BROKEN HILL ENVIRONMENTAL LEAD STUDY

BHELS Year 3 Report

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Executive Summary

The Broken Hill Environmental Lead Study (BHELS) was commissioned by the Broken Hill Environmental Lead Program (BHELP) in 2016 to inform remediation efforts underway and to address lead contamination and exposures. The BHELS is a five-year program, conducted over the 2016 to 2020 period, that included a sampling program spanning three calendar years (January 2017–March 2020).

The overall BHELS program objectives are:

- Determine the likely source areas contributing to airborne lead levels in Broken Hill.
- Measure and compare airborne lead levels and lead mass fractions in total suspended particles (lead-in-TSP) from currently operational mining sectors with other sectors.
- Measure wind-directional airborne ambient lead concentration and lead-in-TSP levels.

The weather in the Broken Hill region is generally hot in summer and cold and dry in winter. The average maximum temperature during summer 2019 was higher by 3.3°C, 1.5°C, and 0.47°C compared to those recorded in 2017, 2018 and long-term average (1960-2017), respectively. The maximum temperatures in 2017, 2018 and 2019 were above the long-term average for most months. The annual total rainfall was 68 mm which was the lowest since 1997. Due to the prevailing hot and dry conditions and higher annual average wind speed, Broken Hill experienced more dust storms in 2019 compared with 2017 and 2018.

This report is the third consecutive report that follows from those produced for Year 1 and Year 2. The two previous reports presented the sampling results and analysis obtained during 2017-2018 and 2018-2019. This Year 3 report presents the results of the third year of sampling (February 2019–March 2020) and provides a comparison with the Year 1 and Year 2 results of the study.

Wind-directional high-volume samplers (D-HVAS) have been employed to collect TSP on glass fibre filters at five sites in Broken Hill, namely the National Parks, Wetlands, Waterboard, Sewerage Pumping Station and Silver City Highway. The D-HVAS sampling collects particles on a weekly basis with equivalent aerodynamic diameters in the range 0.1-100 µm. Sample filters were subsequently weighed and analysed to determine TSP concentrations, Pb-in-TSP content, and ambient Pb concentrations.

Two D-HVAS were deployed at each sampling site. One unit samples during periods when the prevailing wind is blowing from ‘Sector A’ (which places a D-HVAS downwind of predominantly mining areas), and the second unit samples during periods when the wind is blowing from the remaining wind sector or ‘Sector B’.

Dust deposition gauges (DDGs) were installed at each site in March 2018. The non-directional DDGs collected coarse dust samples at each site. The collected dust samples were then analysed for the total deposited dust mass and lead in dust content on a monthly basis.

Findings from the third year of sampling are presented in this report. Major findings of the report include:

- The median ambient lead concentrations and lead-in-TSP levels at each site were consistently higher by a factor of 1.6 to 7.5 in Sector A, where the sampling occurs downwind of selected mining operations, than in Sector B. These results confirm the previous obtained in Year 1 and Year 2.
- Overall average median ambient lead concentrations across all sites indicate that the Sector A lead level are higher by 25% and 18-35% in Year 3 than in Year 1 and in Year 2 respectively. Silver City Highway recorded the highest median ambient lead concentrations over all four monitoring periods, ranging between 0.50 µg/m^3 in Year 1 and 0.91 µg/m^3 in Year 3.

- Episode analysis finds that on a finer time scale (weekly) Sector B lead levels were occasionally higher compared with Sector A. For instance, during the 8–15 January 2019 episode the weekly average ambient lead concentration in Sector B was 0.95 µg/m^3, which was twice as high as in Sector A. The reasons for these occasional high Sector B lead levels is unknown.
- The median ambient lead levels in Sector B were generally low (less than 0.09 µg/m^3) at all sites over the four monitoring periods (covering Years 1-3), except Silver City Highway (0.06 – 0.37 µg/m^3). Note that the small number of Sector B samples at Silver City Highway site could have biased the median concentrations.
- Overall median lead-in-TSP levels were higher in Year 3 than in Year 2 and lower in Year 3 than in Year 1. Silver City Highway site recorded the highest median lead-in-TSP levels consistently over all four monitoring periods. The highest Sector A median lead-in-TSP level was 10,823 mg/kg at Silver City Highway site measured in Year 3.
- Dust Deposition Gauge (DDG) measurements were carried out at each site on a monthly basis during 2018-2020. The lead in deposited dust and the lead-in-dust mass fraction results confirm the D-HVAS results that the Silver City Highway site measures the highest lead levels, with the highest level of 0.016 grams lead/m^2/month measured in Year 3.
- The National Parks site recorded the second-highest monthly lead levels after Silver City Highway site, with the highest level of 0.01 grams lead/m^2/month measured in January 2020. In September 2019, the lead levels were 0.008 grams lead/m^2/month at both Silver City Highway and National Parks site.
- The monthly lead mass as a fraction of the total deposited solid mass was significantly higher at the Silver City Highway site compared to all other sites, ranging from 596 mg/kg to 5,425 mg/kg in Year 3. The maximum monthly lead levels in Year 3 ranged from 1,113 mg/kg at the Wetlands site to 5,425 mg/kg at the Silver City Highway site.
- The monthly lead mass fraction was reduced during the months with significant dust events compared with the months with no considerable dust events, likely due to dilution of lead bearing TSP by non-lead bearing TSP.

Table 1 Median values of measured ambient lead concentrations by sampling site and sampling period.

BHELS Sampling Site	Sector	TSP-Pb (µg/m³)			
		Year 1[a]	Year 2[b]	Year 2[c]	Year 3[d]
National Parks (NP)	A	0.12	0.11	0.15	0.14
	B	0.08	0.06	0.09	0.09
Wetlands (WE)	A	0.08	0.08	0.08	0.08
	B	0.03	0.04	0.04	0.04
Waterboard (WA)	A	0.13	0.13	0.18	0.15
	B*	-	-	0.02	0.02
Sewerage Pumping Station (SPS)	A	0.16	0.10	0.14	0.18
	B	0.06	0.08	0.05	0.08
Silver City Hwy (SC Hwy)	A	0.58[§]	0.50	0.63	0.91
	B	0.06[§]	0.08	0.37	0.15

[a]: Year 1, data based on 365 days' sampling except at Silver City Highway; [b]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days' sampling); [c]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days' sampling); [d]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018 (120 days' sampling).

[§]Samplers installed 3 October 2017 (95 days' sampling in Year 1).

Table 2 Median values of measured lead-in-TSP by sampling site and sampling period.

BHELS Sampling Site	Sector	TSP-Pb (mg/kg)			
		Year 1[a]	Year 2[b]	Year 2[c]	Year 3[d]
National Parks (NP)	A	2,670	2,504	2,024	2,361
	B	1,680	1,134	996	1,349
Wetlands (WE)	A	2,370	1,591	1,713	2,298
	B	1,080	832	482	565
Waterboard (WA)	A	3,850	3,320	2,098	2,654
	B*	-	-	196	654
Sewerage Pumping Station (SPS)	A	4,780	1,244	1,840	3,538
	B	1,550	1,374	462	894
Silver City Hwy (SC Hwy)	A	9,110[§]	8,140	6,416	10,823
	B	2,170[§]	2,135	1,981	2,110

[a]: Year 1, data based on 365 days' sampling except at Silver City Highway; [b]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days' sampling); [c]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days' sampling); [d]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018 (120 days' sampling).

[§]Samplers installed 3 October 2017 (95 days' sampling in Year 1).

The D-HVAS data show that there has been a consistent trend in Sector A and B lead levels across all four monitoring periods over the past three years. In the current monitoring period, the Sector A median ambient lead levels at Sewerage Pumping Station and Silver City Highway increased by 22% and 31% compared to the previous monitoring period in Year 2. The relative Sector A and B lead levels at each site have also been consistently higher in Sector A compared to Sector B.

The Silver City Highway site recorded the highest ambient lead concentrations and lead-in-TSP levels consistently both in Sector A and B from the beginning of the BHELS monitoring program. The monthly DDG results from the Silver City Highway site confirms the high lead levels measured by the D-HVAS.

Given the consistency of the lead measurements over the past three years, the future of the continuous monitoring program needs to be considered. It was recommended in 2020 that a monitoring network be implemented that is compliant with the Ambient Air Quality National Environment Protection Measure (AAQ NEPM)[1]. This network will assess community exposure and allow comparison with the health standard for lead.

AAQ NEPM compliant sampling requires sampling and analysis of TSP and lead for 24 hours every sixth day (i.e., 1 day in 6). The NEPM goal for lead is 0.5 µg/m^3 based on the mean of lead concentrations over a calendar year. The network would make use of the instruments purchased for the BHELS study and would only require on-going operational and analysis costs.

[1]National Environment Protection (Ambient Air Quality) Measure as amended, National Environment Protection Council, 7 July 2003, Canberra.
https://www.legislation.gov.au/Details/C2004H03935 - refer Schedule 2, Standards and Goals.

1 Introduction

Mining activities are major sources of different types of contaminants that can affect the prevailing air quality of the surrounding and downwind areas. Dust and contaminated particles can be produced during mining operations resulting in air pollution events. The impact of airborne particles on human health depends on particle size and chemical composition. Of particular interest here is the presence of heavy metals, such as lead and arsenic, in the aerosols produced by the mining activities.

Broken Hill is an inland mining city with one of the world's largest silver, lead, zinc minerals deposits. The Broken Hill study area is known for accommodating one of the largest lead mining operations in the region including exploration, processing and transport. Lead is the most ubiquitous pollutant in Broken Hill that has been widely investigated to identify the contributions of local sources to the observed lead pollution occurring in the area.

The aim of the Broken Hill Environmental Lead Study (BHELS) study is to assess the relative contribution of emissions of lead-bearing total suspended particles (TSP) from mining areas compared with emissions from non-mining areas of Broken Hill. The outcomes from the study will help direct future efforts to reduce community lead exposure.

The BHELS was commissioned by the EPA in early 2016 to inform remediation efforts in progress as part of the Broken Hill Environmental Lead Program (BHELP).

The first year of the study was conducted between 6 January 2017 to 16 January 2018. The trends in ambient lead levels at 5 sites across Broken Hill were reported in the Year 1 report. The Year 1 report also details the study design, choice of dust sampler, monitoring site locations, and QA/QC procedures. The second year of the study was conducted between 16 January 2018 to 20 February 2019. The trends in ambient lead levels at 5 sites are reported in the Year 2 report and compared with the findings of Year 1 report. The sector arcs were adjusted during Year 2 sampling for some of the D-HVAS to better differentiate lead bearing TSP from mining and non-mining areas in Broken Hill.

Ambient lead levels for the third year of the study cover period from 27 February 2019 to 10 March 2020 are reported in this Year 3 report.

Table 1 describes the BHELS timeline.

This Year 3 report provides an update of the trends in lead levels. For further details on the study, the reader is referred to the Year 1 and Year 2 reports[2,3].

[2] Broken Hill Environmental Lead Study (BHELS) Year 1 Report, Office of Environment and Heritage, September 2018.

[3] Broken Hill Environmental Lead Study (BHELS) Year 2 Report, Office of Environment and Heritage, July 2019.

Table 3 BHELS timeline.

Activity	Timeline
Project inception and study design	Feb – May 2016
Installed and commissioned wind directional high-volume air samplers (D-HVAS or 'Hi-Vols'), developed SOP and maintenance program, data QA/QC protocols	May – Dec 2016
Lead data collection and analysis with annual assessment of results and trends. In 2017 a pilot study was conducted by Macquarie University to apply SEM techniques to differentiate lead-bearing particles.	Jan 2017 – Jan 2020
Completion of Year 1 report including external peer-review and adoption of BHELP comments	Sept 2018
Completion of the Year 2 report including external peer-review	July 2019
Year 3 mid-year review and future outlook	November 2019
Completion of the Year 3 report	February 2021

1.1 The BHELS Sampling Program

TSP has been measured at 5 locations across Broken Hill over the period 27 February 2019 to 10 March 2020. The wind sectors were unchanged in the Year 3 monitoring period from the previous sampling period in Year 2 (post-sector change). The sampling methods and site descriptions have been described in detail in the Year 1 and Year 2 reports.

Figure 1 shows the locations of the 5 sampling sites in Broken Hill. The National Parks site was established to monitor any lead-bearing TSP transported northwards from the vicinity of the Rasp Mine as well as lead-bearing TSP transported south from residential north Broken Hill. The Waterboard site monitors lead-bearing TSP transported south from the vicinity of the Rasp Mine.

The Wetlands site was established to monitor lead bearing TSP from the Rasp Mine and the North Mine. During the Year 1 and 2 study periods, the North Mine was not operational but in Year 3 it was. The Sewerage Pumping Station site was established to monitor lead-bearing TSP transported northwards from Perilya Southern Operations (PSO) and southwards from north residential Broken Hill. The PSO lease includes partially revegetated tailings storage facilities known as Sites A, B, C and D as well as on-site underground lead extraction, a run-off mine lead stockpile, lead processing and rail loading facilities.

The Silver City Highway site was established 600 m south-east of PSO to monitor lead bearing TSP transported easterly and south-easterly from PSO as well as westerly from south residential Broken Hill.

