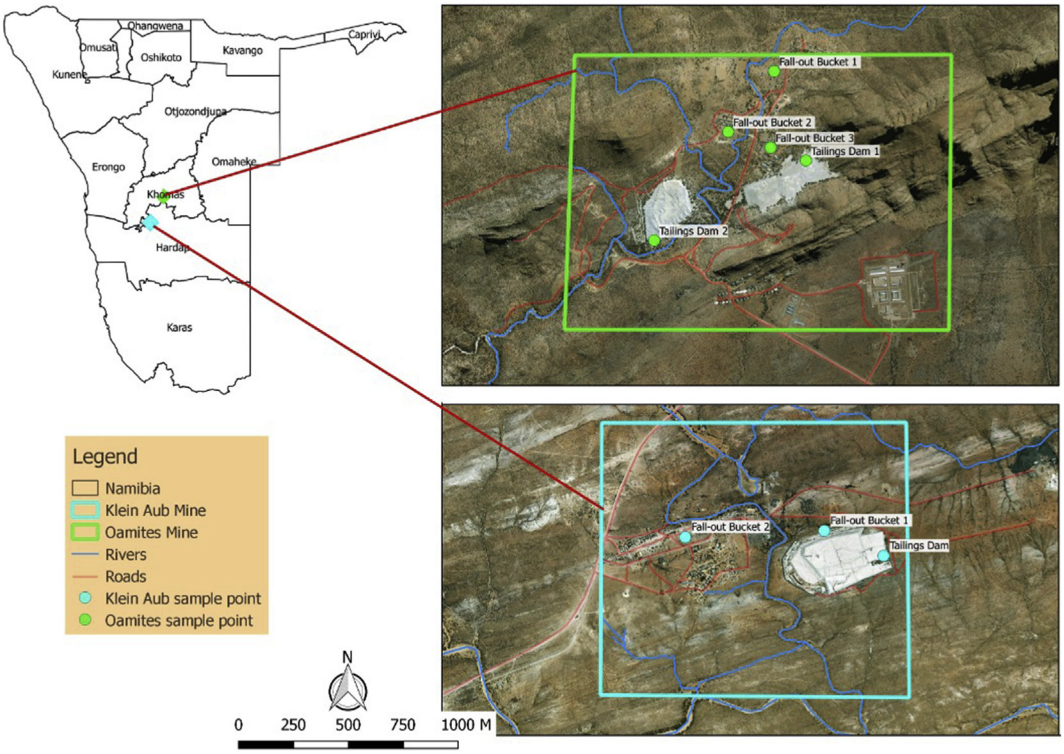

Figure 1. The study areas and the location of sampling points (Uugwanga and Kgabi, 2020).

Figure 2. Shows the community of Klein Aub and the tailings dam in the background.

The topography of Oamites is characterized by a mixture of low hills and steeper koppies at the far western site where the slope is approximately 10% and flat land with a slope of approximately 2% (Green Earth Environmental Consultants, 2019).

The site is currently used as military camp site. The vegetation consists of medium and light grass cover and average coverage of bushes, shrubs and trees (Green Earth Environmental Consultants, 2019). The combination of hills, bushes, shrubs and grasses is shown in Figure 3.

2.3. Data collection and analysis

The dry mass from the samples collected from the three sampling points in Table 1 were used in the HYSPLIT model to compute the trajectories and model the dilution and dispersion. The content from Bucket 2 and 3 (Figure 1) from Oamites could not be recovered due to the presence of baboons on site.

Sampling was conducted from January 2018 to November 2018. Single fallout 5 L buckets with a surface area of 0.043 m^2 filled with a solution of deionized water and hydrogen peroxide were deployed for sampling as per the American Society for Testing and Materials standard method for collection and analysis of fallout dust (ASTM D1739) (American Society for Testing and Materials (ASTM) (American Society for Testing and Materials (ASTM), 2004). The hydrogen peroxide was added to prevent the growth of algae in the bucket. The content of the buckets was extracted or filtered onto 110 mm ashless filters using a Buchner Funnel connected to a diaphragm vacuuming pump and allowed to naturally dry in the laboratory at Namibia University of Science and Technology (NUST). The empty filter papers were individually weighed before extraction as well as after filtration once the content had dried to obtain the mass of particulate matter.

Figure 3. Shows the tailings dam (Dam 2) and mountains in the background at Oamites.

The HYSPLIT model and its supporting features were obtained from the Real-time Environmental Application and Display System (READY) on the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) (Rolph et al., 2017). To compute the dispersion and dilution, meteorological data and mass concentrations of the particulate matter were entered into the model using the Graphic User Interface (GUI) installed on a personal computer. GUI opens up four menus; Meteorology, Trajectory, Concentration and Advanced. The Meteorologys menu was used to convert meteorological data (wind speed, wind direction) obtained from the Southern African Science Services Centre for Climate Change and Adaptive Land Management (SASSCAL) (2020) to ARL format that is compatible with the HYSPLIT model. The Concentration Menu was used to setup and define the air concentration features such as the particulate matter mass, location, grid size and emission rate. The Advanced Menu was used to setup the configuration of the particle/puff release settings.

The default mixing depth of 1500 m was used and the stability category was set based on the stability categories guidelines by Rolph et al. (2017). The mixing layer height affects the near-surface air pollution concentration because it determines the volume in which the emitted pollutants are dispersed (Wang and Wang, 2014). The default 1500 m used as the mixing layer depth is close to the averages calculated by Kgabi et al. (2015). Further studies can be done to determine the atmospheric boundary layer and stability.

The HYSPLT dispersion model calculates the dispersion of particles by assuming either a particle or puff release (Kgabi and Mokgwetsi, 2009). In the puff model, particles expand until they exceed the meteorological grid cell space and split into several new smaller puffs, with their own share of pollutant mass (Draxler, 1982). In this paper, the particle dispersion approach was applied in a 3D particle horizontal and vertical release mode. The particle model combines the particle and puff methods by assuming a puff distribution in the horizontal direction and particle distribution in the vertical direction (Draxler, 1982).

3. Results and discussion

Mass concentrations and meteorological parameters are closely related and both play an important role in the deposition, dispersion and dilution of particulate matter (Wang et al., 2019). Tables 2 and 3 shows the summary of meteorological data and fallout dust mass for Klein Aub and Oamites sites respectively. Generally, Namibia has only two seasons, namely, summer which run from November to April (also known as the rainy season) and winter from May to October (dry season) (Namibia Weather, 2020; Namibia, 2020).

Average temperatures ranged between 7.7 °C and 35.2 °C in summer and -5.8 °C and 35 °C in winter for Klein Aub. According to Wang et al. (2019), high temperatures may lead to the efficient dispersion of pollutants, which results in an inverse relationship between temperature and PM concentrations. Wind speed was especially high during the winter months, with averages between 0.3 m/s and 2.3 m/s and the maximum speed ranging between 9.1 m/s and 12.9 m/s. The wind direction varies, with an Easterly to South Easterly wind direction in summer and South Easterly to South Westerly wind in the winter months.

Temperatures for Oamites are slightly high compared to Klein Aub, ranging between a minimum of 1.3 °C in July and 34.9 °C in October. Maximum highest wind speed of above 10 m/s were recorded for May and July to September (Table 3). Oamites is dominated by the Eastern (E) wind in most months and South Easterly (SE) wind noted in November,

Table 1. Sampling points.

Site	Sampling Point	Description	Latitude	Longitude
Klein Aub	Bucket 1	Non-residential	-23.790167	16.646167
	Bucket 2	Residential area	-23.7906944	16.633722
Oamites	Bucket 1	Residential area	-22.975611	17.0738056

January and February. Meteorological parameters such as rainfall, wind speed and wind direction are especially important as they all affect the transportation, dispersion and dilution of particulate matter differently. Rainfall scouring process for instance can significantly reduce the mass concentrations of particulate matter, while, an increase in the wind speed increases the horizontal dispersion capacity subsequently resulting in a reduction in mass concentrations (Wang et al., 2019).

3.1. Dilution and dispersion

The monthly dilution and dispersion simulations of the three sites are presented in Figure 4 (Klein Aub residential area in summer), Figure 5 (Klein Aub non-residential area in summer), Figure 6 (Klein Aub residential area in winter), Figure 7 (Klein Aub residential area in winter) and Figure 8 (Oamites). The simulations indicate how much pollutant is dispersed and where they are transported to and how diluted they are.

3.1.1. Klein Aub

Summer. Figure 2 Dispersion simulations indicate significant dispersions towards the north-west direction in all months except November which is more towards WSW direction. Pollutant concentrations in January were slightly over the 150 km radius, followed by February and the rest of the months were between 100 km and 150 km radius. High concentrations of 1.0E-7 μg/m^3 were evidently dispersed over a 100 km radius in January, March and November.

The widespread dispersion of particulate matter in January and to a far distance can be attributed to a combination of low rainfall, high maximum wind speed and temperature (Table 2). Other contributing and impacting factors of importance to the dispersion of particulate matter include the particle size and topography (Khairullah et al., 2017). The concern with the topography is that the dispersion of pollutants in an area that is not flat can cause an obstruction in dispersion path.