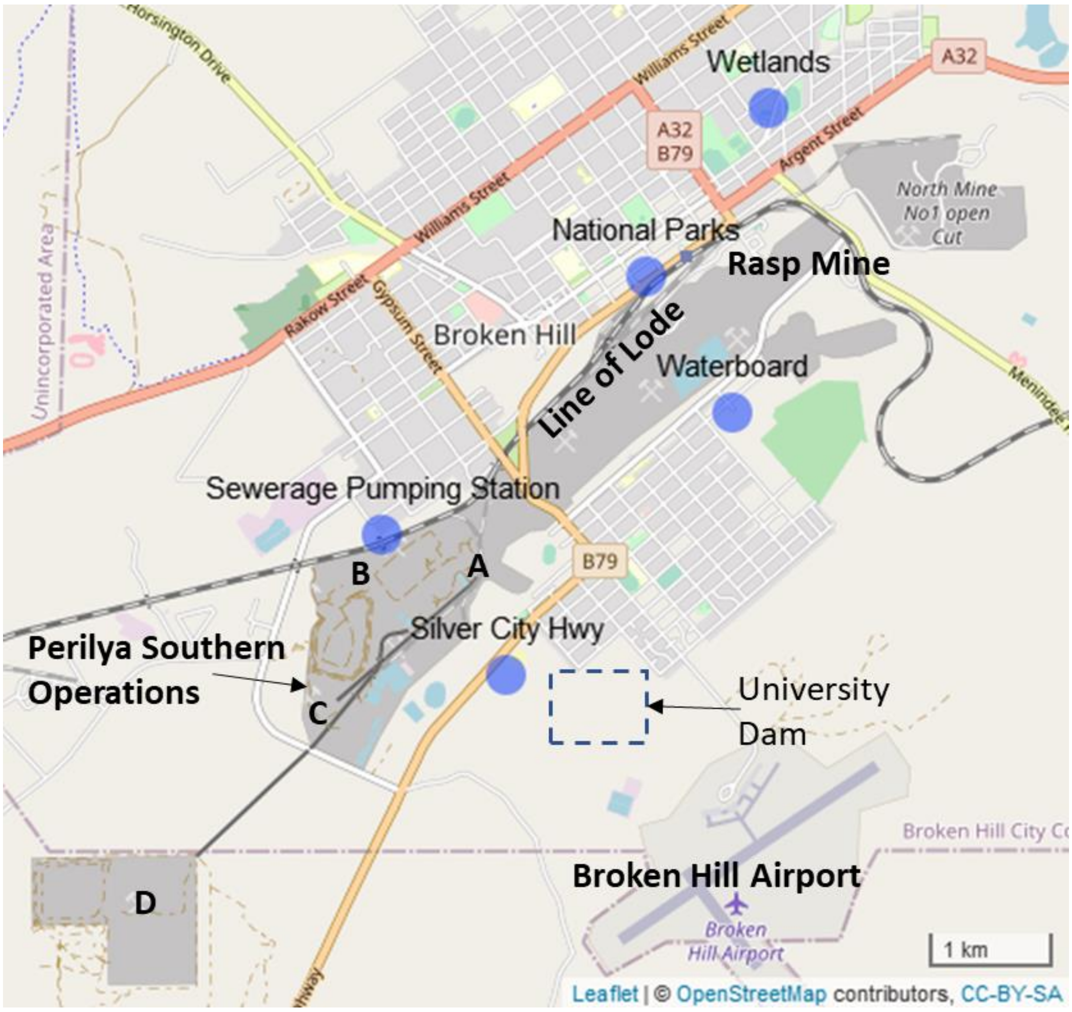

Figure 1 Sampling site locations around Broken Hill indicated by the blue dots. A, B, C, and D represents tailings storage facilities for the Perilya Southern Operations (PSO).

1.2 Sampling Methodology

The sampling methodology has been described in detail in the Year 1 and year 2 report. Therefore, only a brief summary has been provided in this report.

Wind-directional high-volume samplers (D-HVAS) have been employed to collect TSP on glass fibre filters. The D-HVAS sampling collects particles with equivalent aerodynamic diameters in the range 0.1-100 µm.

Two samplers are located at each sampling site. One samples in a sector of wind directions downwind of potential sources of lead-bearing TSP such as mining sites (called Sector A samplers in this report). The other samples in predominantly non-mining sectors (called Sector B). Each D-HVAS has a wind sensor located about 2 m above ground level to measure local wind speed and direction. The D-HVAS have been set up to operate only when the wind speed exceeds 0.2 m/s and the wind blows from a pre-defined wind sector for a minimum of 90 seconds. These parameters were established and documented in the Year 1 report.

Filters are collected every 7 days and sent to an external laboratory for lead analysis. The samples are invalidated if the D-HVAS operates for less than 8 hours per 7 days. The samplers have a maximum flow rate of 80 m^3/hr.

Appendix A details the number of valid and invalid samples at each site and the reasons for invalidation.

It should be noted that because of the conditions imposed here on the D-HVAS operation, the lead sampling carried out under the BHELS is not compliant with Ambient Air Quality - National Environment Protection Measure (AAQ-NEPM) sampling as AAQ-NEPM sampling is based on 24-hour sampling every sixth day. The NEPM standard is 0.5 µg/m^3 based on the arithmetic mean of lead concentrations over a calendar year.

The wind sector for Sector A and Sector B at each site in the year 3 report has remained same as described in the Year 2 report's post-sector change. The wind sectors for the Year 3 report are summarized below. They are shown graphically in Section 4 which discusses the results from each site.

National Parks

- Sector A: 60°- 225°
- Sector B: 245°- 30°

Wetlands

- Sector A: 75°- 220°
- Sector B: 260°- 30°

Waterboard

- Sector A: 220°- 70°
- Sector B: 90°- 205°

Sewerage Pumping Station

- Sector A: 130°- 230°
- Sector B: 260°- 30°

Silver City Highway

- Sector A: 225°- 40°
- Sector B: 60°- 200°

2 Meteorology and Climate in 2019

The meteorology and weather pattern in the Broken Hill were described in the Year 1 and 2 reports by analysing Bureau of Meteorology (BoM) Broken Hill Airport site data. The Broken Hill climate is essentially a hot and dry with several dust storm events per year. Winters are relatively mild and dry, while the summers are relatively hot and dry.

2.1 Wind Flow Patterns in Broken Hill

The long term (2000-2017), 2017, 2018, and 2019 wind speed and wind direction measured at Broken Hill Airport Automatic Weather Station (AWS) and are shown in the wind rose diagrams in the Figure 2. The long-term average wind speed in 2000-2017, 2017, 2018, and 2019 was 4.77, 4.88, 4.96, and 5.12 m/s, respectively. The annual average wind speed in 2019 was higher than 2017 and 2018, and about 7% higher than the long-term average (2000-2017). For instance, the annual average wind speed in 2019 was about 6.73% higher than the long term average (2000-2017).

The regional wind flow direction was generally from the south- south west, the south, the south-south east and the north-east. The most frequent winds are south-south west and south-south east with some north-north east; the strongest winds are in the south-west sector. Figure 2 shows that the wind direction pattern in 2019 was similar to previous years. The stronger and more frequent winds from the south and south west place the northern part of the Broken Hill township downwind of the Line of Lode (LoL).

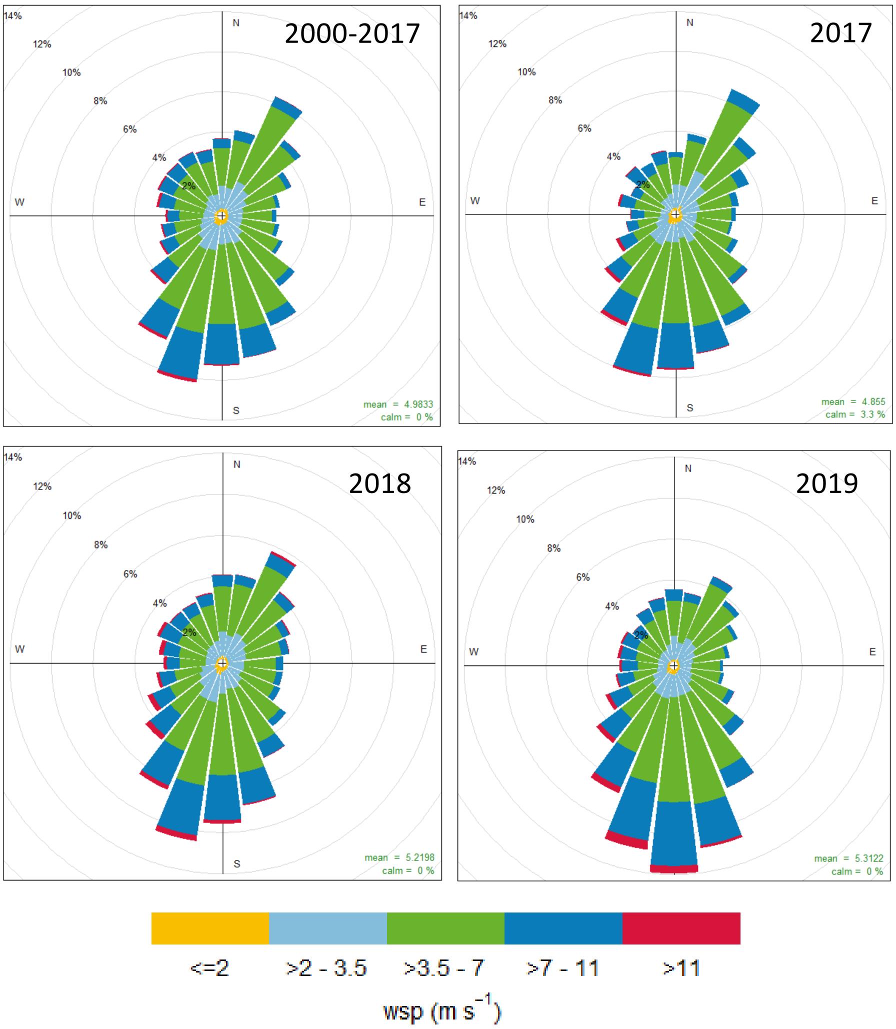

Figure 2 **Long-term (2000-2017), 2017, 2018 and 2019 wind rose for Broken Hill Airport AWS.**

2.2 Trends in Ambient Temperature

Figure 3 shows the monthly mean maximum temperatures measured at Broken Hill Airport AWS from 1960 to 2017 and the maximum monthly temperatures in 2017, 2018 and 2019. The average of the monthly maximum temperatures during Summer 2019 was higher by 3.3°C, 1.5°C, and 0.47°C compared to those recorded in 2017, 2018 and long-term average (1960-2017), respectively. The maximum monthly temperature was 38.3°C in January 2019, which was higher by 2.2°C, 1.5°C and 4.7°C than those measured in 2017, 2018, and the long-term average, respectively. The maximum temperatures in 2017, 2018 and 2019 were above the long-term average for the most months.

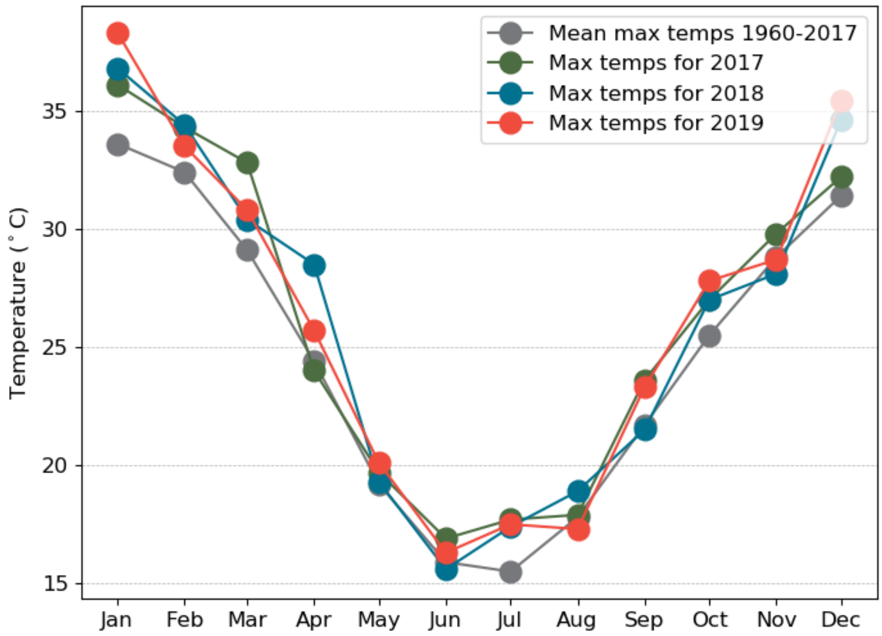

Figure 3 **Long term (1960-2017) mean monthly maximum temperatures, and 2017, 2018 and 2019 maximum monthly temperatures at Broken Hill Airport AWS.**

2.3 Trends in Annual Rainfall

Figure 4 shows the total annual rainfall from 1997 to 2019 measured at Broken Hill Airport AWS.

The annual rainfall was 68 mm in 2019 which was the lowest since 1997 (Figure 4). The annual rainfall decreased by more than five-times in 2019 compared to the annual rainfall in 2016. The annual total rainfalls in 2017, 2018, and 2019 were lower by 120 mm, 133 mm, and 161 mm than the 1997-2018 average of 229 mm, respectively.

Figure 5 compares the 2017, 2018, and 2019 monthly total rainfall to the average and maximum monthly rainfall over 1997-2019.

In 2017–2019, while the monthly average rainfall in the dry months (May to August) were similar, there were variations in the rainfall during the wet months (October to December). The rainfall during the 2019 wet months was significantly lower than in 2017 and 2018. The wettest month in 2019 was March with 19.2 mm of rain.

The monthly average rainfall during 2017-2019 was mostly below the long-term monthly averages, except April and November in 2017, October and November in 2019, and March 2019. Figure 5 shows that during most months of 2019 the rainfall was significantly lower compared to 2017, 2018 and the long-term average.

Due to the prevailing hot and dry conditions and higher annual average wind speed, Broken Hill experienced more dust storms in 2019 compared with 2017 and 2018.

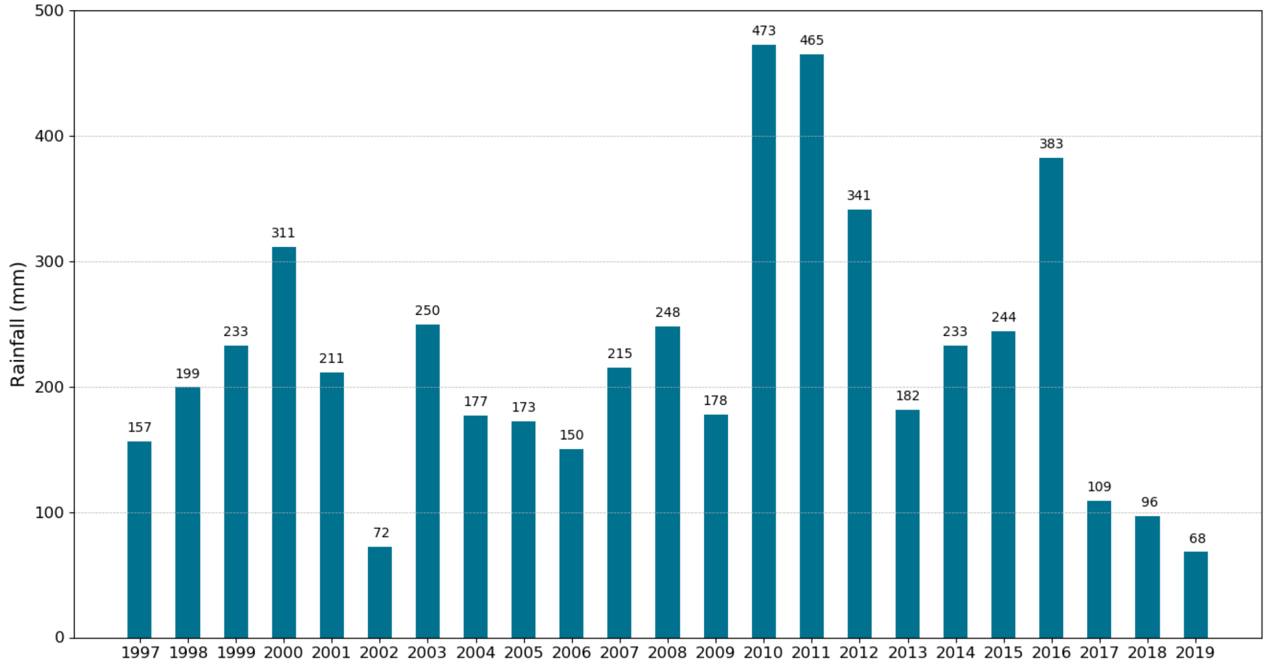

Figure 4 Annual rainfall over the 1997–2019 period measured at Broken Hill Airport.

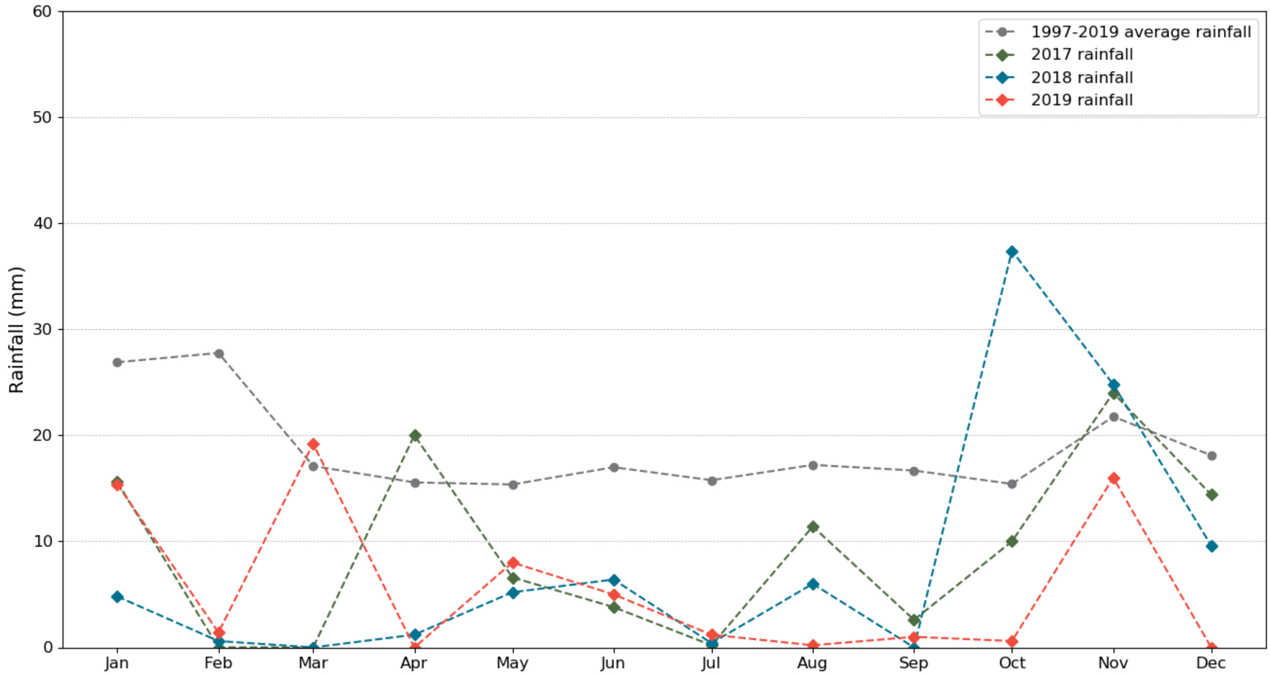

Figure 5 Monthly total rainfall in 2017, 2018 and 2019 compared to the 1997-2019 monthly average and maximum monthly rainfall measured at Broken Hill Airport.

3 Results

This section presents the ambient concentrations of total suspended particles (TSP) in the units of microgram per cubic metre (μg/m^3), ambient lead concentrations in μg/m^3, the lead-in-TSP mass fractions or lead-in-TSP in mg/kg, and total lead mass in milligram (mg) at each site by sampling sector for Year 3. As presented in Year 1 and Year 2 reports, there was no correlation between elevated ambient TSP and ambient lead concentration. However, elevated ambient TSP concentration has a relatively strong influence on lead-in-TSP levels. Similar results were also found in Year 3, indicating high TSP levels are generally caused by regional dust storms driven by synoptic winds which transports dust with low lead levels into the Broken Hill sites.

3.1 Measures of lead levels

Lead concentration was calculated and presented in this study in three different methods. The first measures the lead concentration in ambient air, which estimates the mass of lead in a volume of ambient air collected at a particular sampling location. The lead and TSP samples are collected on glass fibre filters at each site by sector over a week and then the samples were transferred to an external laboratory for chemical analysis. The measured lead concentration is a weekly average based on the total mass of lead collected on a filter divided by the total air passing through the sampler in a given week. The weekly average concentration of ambient lead was calculated at each site by sector, which quantified the mass of lead in a volume of air that has moved over a mining (Sector A) or a non-mining (Sector B) area and then subsequently passed over the monitoring sites. The unit of this measurement is μg/m^3.

The second measure used in this study is the lead-in-TSP mass fraction. The measure is based on total mass of lead divided by the total mass of TSP measured per week. The weekly average concentration of the lead-in-TSP mass fraction is a measure of the lead richness of the TSP. The unit of this measurement is milligram of lead per kilogram of TSP, which has been presented in this report as mg/kg. Like the ambient lead concentration, generally the lead-in-TSP mass fraction was higher in Sector A than in Sector B, although the relative differences were dependent on the position of the sampling sites in relation to mining sites. A key point is that ambient Pb mass is equal to the product of TSP and the Pb-in-TSP mass fraction. In general, the Pb-in-TSP is the dominant factor.

This study's third measure is the total lead mass (mg) obtained from all valid samples at each site by sector.

3.2 TSP, lead concentration, mass fraction and total mass in Year 3

Figure 6 presents boxplots of the ambient TSP levels, ambient lead concentration and lead mass fraction. The left and right whiskers show the minimum and maximum values, the left- and right-hand end of the box show the first and third quartile values respectively, and the black vertical lines show the median values. The maximum and minimum values in the boxplots are determined by a predefined formula based in interquartile range (the difference between first and third quartile). The hollow circles are outside of the maximum and minimum values and defined as the boxplots' outlier values.

The median TSP concentrations ranged between 38 and 88 μg/m^3 at Sector A and 26 and 112 μg/m^3 at Sector B. The significant variation in median concentration was due to the impacts of dust storm episodes as well as elevated local dust. The median TSP concentration for Sector B was on average 35% higher than Sector A at all sites except Waterboard site. The Sector B concentration at the Waterboard site was 26 µg/m^3 which is about 72% lower than the Sector A. The maximum median TSP concentration was 112 µg/m^3 at Sector B at Silver City Highway site.

Figure 6 Boxplot of weekly average TSP levels (top), ambient lead (Pb) concentrations (middle) and Pb mass fraction (bottom) at all sites.

The highest weekly median ambient lead concentration among all sites and sectors was 0.91 µg/m^3 measured at the Silver City Highway site (Figure 6). The Year 1 and Year 2 reports also reported the highest lead concentration was found at the Silver City Highway site. The Silver City Highway site is located 600 m south of Perilya Southern Operations (PSO). Apart from the Silver City Highway site, the Sector A concentrations showed minimal variation, ranging between 0.08 (Wetlands) to 0.18 µg/m^3 (Sewerage Pumping Station). As expected, the median concentration for Sector A was on average 50% higher than Sector B. However, on a weekly time scale, lead levels in Sector B could be higher than in Sector A. This will be discussed in the analysis of high lead episodes for each site later in this report. Sector B lead-in-TSP levels were 4%, 6%, 9% of time higher than Sector A at National Parks, Sewerage Pumping Station, and Waterboard station, respectively. Sector B lead-in-TSP levels at Wetlands station did not exceed the levels in Sector A. Ambient lead concentrations were 30%, 6%, 4%, and 9% of time higher in Sector B than in Sector A at National Parks, Sewerage Pumping Station, and Waterboard and Wetlands station, respectively. Silver City Highway site did not record any data where lead levels are higher in Sector B than in Sector A.

Like the ambient lead concentration, the lead mass fraction was also higher in Sector A than Sector B at all sites. The median lead mass fraction for the Sector A and Sector B ranged between 2,298 (Wetlands) – 10,822 mg/kg (Silver City Highway); and 565 (Wetlands) – 2,109 mg/kg (Silver City Highway), respectively. The median lead mass fraction was approximately 70% higher in Sector A than in Sector B.

However, as described in the Year 2 report, the high Sector B lead mass fractions indicate that lead rich TSP has likely deposited at some time (recently and historically) in residential north and south Broken Hill. The deposition pattern is not even in these residential areas – lead concentration gradients would be expected depending on how close a residential area is to a mine or the Line of Lode, and the direction of prevailing winds in a residential area.

A 2019 Interim report[4] presented topsoil measurements in the vicinity of the Silver City Highway site. High topsoil lead was found close (1-200 m) from the sampling site with lead levels decreasing further out from the mine. It is likely that lead-bearing TSP that is deposited relatively close to the mine (by W and SW and NW winds) is subsequently being resuspended (and mixed with other dust) and transported in a SW direction by NE winds giving rise to relatively high Sector B lead levels. Topsoil measurement have not been performed at the other sampling sites so we surmise that similar lead deposition patterns can be inferred from the direction of prevailing winds and distance from mines and the Line of Lode.

In the case of Silver City Highway, it is clear from Figure 6 that the ambient lead concentration and mass fraction in Sector A was much higher than in Sector B, the major limitation in the comparison was that there were only 2.7 days of valid sampling data for Sector B (Figure 7). Nonetheless, the total lead mass measured in Sector A at the Silver City Highway site was on average more than three times higher compared to the National Parks, Sewerage Pumping Station and Waterboard sites; and more than five-times higher compared with the Wetlands site, indicating elevated lead levels close to Perilya Southern Operations, decreasing to low levels in the western part of residential south Broken Hill as found in topsoil measurement described in the 2019 Interim report.

It should be noted that at three sites, namely National Parks, Wetlands and Waterboard, the sector B winds were northerly. Silver City Highway had very few Sector B data, and the differences between Sector A and B were much smaller at the Waterboard site.

[4] 2019 BHELS Interim Report, NSW DPIE, November 2019.

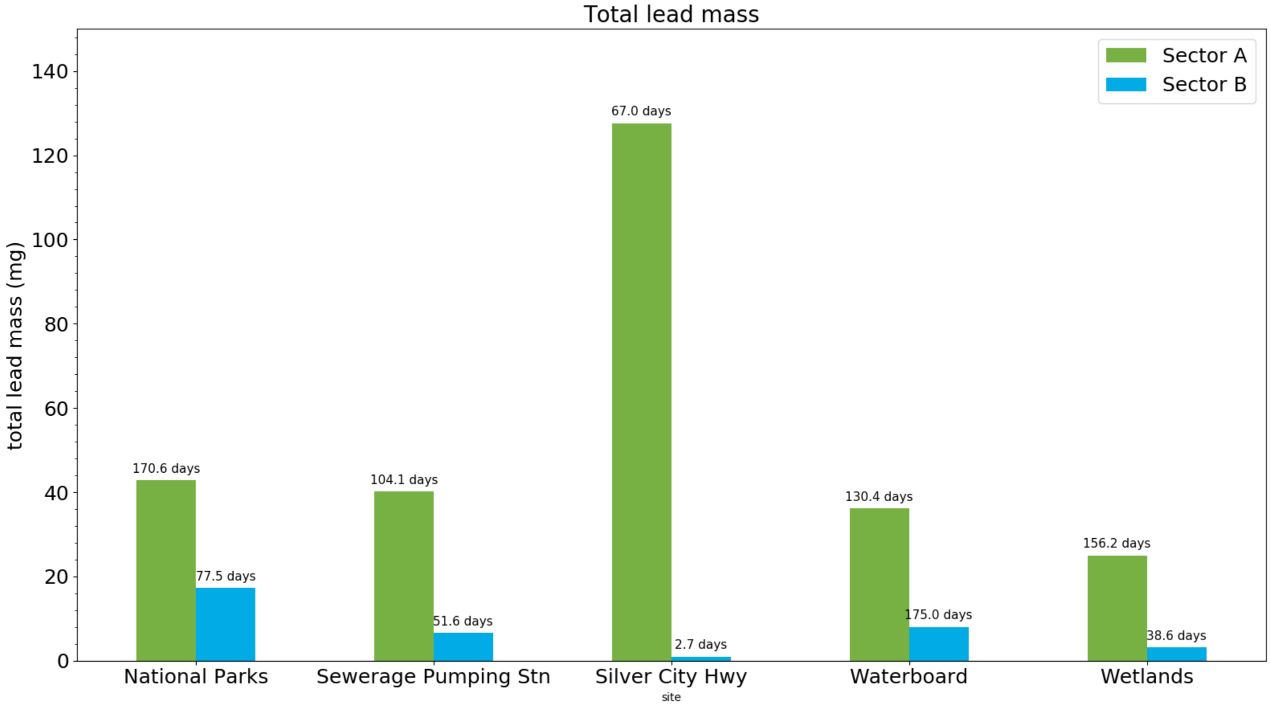

Figure 7 Total lead mass measured at each site. The number of days' of valid sampling in each sector is shown above each bar.

3.3 Lead levels and analysis of high lead episodes

3.3.1 Results: National Parks site

The National Parks site is located 250 m north east of the rail corridor and 400 north east of the LoL.