Particle concentrations in April which recorded the highest average wind speed showed traces of concentrations of 1.0E-15 μg/m^3 (yellow) within the 100 km radius. This could be due to the fact the strong wind speed may have resulted in a more rapid dilution of particulate matter (Kgabi and Mokgwetsi, 2009) or stronger turbulence (Zhang et al., 2017) as evidence in small traces of yellow concentrations within the puff. The dilution in Figure 2 indicated rapid dilution of particles in February, with no evidence of high concentrated particles 1.0E-5 μg/m^3. This could be attributed to a combination of high temperatures ranging between 12.1 °C–33 °C and high rainfall of 69.6 mm. Rainfall reduces the mass concentration of particulate matter through wet deposition and removal (Zhang et al., 2017).

Figure 3 Dispersion puffs for the non-residential area in summer did not exceed the 150 km radius. The yellow colour represents high mass concentrations which have only been dispersed in trace amounts outside the 50 km radius, observably with exception to March. The high concentrated particles of 1.0E-5 μg/m^3 exceeding a 100 km radius in March could be due to the high wind speed of 1.5 m/s in April (Table 2), which contributes to great dispersion of pollutants (Kgabi and Mokgwetsi, 2009).

Table 2. Monthly average meteorological data for Klein Aub (closest weather station: Narais – Duruchaus, ID: 31206) and recorded particulate matter mass (g).

Season	Month	Temperature (°C)			Rainfall (mm)	Wind direction (Degrees from true North)	Wind Speed (m/s)		Particulate Matter Mass (g)	
		Avg	Min	Max			Avg	Max	Res.	Non-res.
Summer	January	25.2	10.2	35.2	3.2	100 (E)	0.7	9	1.11	0.18
	February	23.1	12.1	33	69.6	128 (SE)	1	9.4	1.74	0.22
	March	21.8	11.7	31.9	67.9	144 (SE)	1.5	7.8	0.86	0.89
	April	19	7.8	28.2	74.3	142 (SE)	1.6	7.6	24.40	1.36
	November	24.4	7.5	34.8	4.4	70 (ENE)	0.6	8.7	3.37	6.70
Winter	May	15.8	2.6	26.4	10.9	145 (SE)	2.2	12.5	10	0.76
	June	13.6	1.6	25.9	0	140 (SE)	2.2	10	5.23	1.63
	July	12.3	-3.7	25.6	4.8	211 (SSW)	1.1	9.1	6.70	2.64
	August	14.3	-5.8	29	0	133 (SE)	2.3	12.9	6.64	3.20
	September	18.3	-0.1	32.8	0	110 (ESE)	1.5	9.4	10.51	3.21
	October	22.6	7.7	35	11.8	218 (SW)	0.3	11.6	21	13.16

Res ~ Residential; Non-res ~ Non-residential.

Table 3. Monthly average meteorological data for Oamites (closest weather station Windhoek (NBRI), ID: 31209) and recorded particulate matter mass (g).

Month	Temperature (°C)			Rainfall (mm)	Wind direction (Degrees from true North)	Wind Speed (m/s)		Particulate Matter Mass (g)
	Avg	Min	Max			Avg	Max	
January	25.5	16.3	34.2	4.6	-	0.5	9.2	-
February	23.8	15	33.3	29.5	-	0.5	9	-
March	22	14	31.3	81.7	-	0.4	9.6	-
April	19.7	11.7	27.4	104.3	0.009	1.1	6.7	0.009
May	17.6	7.2	25.2	4.1	-	1.2	10.2	-
June	15.7	6.2	24.9	0	0.38	1.5	9	0.38
July	13.8	1.3	24.9	0.7	0.80	2.8	10.1	0.80
August	17	2.5	28	0	-	0.8	10	-
September	20.9	3.1	31.8	0	0.30	0.7	10.1	0.30
October	23.6	11.6	34.9	13.7	0.33	1.2	9.7	0.33
November	25.4	11.8	34.3	0.8	0.12	0.7	8.7	0.12