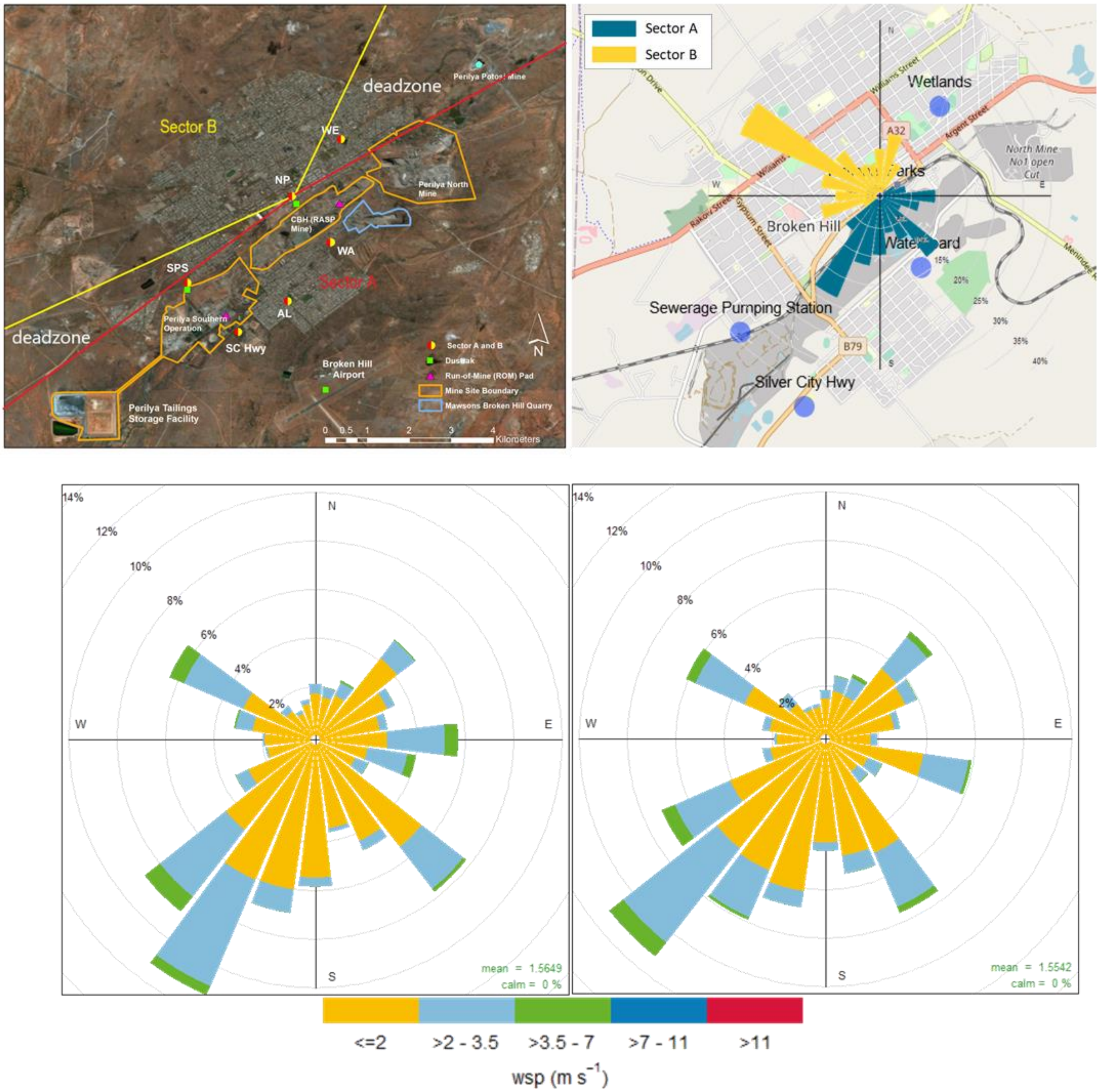

Figure 8 National Parks office site. Top panel: wind sampling sectors on the left; all wind directions coinciding with Sector A and B sampling on the right. Bottom panel: complete wind roses recorded by the Sector A (left) and Sector B (right) D-HVAS anemometers.

The local wind patterns are influenced by the mine overburden dumps and nearby buildings. The complete wind roses in Figure 8 show the winds were predominantly from the south west, south east and north east. The wind patterns were influenced by the overburden dumps along with the Line of Lode with airflow aligned south-west to north-east, parallel to these features. There is also a north-westerly lobe, the predominant direction for Sector B winds. The similar wind flow patterns were also reported in the Year 1 and Year 2 report. As the samplers are placed on the National Park building roof, the airflow may also be influenced by any turbulence created by nearby buildings.

The total number of valid sampling days was 171 days for Sector A and 77 days for Sector B. As presented in Appendix A, the total number of valid filter samples was 52 for Sector A and 43 for Sector B. The total number of invalid samples for Sector B was higher due to low sampling times.

Figure 9 shows that the weekly average ambient TSP concentrations were significantly higher between November 2019 to February 2020, indicating the impact of local and regional dust storms. The highest number of TSP levels were recorded at Sector B during October 2019 to February 2020 as a result of Sector B winds from the north east and north west. However, lead-in-TSP peaks were predominantly from Sector A. There are 30% of time ambient lead concentration was higher in Sector A.

The median ambient Pb concentration in Sector A and Sector B were 0.14 and 0.09 µg/m^3 respectively. The median lead-in-TSP levels in Sector A and Sector B were 2,361 and 1,349 mg/kg. In general, when the samplers were downwind of the mining sites and the rail corridor, the lead-in-TSP levels were relatively high. The ambient lead concentrations in Sector B were mostly higher than Sector A during elevated TSP concentrations, from November 2019 to February 2020, indicating existence lead-rich TSP in north Broken Hill, likely in the vicinity of the National Parks building which is ~2-300 m away from the Rasp Mine.

The episode analyses below provide more specific information on the sources of lead measured at the National Parks site.

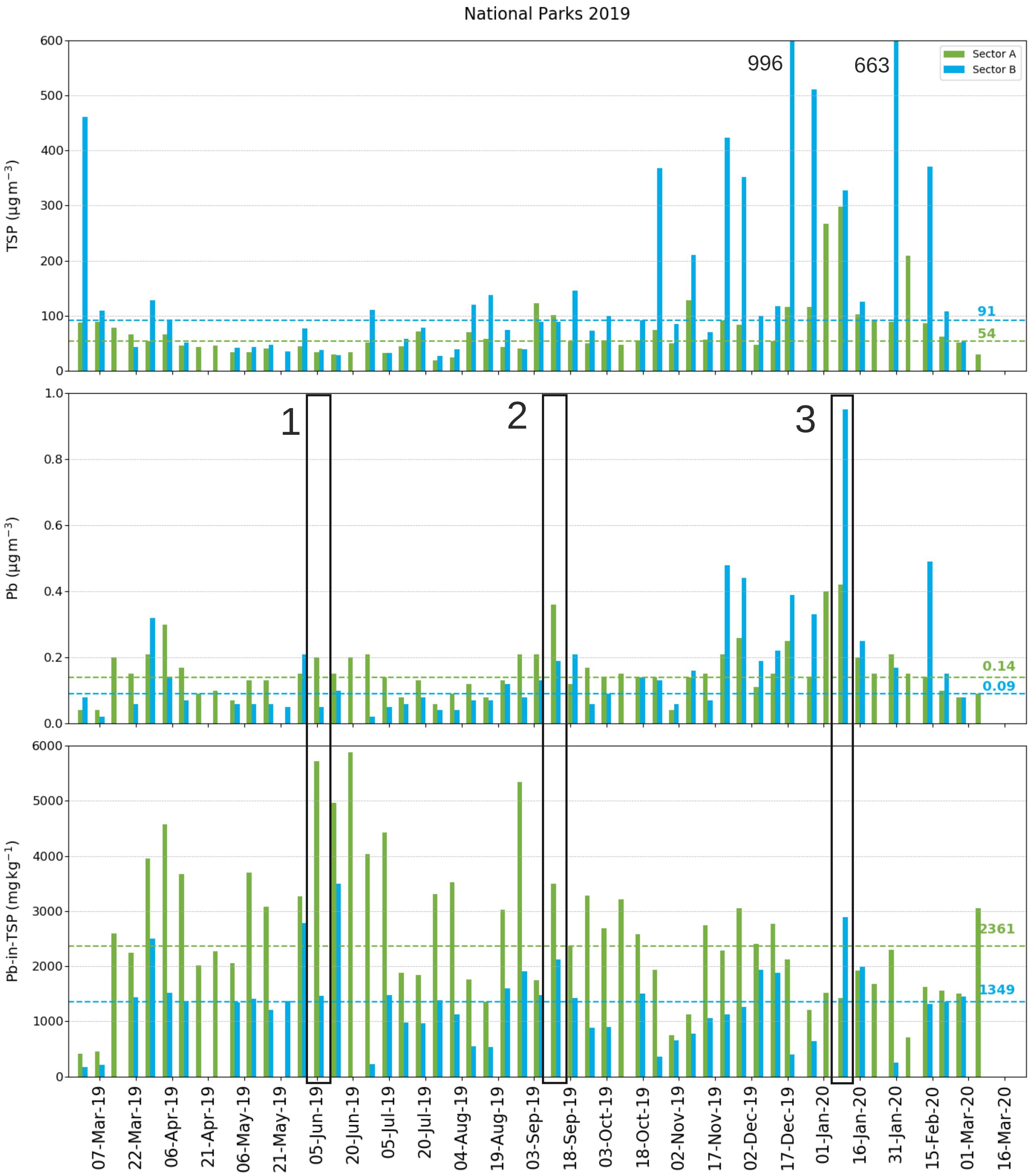

Figure 9 Weekly TSP concentration, ambient lead concentration and lead-in-TSP mass fraction measured at National Park site. The dashed lines represent overall median concentration and the vertical boxes represent high lead episodes.

Episode 1 at National Parks, 5 – 12 June 2019.

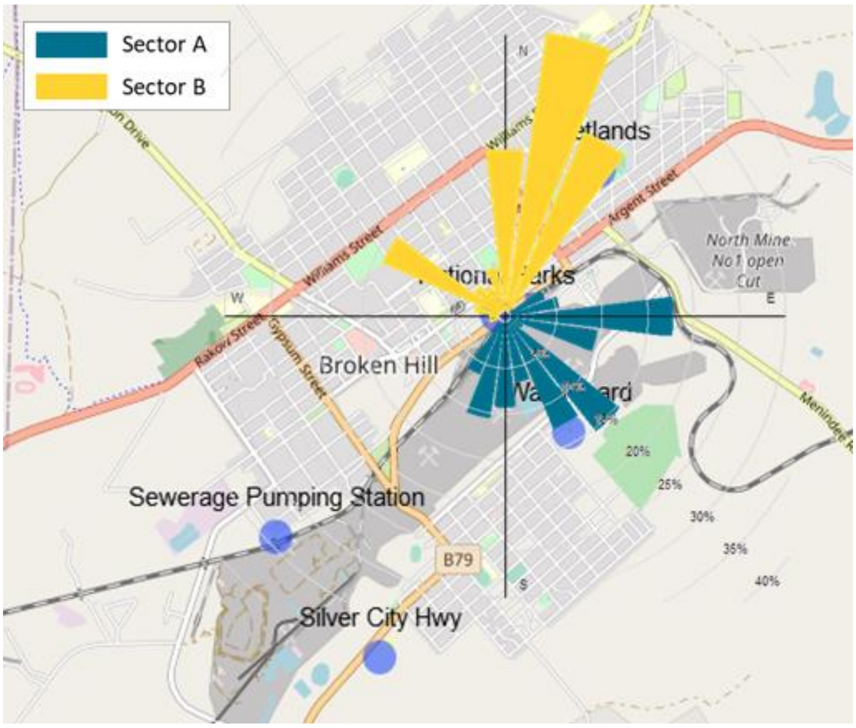

Figure 10 Wind direction coinciding with Sector A and Sector B at the National Park site during 5-12 June 2019.

This episode was selected considering the second highest lead-in-TSP level in Sector A. Figure 10 shows that the south-east, south-west and easterly winds in Sector A during 5 – 12 June 2019 placed the sampler downwind of the Rasp Mine, North Mine and railway line. The Sector B winds were predominantly northerly placing the sampler downwind of residential north Broken Hill.

During this episode:

- Weekly average ambient TSP concentrations were relatively low and similar in both sectors: 34.2 µg/m^3 for Sector A and 37.5 µg/m^3 for Sector B.
- Weekly average ambient lead concentrations were 0.2 and 0.05 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 5,722 and 1,459 mg/kg for Sector A and Sector B respectively.

While the TSP levels were similar in both sectors, ambient lead and lead-in-TSP levels were approximately four-times higher in Sector A compared to Sector B, indicating the strong influence of nearby mining activities.

Episode 2 at National Parks, 11 – 18 September 2019.

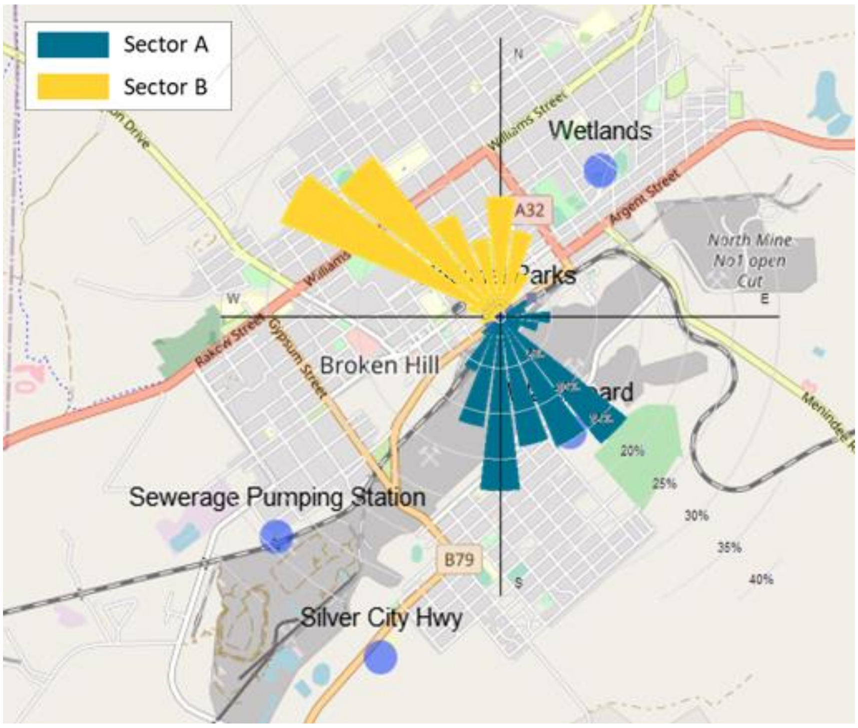

Figure 11 Wind direction coinciding with Sector A and Sector B at the National Park site during 11-18 September 2019.