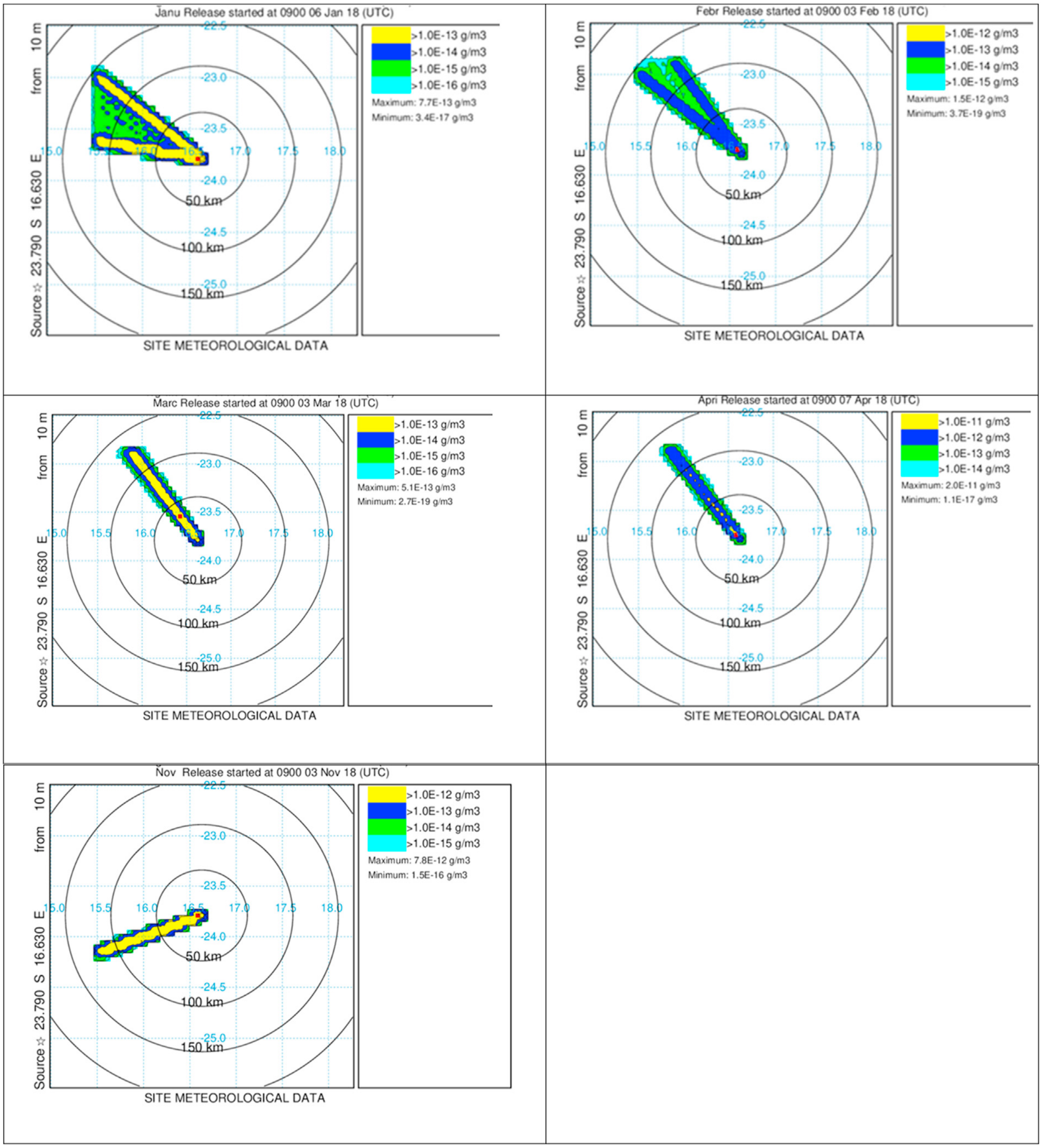

Figure 4. Monthly dispersion of particulate matter at the residential sampling point in summer.

The dispersion direction follows a similar trend with the residential sampling point, which is expected given that the two points share meteorological parameters.

There is generally a rapid dilution of pollutants in all months with exception to March, which recorded concentrations of 1.0E-7 μg/m^3 outside the 100 km radius. It can be argued that a combination of low temperatures and high rainfall may have caused the particles to be denser and heavier, resulting in the slow dilution of particles (Kgabi and Mokgwetsi, 2009). The non-residential sampling point is within a 5 km radius of the residential area and within a 100 m of the tailings dam, thus representing the tailings dam as a source. According to Hahn et al. (2004) the wind monitoring programme indicated that tailings contaminated dust from the tailings dam in Klein Aub is transported by the Easterly wind to the residential area. Thus, the dispersion towards the north-west direction in January to April and south-west in November, suggests that this source (tailings dam) does not directly affect the community of Klein Aub during summer.

Winter. Figure 4: The puffs simulations from June to October are widespread and have split into one or more puffs. High concentrations (1.0E-5 μg/m^3) exceeding the 100 km radius were recorded towards the NE direction in May, June, July and October and WNW in August.

Figure 5: The puff distribution and split is similar to that of the residential area, however, the dispersion of the high concentrated particles (yellow) is slightly lower and kept within a 100 km radius. This low dispersion rate in comparison to the residential area dispersion, could be attributed to the low mass concentrations (Table 2). Since the community of Klein Aub is located within a 5 km radius of the tailings dam, the