This episode was selected considering elevated lead-in-TSP levels and ambient lead concentrations and relatively low TSP levels in both Sectors A and B. Figure 11 shows the south to south-easterly winds in Sector A placed the sampler downwind of the Rasp mine and railway, which is slightly different from Episode 1. The frequency of Sector B winds was predominantly west to north-westerly placing the sampler downwind of western part of north Broken Hill.

During this episode:

- Weekly average ambient TSP concentrations were 101.6 and 89.6 µg/m^3 in Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.36 and 0.19 µg/m^3 in Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 3,498 and 2,122 mg/kg in Sector A and Sector B respectively.

The weekly average ambient lead and lead-in-TSP levels were about two-times higher in Sector A compared to Sector B, indicating the influence of nearby mining activities. The lead levels in Sector B were about four-times higher in Episode 2 compared to Episode 1. The Sector B wind frequency in Episode 2 was mostly north-westerly; whereas winds were mostly north-easterly during Episode 1. Although Sector B was downwind of residential north Broken Hill and non-mining areas in both episodes 1 and 2, the reason for the hight is likely that the north-westerly winds are associated with higher lead concentration in Sector B is unknownlevels compared to north-easterly wind.

Episode 3 at National Parks, 8 – 15 January 2020

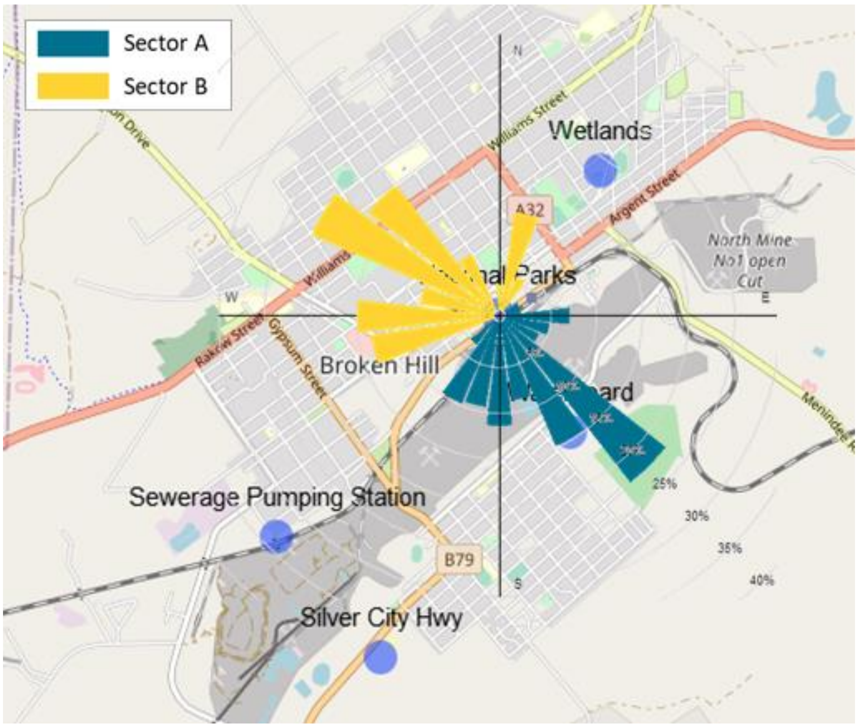

Figure 12 Wind direction coinciding with Sector A and Sector B at the National Park site during 8-15 January 2020.

This episode was selected considering the highest ambient lead concentration in Sector B as well as the significantly higher lead levels in Sector B than in Sector A. Figure 12 shows that the predominant Sector A wind was south, south-east and south-westerly placing the sampler downwind of the Rasp Mine and railway line. The Sector B winds were predominantly north-westerly.

During this episode:

- Weekly average ambient TSP concentrations were relatively high due to smoke haze: 298 µg/m^3 for Sector A and 328 µg/m^3 for Sector B.
- Weekly average ambient lead concentrations were 0.42 and 0.95 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP were 1,426 and 2,892 mg/kg for Sector A and Sector B respectively.

The weekly average ambient lead concentration in Sector B was twice as high as in Sector A during this episode; and more than 10 times higher than the overall median ambient lead concentration during Year 3, which is also the highest weekly average lead level in Sector B. The reason for the high lead concentration in Sector B is unknown. The frequency of the wind direction in Sector B placed the site downwind of residential Broken Hill, similar to Episodes 1 and 2, yet the ambient lead concentrations in Sector B was nineteen times and five times higher in Episode 3 than in Episode 1 and 2, respectively.

3.3.2 Results: Wetlands site

The Wetlands site is approximately 1.4 km north east of the LoL and is much less influenced by terrain features compared to the National Parks site.

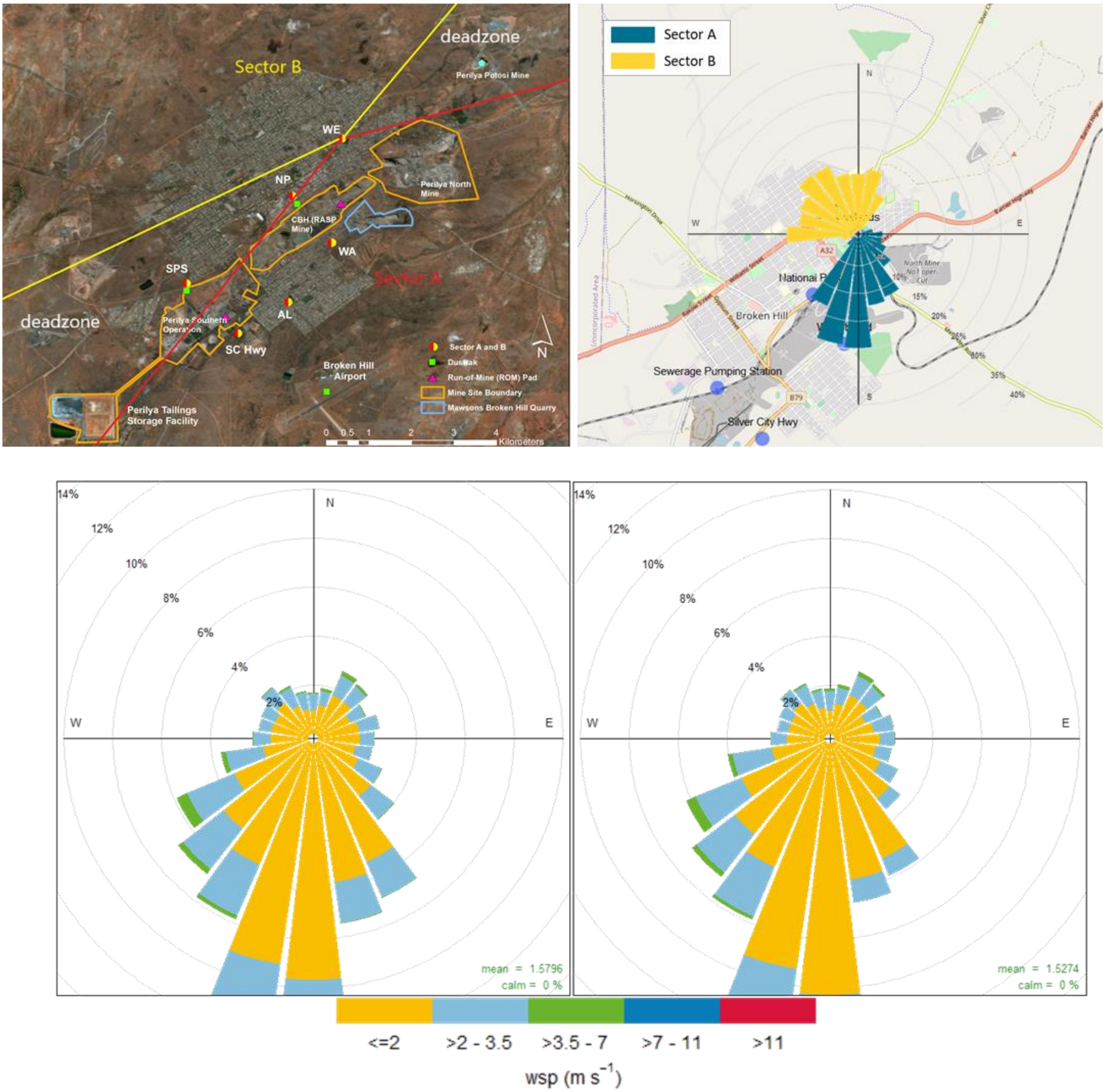

Figure 13 **Wetlands site. Top panel: wind sampling sectors on the left; all wind directions coinciding with Sector A and B sampling on the right. Bottom panel: complete wind roses recorded by the Sector A (left) and Sector B (right) D-HVAS anemometers.**

The complete wind roses in Figure 13 show the winds were predominantly south, south-west and south-easterly, similar to the wind pattern in the Year 2 report and the regional wind patterns observed at Broken Hill Airport as shown in Figure 2.

The Sector A wind sector in broad enough to capture lead bearing TSP emissions from the mining operations. The Sector B wind sector focuses on residential north Broken Hill.

The total number of valid sampling days were 130 days for Sector A and 175 days for Sector B. As presented in Appendix A, the total number of valid filter samples were 54 for Sector A and 38 for Sector B.

The median ambient Pb concentrations in Sector A and Sector B were 0.08 and 0.04 $\mu g/m^3$ respectively. The median lead-in-TSP levels in Sector A and Sector B were 2,298 and 565 mg/kg respectively. In general, the lead levels measured in both sectors were amongst the lowest of all the sampling sites. The Wetlands site is the farthest away from the major mining sources (the closest source is the Rasp mine which is 1.4 km to the south west), which is the most likely reason for the low lead levels observed at this site.

The episode analyses below provide more specific information on the sources of lead measured at the Wetlands site.

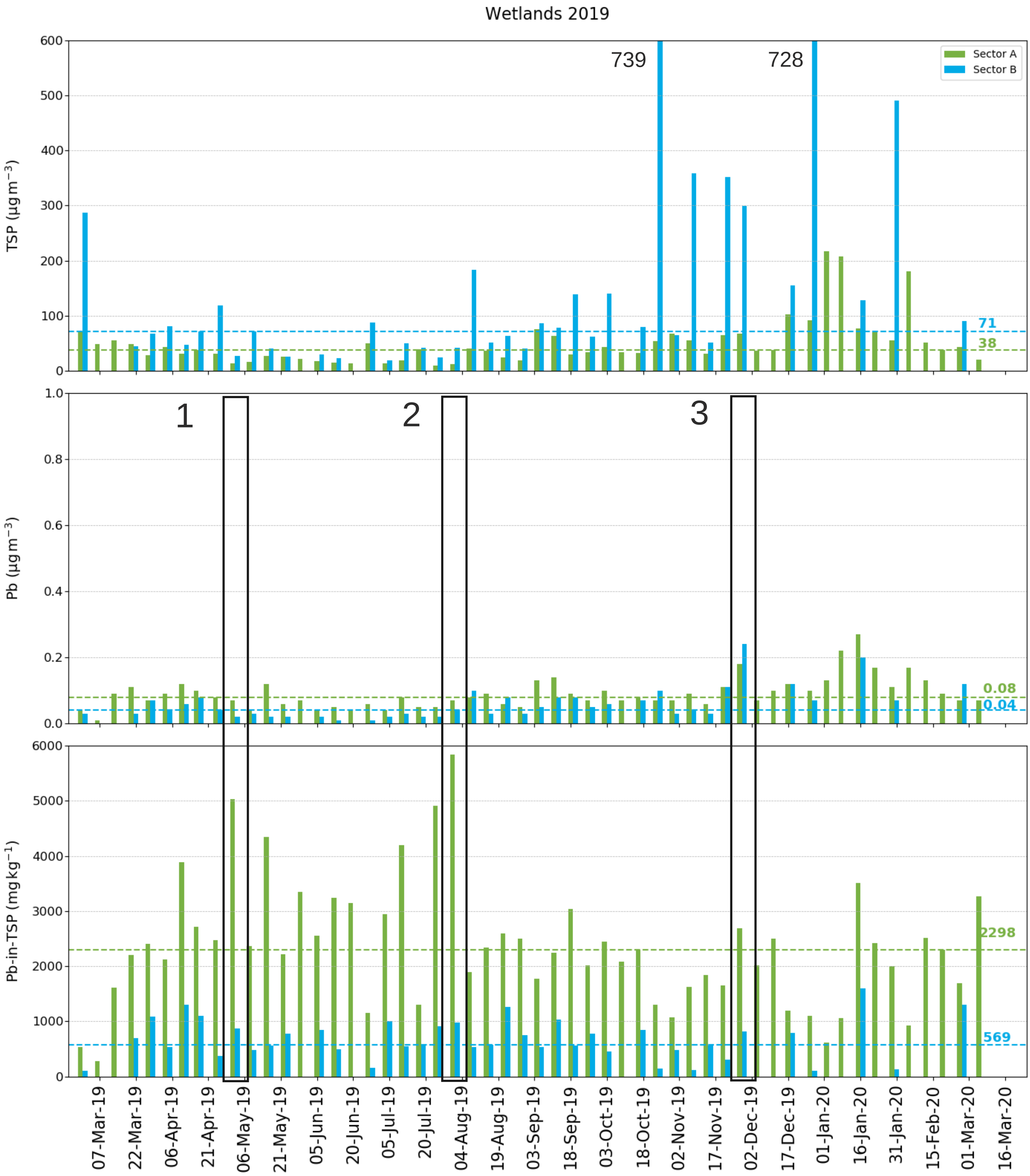

Figure 14 **Weekly TSP concentration, ambient lead concentration and lead-in-TSP mass fraction measured at Wetlands site. The dashed lines represent overall median concentration and the vertical boxes represent high lead episodes.**

Episode 1 at Wetlands, 1-8 May 2019

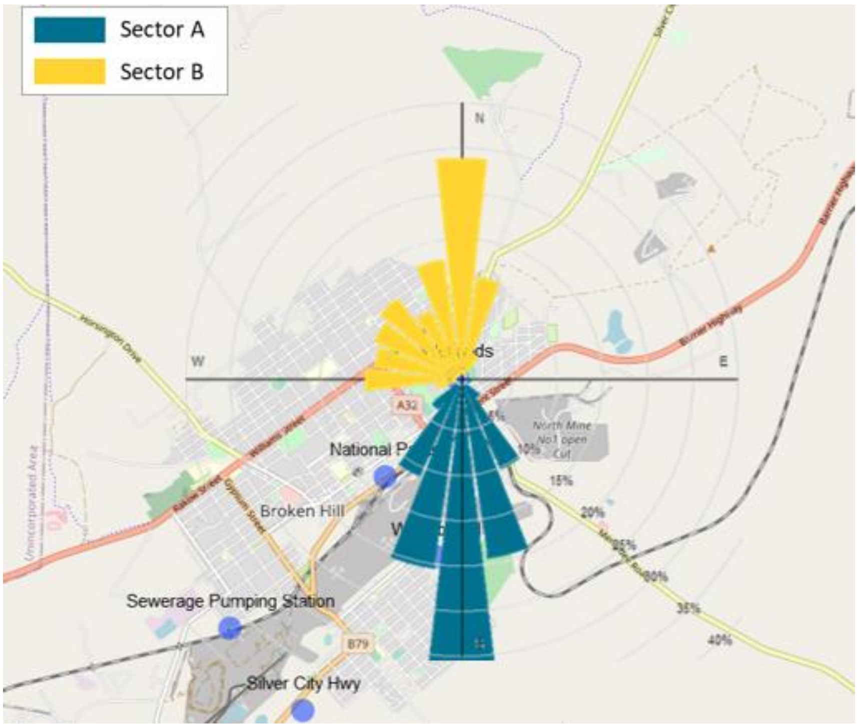

Figure 15 Wind direction coinciding with Sector A and Sector B at the Wetlands site during 1-8 May 2019.