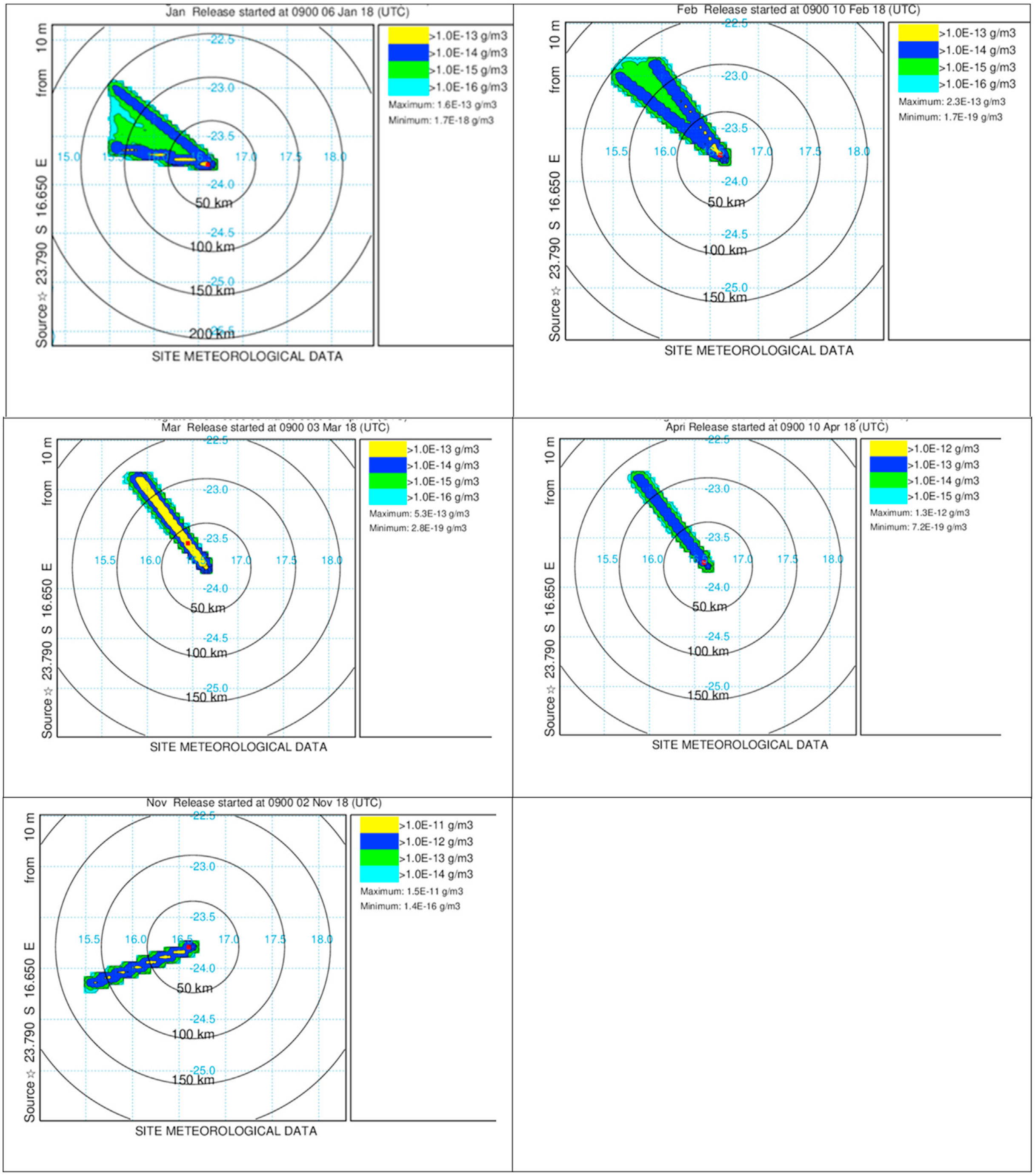

Figure 5. Monthly dispersion of particulate matter at the non-residential sampling point in summer.

simulations suggest that this community is exposed to high concentrations of tailings contaminated particulate matter during most of the winter months. However, the concentrations are relatively low compared to the OSHA guidelines for elements such as Al, Si, Cl, P, S, K, Ca, Ti, Fe, Zn and Cu which were identified by the Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM-EDX) analysis (Uugwanga and Kgabi, 2020).

The particles dispersed in July and August are mostly from the second highest tier (blue) down, which are less concentrated, with concentrations ranging between 1.0E-7 μg/m^3 and 1.0E-9 μg/m^3. Generally, the low temperatures and seldom rainfall in winter compared to significantly high temperatures and rainfall in the summer months, have contributed to the slow dilution of particulate matter in winter.

3.1.2. Oamites

The seasonal variations of the dispersion and dilution simulations of Oamites could not be assessed due to an incomplete data set. Oamites dispersion is dominated by a WSW direction, specifically observed in April, June, July and September (Figure 6). The Oamites community is affected by tailings contaminated dust through ENE

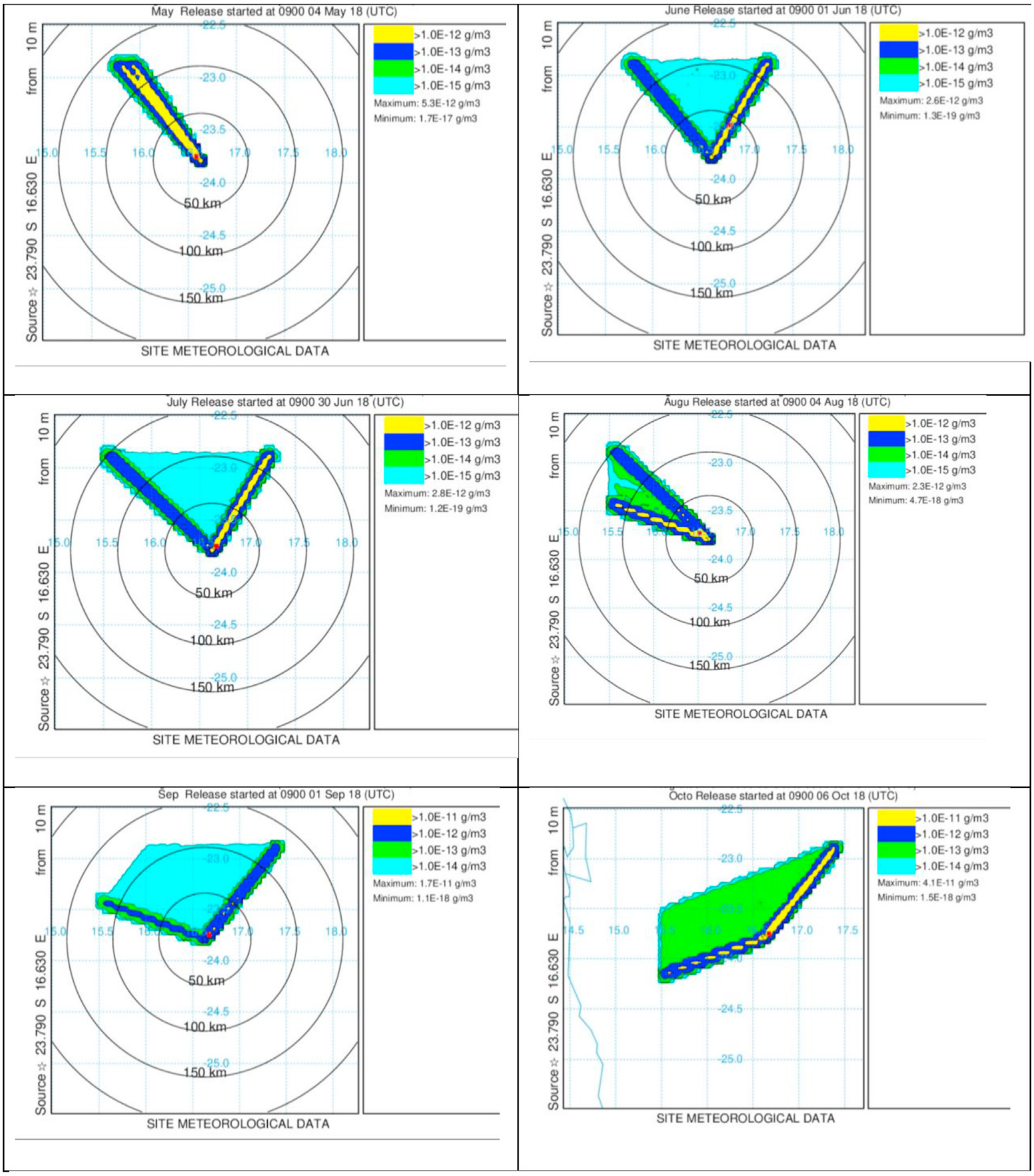

Figure 6. Monthly dispersion of particulate matter at the residential sampling point in winter.