This episode was selected considering the second highest lead-in-TSP in Sector A. Figure 15 shows that the Sector A winds were predominantly from the south-southwest and south-southeast, placing the sampler downwind of the rail corridor and Rasp Mine. The sector B winds were predominantly north westerly, placing the sampler downwind of residential north Broken Hill. No dust events were noted in the event log.

During this episode:

- Weekly average ambient TSP concentrations were 13.8 µg/m^3 for Sector A and 26.6 µg/m^3 for Sector B
- Weekly average ambient lead concentrations were 0.07 and 0.02 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 5,033 and 869 mg/kg for Sector A and Sector B respectively.

The ambient lead concentration was more than three times higher in Sector A compared to Sector B, and the lead-in-TSP was about six times higher in Sector A compared to Sector B. The higher lead levels in Sector A indicates the influence of mining activities. The ambient lead concentrations during this episode were lower than the overall site median concentrations, and the lead-in-TSP levels were higher than the site median levels, indicating the presence of a higher proportion of lead in the TSP samples during this episode. It is also highly likely that the lead-bearing coarse TSP was being transported by southerly winds passing over active mining sites (the northern part of the Rasp mine) and the railway ore loading areas and was being resuspended and mixed with other dust.

Episode 2 at Wetlands, 31 July – 07 August 2019

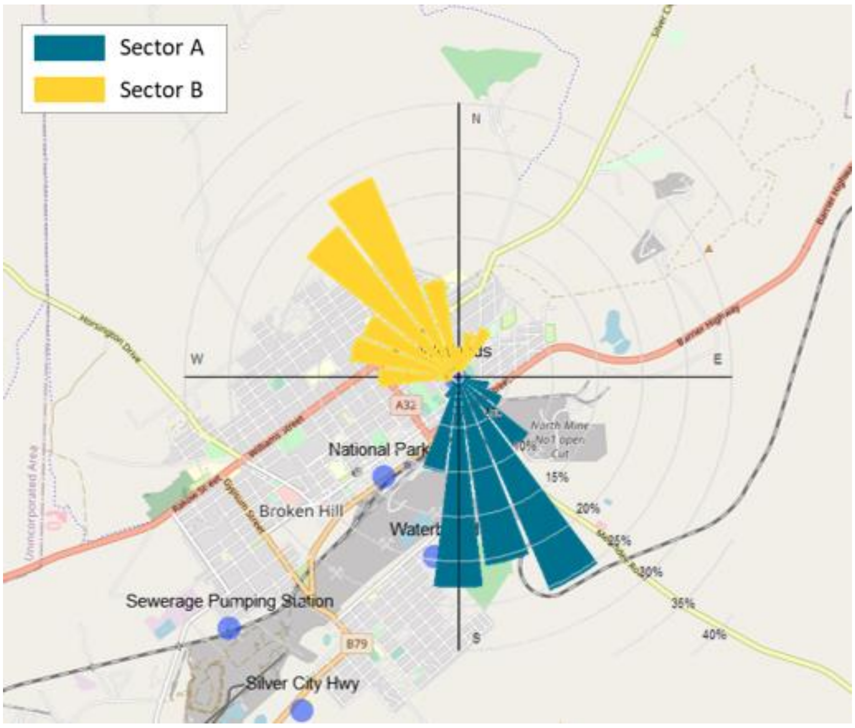

Figure 16. Wind direction coinciding with Sector A and Sector B at the Wetlands site during 31 July to 7 August 2019.

This episode was selected considering the highest lead-in-TSP level in Sector A. Figure 16 shows that the Sector A winds were predominantly from the south and south east, placing the sampler downwind of the rail corridor and Rasp Mine. The sector B winds were predominantly from the west and north west, placing the sampler downwind of residential north Broken Hill. No dust events were noted in the event log.

During this episode:

- Weekly average ambient TSP concentrations were relatively low: 12.4 µg/m^3 for Sector A and 41.8 µg/m^3 for Sector B
- Weekly average ambient lead concentrations were 0.07 and 0.04 µg/m^3 in Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 5,838 and 977 mg/kg in Sector A and Sector B respectively.

The ambient lead level was about two times higher in Sector A compared to Sector B, and the lead-in-TSP level was about six times higher in Sector A compared to Sector B. In spite of the relatively low overall Sector A median lead-in-TSP level, the site still recorded the highest Pb-in-TSP in Sector A for this week. The lead-in-TSP level was comparable to Episode 1 at the National Parks site which is closer to the Rasp Mine than the Wetlands site.

Note that although the overall Sector A median Pb-in-TSP level was the lowest of all sites (likely due to its distance from the North Mine), it was still comparable to median levels at the National Parks and Waterboard sites, which are much closer to mine sites and the LoL. This also applies to Sector B median levels.

The Sector A winds were from the south and south-east placing the sampler downwind of the Rasp Mine, indicating the lead bearing dust at Sector A was likely from mining activities. Sector B winds were from the north-west placing the sampler downwind of residential areas north of the sampler.

Therefore, it is highly likely that the lead-bearing TSP was deposited in north Broken Hill and then resuspended by the north westerly winds.

Episode 3 at Wetlands, 27 November – 4 December 2019

Figure 17. Wind direction coinciding with Sector A and Sector B at the Wetlands site during 27 November to 4 December 2019

This episode was selected considering the highest ambient lead concentration in Sector B, which had exceeded the Sector A concentration. Figure 17 shows that the Sector A winds were predominantly from the south and south west, placing the sampler downwind of the rail corridor and Rasp Mine. The sector B winds were predominantly from the west and west north west, placing the sampler downwind of the residential north Broken Hill. A dust storm was noted in the event log during this episode resulting in elevated local dust and reduced visibility.

During this episode:

- Weekly average ambient TSP concentrations were 68 and 300 µg/m^3 in Sector A and Sector B respectively.
- Weekly average ambient lead concentration was 0.18 and 0.24 µg/m^3 in Sector A and Sector B respectively.
- Weekly average lead-in-TSP were 2,688 and 817 mg/kg in Sector A and Sector B respectively.

During this episode, the highest weekly ambient lead concentration was recorded in Sector B, which is higher by 33% compared to Sector A. Sector B winds were from the west and west-north-west placing the sampler downwind of residential areas, similar to the Episode 1. Therefore, it is plausible that the lead-bearing TSP in Sector B that was deposited in the past was lifted by the north westerly winds during the dust storm event.

The ambient lead concentrations in Episode 3 were significantly higher in both sectors compared to the Episodes 1 and 2, reflecting the impact of turbulent winds associated with the dust storm during this episode. However, the lead-in-TSP in Sector B was more than three times lower compared to Sector A, which was most likely caused by the dilution of lead bearing dust by an influx of non-lead bearing dust.

3.3.3 Results: Waterboard site

The waterboard site is located on an elevated ground 500 m south west of the LoL.

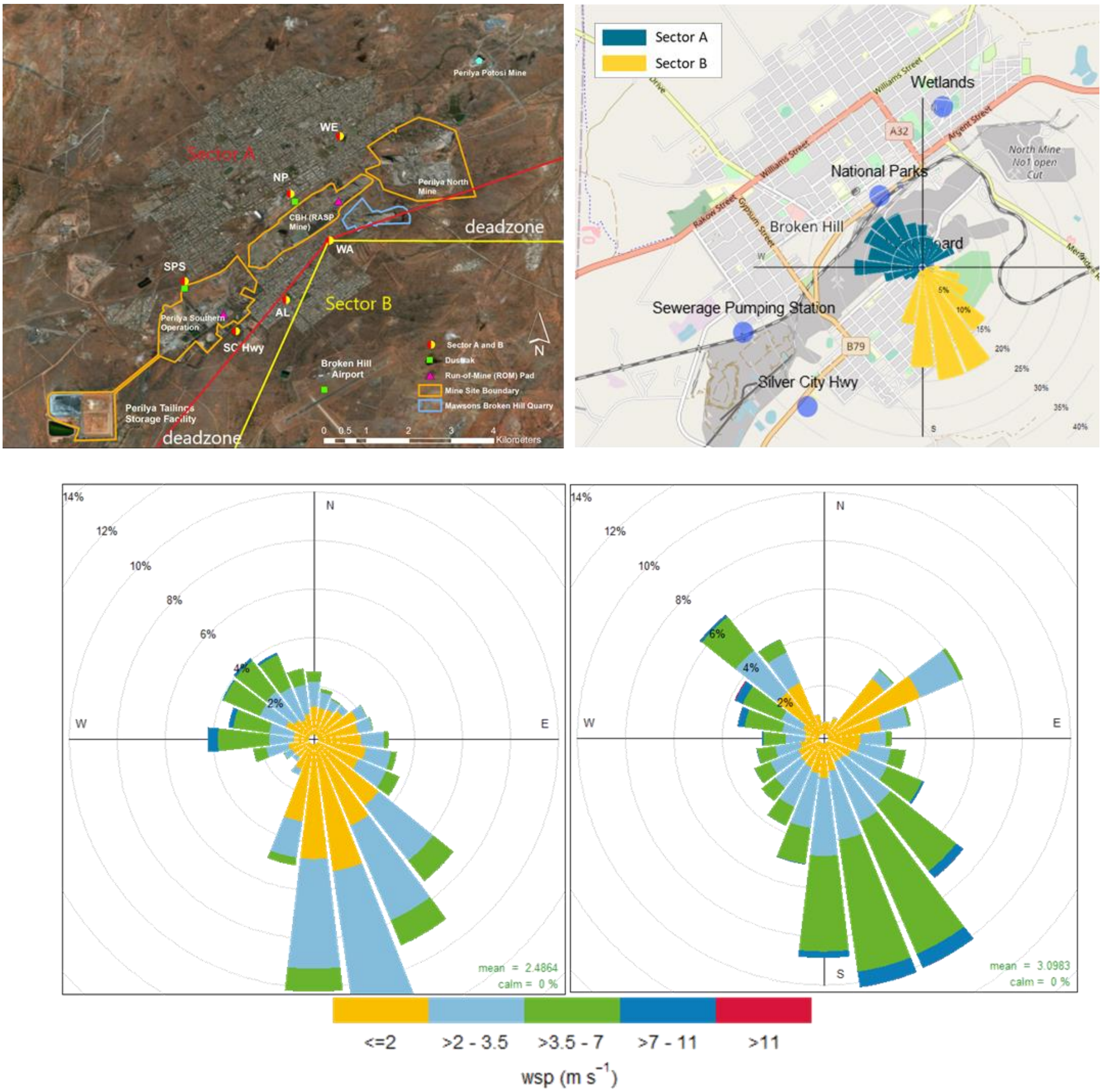

Figure 18 Waterboard site. Top panel: wind sampling sectors on the left; all wind directions coinciding with Sector A and B sampling on the right. Bottom panel: complete wind roses recorded by the Sector A (left) and Sector B (right) D-HVAS anemometers.

The complete wind roses in Figure 18 show that the winds were predominantly south, south-west and south-easterly, which is similar to the wind pattern in the Year 2 report. The site experienced strong winds (>7 ms^{-1}) from the west and north west.

The total valid sampling days were 130 days for Sector A and 175 days for Sector B (Figure 7). As presented in the Appendix A, the total number of valid filter samples were 51 for Sector A and 53 for Sector B.

Figure 19 shows that the median ambient Pb concentration in Sector A and Sector B were 0.15 µg/m^3 and 0.02 µg/m^3 respectively. The median lead-in-TSP in Sector A and Sector B were 2,654 and 654 mg/kg. The overall median lead levels in Sector A at the Waterboard site were higher than those measured at the National Parks and Wetlands sites. The Sector A sampler captured the lead emissions from mining activities at the Rasp Mine, Perilya North Mine and Perilya Southern Operations.

The episode analyses below provide more specific information on the sources of lead measured at the Waterboard site.