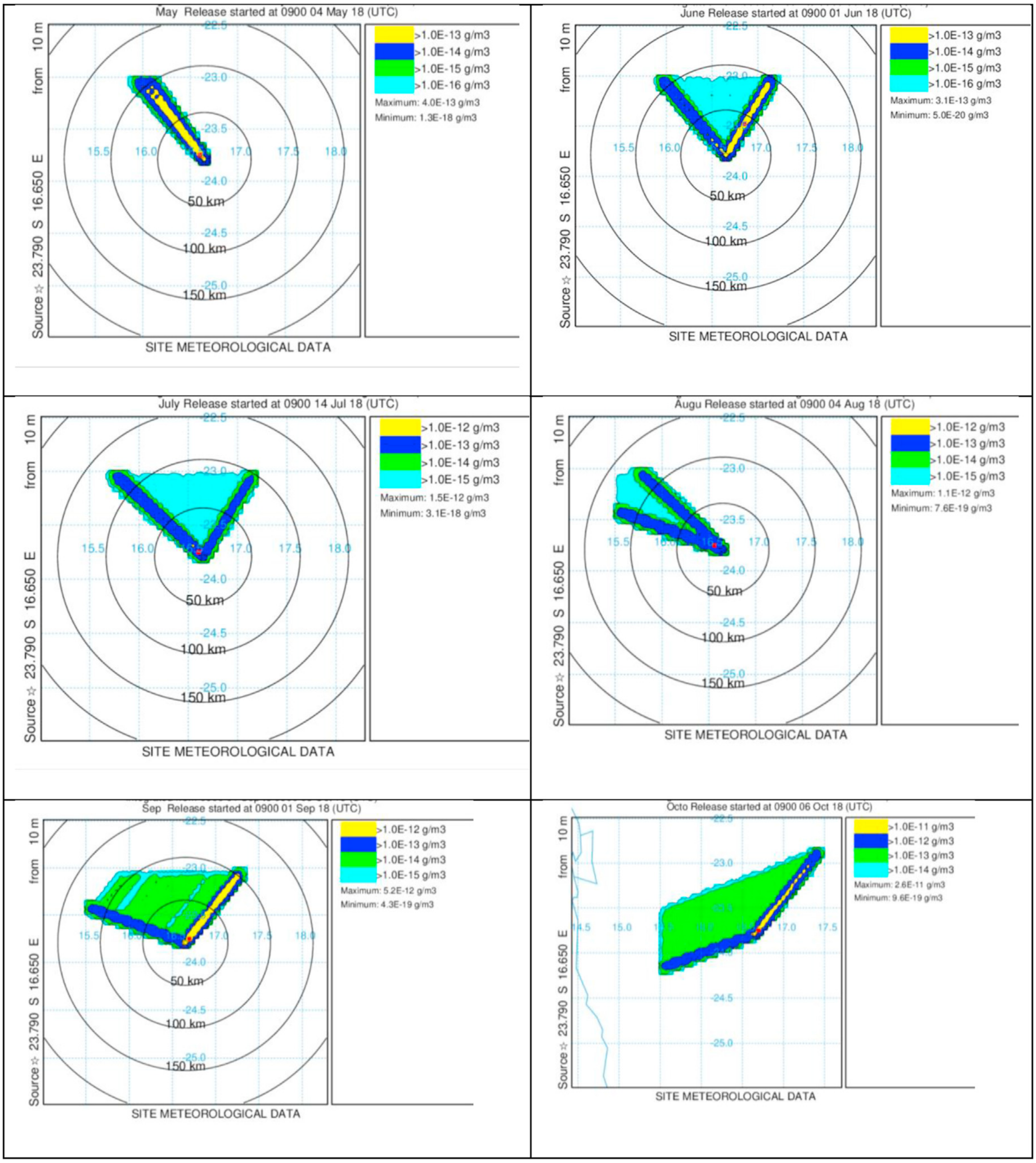

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Figure 7. Monthly dispersion of particulate matter at the non-residential sampling point in winter.