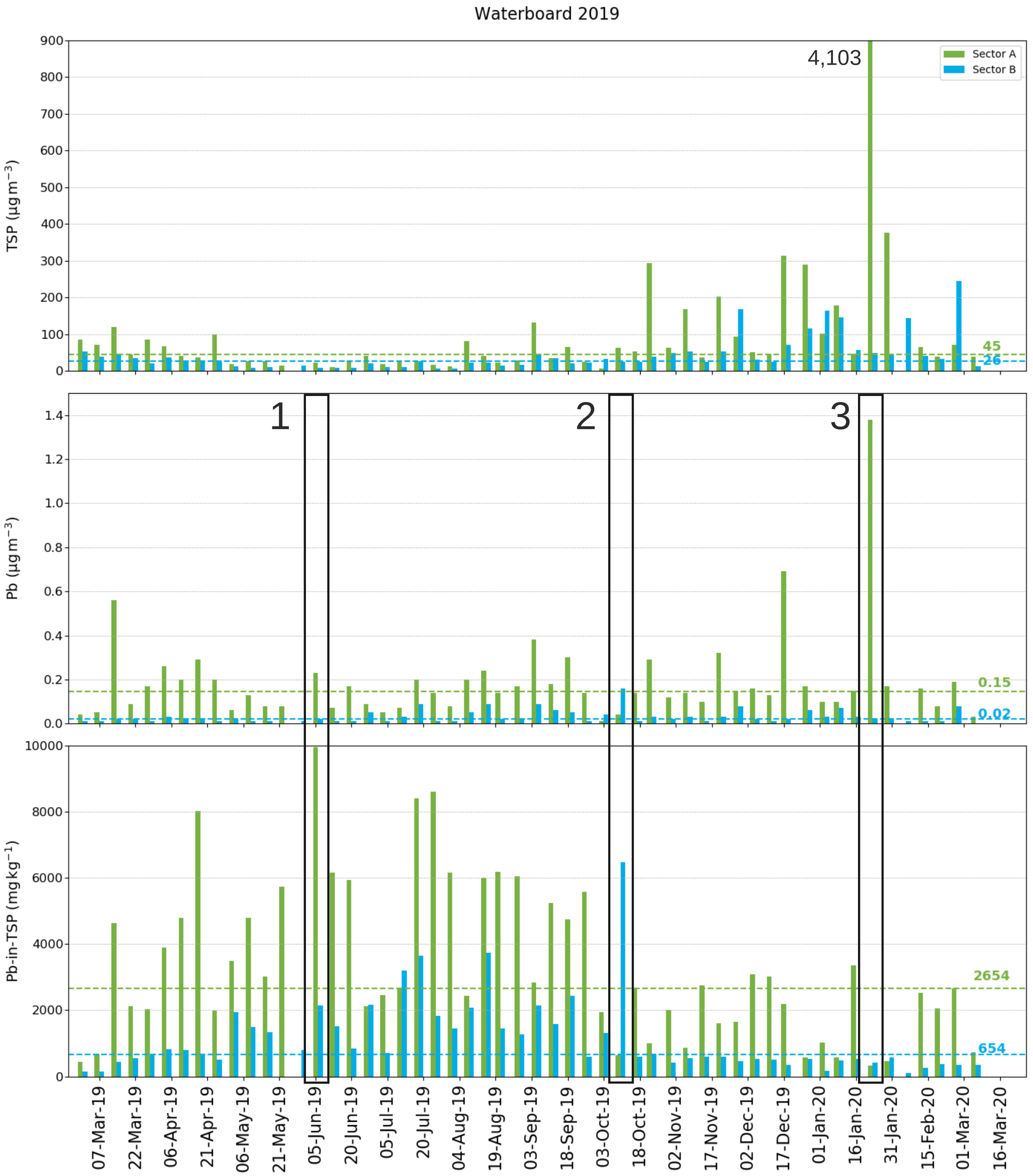

Figure 19 Weekly TSP concentration, ambient lead concentration and lead-in-TSP mass fraction measured at Waterboard site. The dashed lines represent overall median concentration and the vertical boxes represent high lead episodes.

Episode 1 at Waterboard, 5 – 12 June 2019

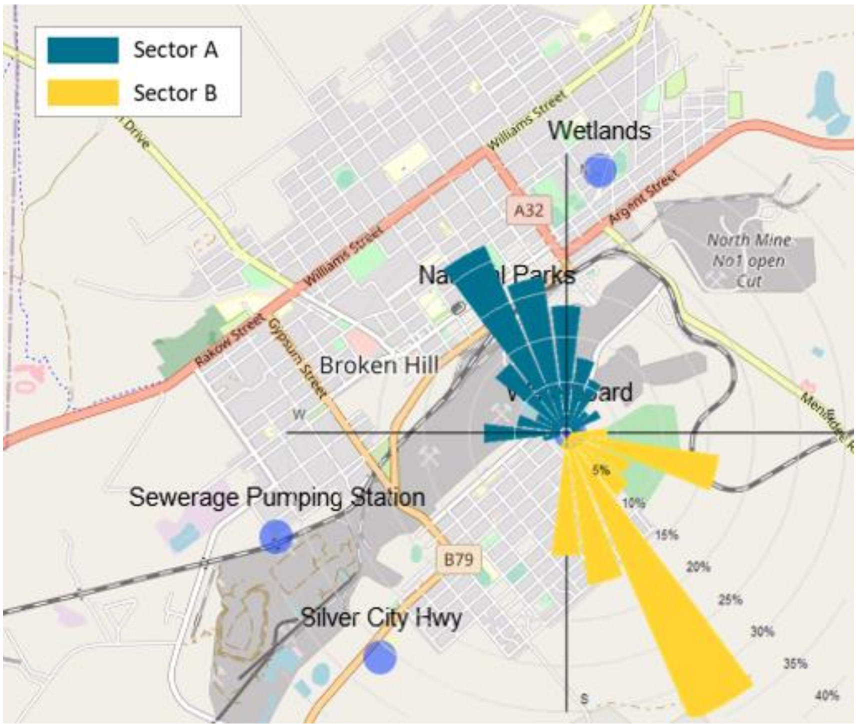

Figure 20 Wind direction coinciding with Sector A and Sector B at the Waterboard site during 5-12 June 2019.

This episode was selected considering the highest lead-in-TSP level in Sector A while the TSP level was below site median. Figure 20 shows that the Sector A winds were predominantly from the north west, placing the sampler downwind of the Rasp Mine. The sector B winds were predominantly from the south east, placing the sampler downwind of residential south Broken Hill. No dust events were noted in the event log.

During this episode:

- Weekly average ambient TSP concentrations were 22.9 µg/m^3 and 8.13 µg/m^3 in Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.23 and 0.02 µg/m^3 in Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 9,954 and 2,146 mg/kg in Sector A and Sector B respectively.

The weekly ambient lead level in Sector A was 35% higher than the overall median value, and the weekly lead-in-TSP was the highest in Sector A, which was 375% higher than the site median. The most likely source of the elevated lead bearing dust in Sector A was from the Rasp Mine. While the exact source of lead-bearing TSP in Sector B cannot be determined, it is plausible that the lead-rich TSP was likely deposited at some time (recently and historically) in residential south Broken Hill and is subsequently being resuspended (and mixed with other dust) and transported in a northerly direction.

Episode 2 at Waterboard, 9 – 16 October 2019

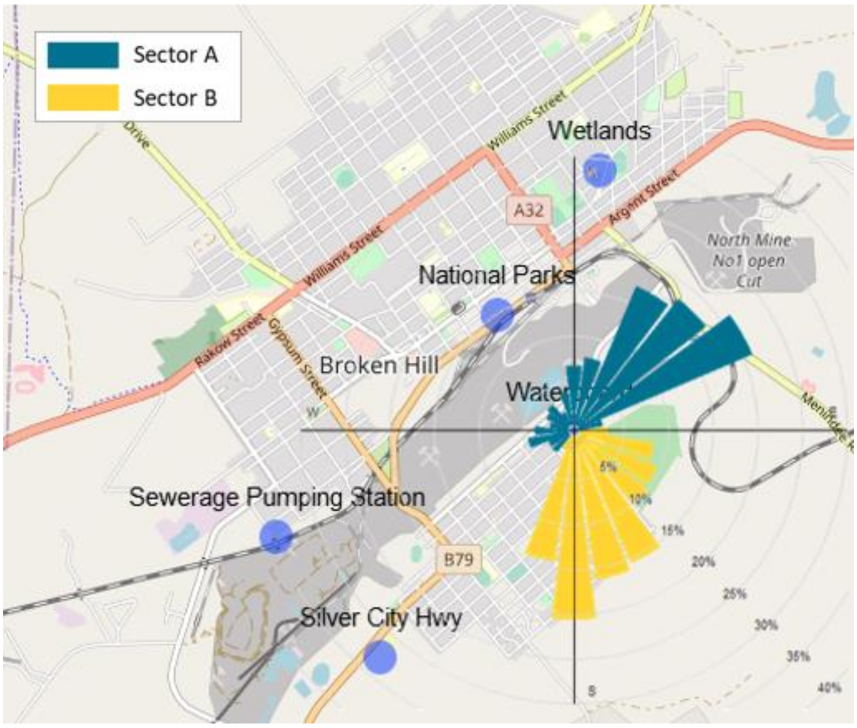

Figure 21 Wind direction coinciding with Sector A and Sector B at the Waterboard site during 9-16 October 2019.

This episode was selected considering the highest lead-in-TSP level in Sector B. Figure 21 shows that the Sector A winds were predominantly from the north, north north-east and north east and Sector B winds were from the south and south east. No dust events were noted in the event log.

During this episode:

- Weekly average ambient TSP concentrations were 62.3 µg/m^3 and 23.9 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.04 and 0.16 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP were 637 and 6,486 mg/kg for Sector A and Sector B respectively.

The highest weekly ambient lead and lead-in-TSP in Sector B was recorded in this episode. The ambient lead levels and TSP-in-lead in Sector A were four and ten times lower than Sector B respectively. The winds in Sector A were from the north, north east and north north-east during the episode. There was no mining activity to the north east of the sampling site and this may explain the relatively low Sector A lead levels.

The reason for the significantly higher level of ambient lead and lead-in-TSP in Sector B is unknown as the sampling site was downwind of residential South Broken Hill. However, it is plausible that the lead-rich TSP was likely deposited at some time (recently and historically) in residential south Broken Hill and is subsequently being resuspended (and mixed with other dust) and transported in a northerly direction.

Episode 3 at Waterboard, 22 – 29 January 2020

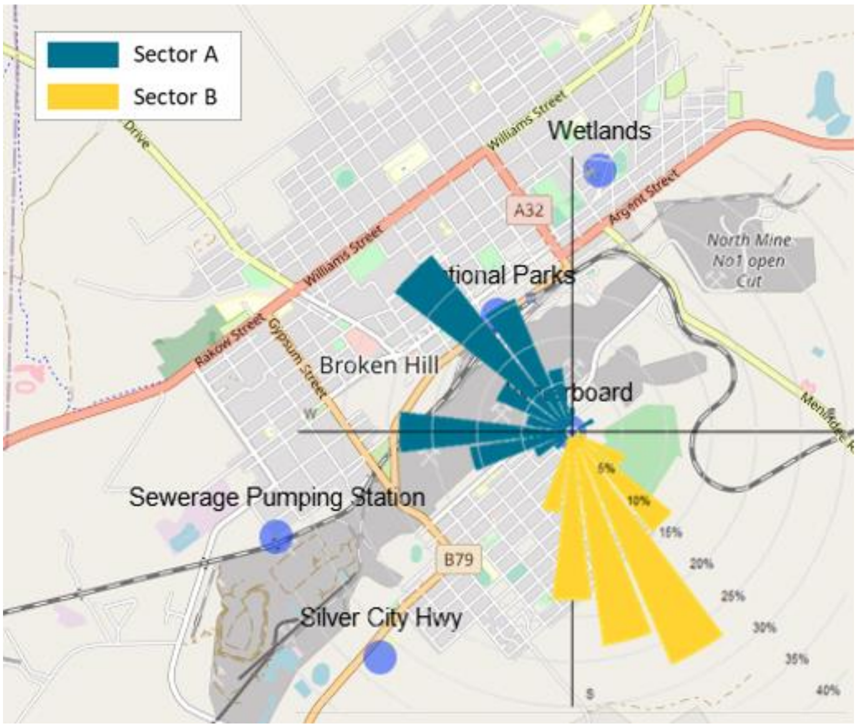

Figure 22 Wind direction coinciding with Sector A and Sector B at the Waterboard site during 22-29 January 2020.

This episode was selected considering the highest ambient lead concentration and TSP levels in Sector A. Figure 22 shows that the Sector A winds were predominantly from the west and north west, which placed the station downwind of the Rasp Mine, and Sector B winds were from the south and south east. A dust storm was noted in the event log during this episode resulting elevated local dust and reduced visibility.

During this episode:

- Weekly average ambient TSP concentrations were 4,103 µg/m^3 and 49 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 1.38 and 0.02 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP were 335 and 411 mg/kg for Sector A and Sector B respectively.

The TSP concentration was over 83 times higher in Sector A than in Sector B as strong northerly winds were observed during the dust storm in this week. The highest weekly ambient lead concentration was recorded in Sector A, which was over nine times higher than the site median concentration. The cause of the high ambient lead concentration in Sector A was likely from the mining activities. Also it is highly likely that the high wind speed and turbulence during the dust storm lifted lead-bearing TSP and transported it south easterly wind to the sampler. The lead-in-TSP in Sector A was about eight times lower than the site median level indicating dilution of lead bearing dust by an influx of either non-lead bearing dust or dust with much lower lead loading during dust storm.

As noted in Episodes 1 and 2, the precise source of lead-bearing TSP in Sector B is unknown as the sampling site was downwind of residential south Broken Hill. However, it is plausible that the lead-rich TSP was likely deposited at some time (recently and historically) in residential south Broken Hill and is subsequently being resuspended (and mixed with other dust) and transported in a northerly direction.

3.3.4 Results: Sewerage Pumping Station site

The monitoring site is located approximately 100 m north of the rail corridor and 350-500 m north of tailings storage facilities.