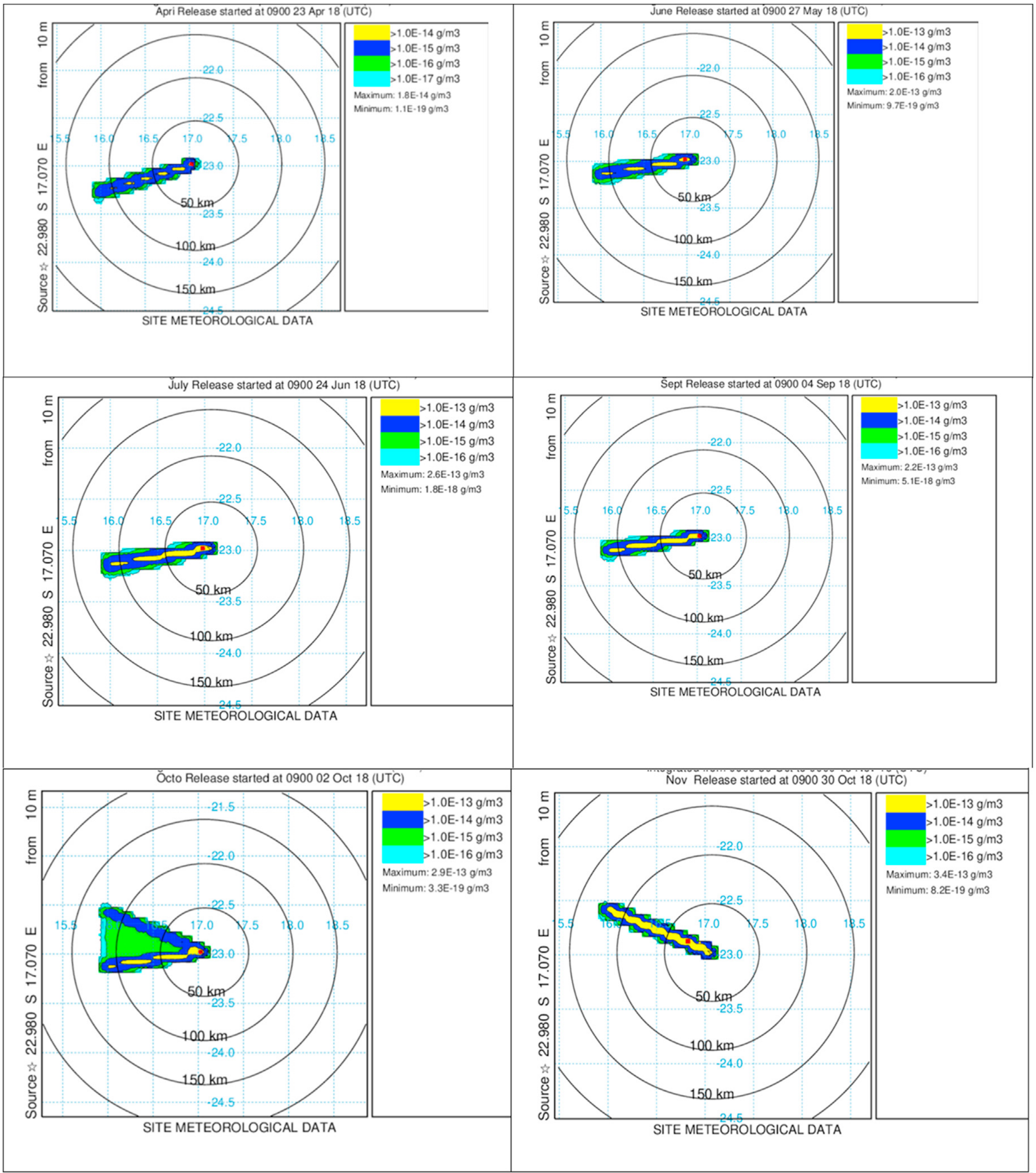
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Figure 8. Monthly dispersion of particulate matter at Oamites.

direction from the SW tailings dam and ENE and NNE wind from the NE tailings dam (Hahn et al., 2004). All the dispersion simulations were within the SW grid, thus indicating that the accommodation camp located at 23°47′24.6 S; 016°38′46.2 E is not directly affected by the tailings dust.

The dilution indicated small traces of concentrated particles (1.0E-7 μg/m^3) outside a 100 km radius in all months except November, which has a solid dispersion exceeding a 100 km radius zone. However, the concentrations of 1.0E-7 μg/m^3 are relatively low compared to the OSHA guidelines for elements such as Al, Si, Cl, P, S, K, Ca, Ti, Fe and Zn which were identified by the Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM-EDX) analysis (Uugwanga and Kgabi, 2020).

4. Conclusion

The HYSPLIT model was used to model the dilution and dispersion of particulate matter in the surrounding of two abandoned mine sites (Klein Aub and Oamites) to the nearby communities. Specifically, the particle dispersion approach in a 3D particle horizontal and vertical release mode was used. The simulations indicated a relationship between mass concentrations and meteorological parameters such as the wind speed, rainfall and temperature and their impacts on the dilution and dispersion of particulate matter to nearby communities.

Dispersion simulations of the non-residential point in Klein Aub indicated that the community is mainly affected by the tailings dust through the Easterly wind which transports tailings contaminated dust to the residential area during most of the winter months. Whereas, the dispersion simulations of the non-residential point in summer indicated that particles are dispersed towards the north-west direction in January to April and south-west in November, suggesting that this source (tailings dam) does not directly affect the community of Klein Aub during the said season. Oamites dispersion simulations of the residential point located at 23°47′24.6 S; 016°38′46.2 E also indicated that this point is not directly affected by the tailings dust.

The results suggest that the influence of the wind direction and wind speed is more on the dispersion than dilution. The wind or lack of thereof can cause the particulate matter to move or accumulate around the pollution source. Whereas, precipitation can significantly reduce the mass concentrations of particulate matter through wet deposition and removal or can cause the particles to become denser and heavier resulting in slow dilution. The results indicated that the dilution of particulate matter was mainly influence by the temperature, with generally low dilution observed in the cold winter months. The content of the two sampling points at Oamites (tailings dam and residential area) could not be retrieved due to the presence of baboons onsite that were constantly taking away the buckets. Thus, this study would like to recommend further studies to be done to determine the atmospheric boundary layer and stability as well as for future studies on dust measurements in areas with baboons or monkeys to consider using fixed monitoring equipment that cannot be easily moved or tempered with.

Declarations

Author contribution statement

Martha N. Uugwanga: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Nnenesi A. Kgabi: Conceived and designed the experiments.

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Data availability statement

Data is contained within the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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