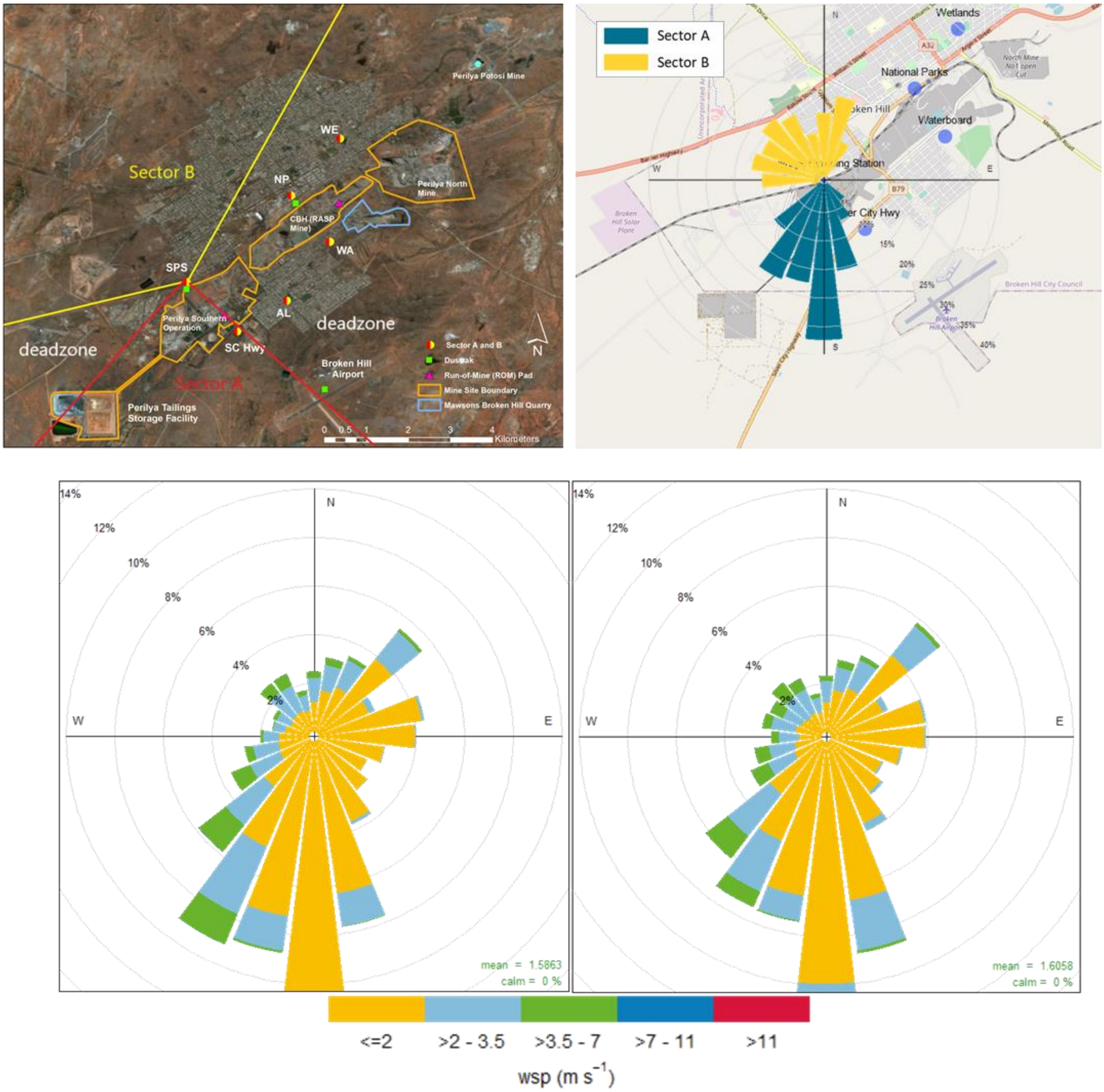

Figure 23 Sewerage Pumping Station site. Top panel: wind sampling sectors on the left; all wind directions coinciding with Sector A and B sampling on the right. Bottom panel: complete wind roses recorded by the Sector A (left) and Sector B (right) D-HVAS anemometers.

The complete wind roses in Figure 23 show that the winds were predominantly from the south, south west and south east, which is similar to the overall wind flow pattern at other sites. The Sector A wind sector samples lead bearing dusts from Perilya Southern Operations and Perilya tailings storage facility. Sector B samples TSP from residential north Broken Hill.

The total valid number of sampling days was 104 days for Sector A and 51 days for Sector B. As presented in Appendix A, the total number of valid filter samples was 50 for Sector A and 43 for Sector B.

The median ambient lead concentration in Sector A and Sector B was 0.18 and 0.08 µg/m^3 respectively, which were significantly higher than observed at the National Parks, Wetlands, and Waterboard sites. The median lead-in-TSP was also significantly higher at Sewerage Pumping Station than observed at the National Parks, Wetlands, and Waterboard sites.

In general, both sectors' lead levels were amongst the highest of all the sampling sites, except at Silver City Highway and National Parks (Sector B). The elevated lead levels observed in Sector A were likely a result of the sampler being downwind (to the north) of the active mining and tailings storage facilities associated with Perilya Southern Operations. The rail corridor also operates ~100 m north of the sampling site.

The episode analyses below provide more specific information on the sources of lead measured at the Sewerage Pumping Station site.

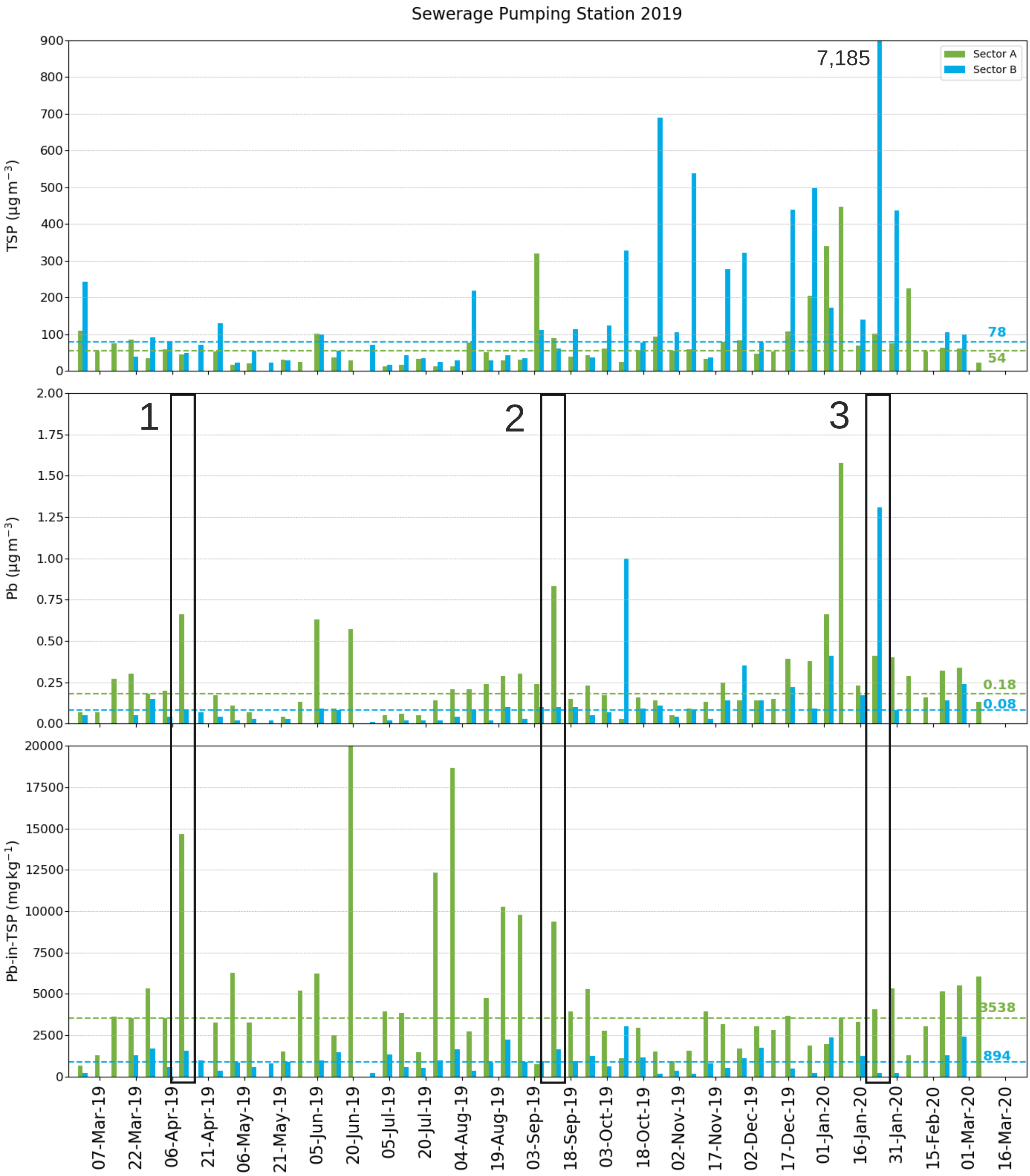

Figure 24 **Weekly TSP concentration, ambient lead concentration and lead-in-TSP mass fraction measured at Sewerage Pumping Station site. The dashed lines represent overall median concentration and the vertical boxes represent high lead episodes.**

Episode 1 at Sewerage Pumping Station, 10 – 16 April 2020

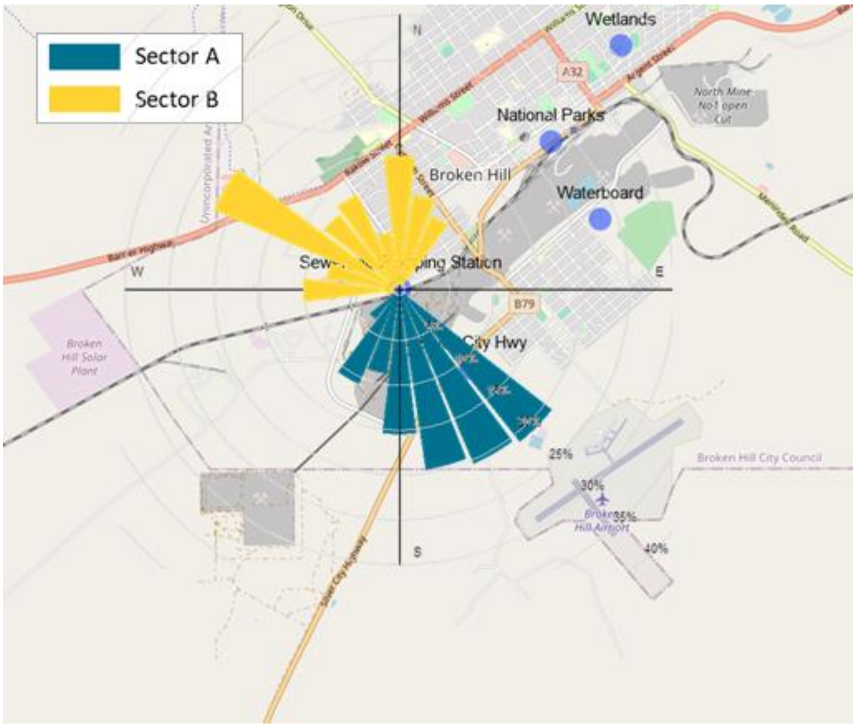

Figure 25 Wind direction coinciding with Sector A and Sector B at the Sewerage Pumping Station site during 10-16 April 2019.

This episode was selected considering the elevated lead-in-TSP level and ambient lead concentration in Sector A. Figure 25 shows that the Sector A winds were predominantly from the south, south south-east and south east placing the station downwind of the Perilya Southern Operations. Sector B winds were from the north, which transports dust from the residential areas north and north east part of Broken Hill. The winds from the west, west north-west, north west and north in Sector B are likely to transport dust from the non-mining areas.

During this episode:

- Weekly average ambient TSP concentrations were 44.6 µg/m^3 and 49 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.66 and 0.08 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 14,685 and 1,559 mg/kg for Sector A and Sector B respectively.

The ambient lead and lead-in-TSP observed in Sector A were 3.7 and 4.2 times higher than the overall site median values. While the ambient lead level in Sector B during this episode was similar to the site median, the TSP-in-lead was almost double of the site median value. TSP concentrations in both Sectors A and B were below the site median, which indicates no dust events during this week and lower possibility of transported dust far from the station. Yet Sector A recoded the third highest lead-in-TSP levels during this episode. During this week, the predominant wind was from the south-south-east placing the station downwind of PSO, which was the most likely source.

Episode 2 at Sewerage Pumping Station, 11 – 18 September 2019

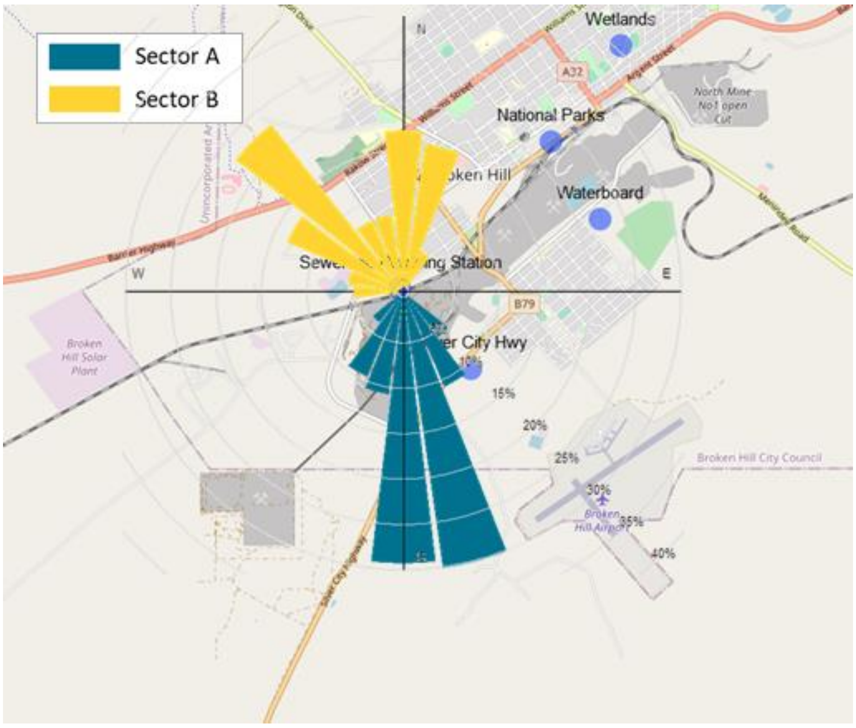

Figure 26 Wind direction coinciding with Sector A and Sector B at the Sewerage Pumping Station site during 11-18 September 2019.

This episode was selected considering the second highest lead concentration in Sector A. Figure 26 shows that the Sector A winds were predominantly from the south and Sector B winds were from the north and north west, which is similar to the episode 1.

During this episode:

- Weekly average ambient TSP concentrations were 88 µg/m^3 and 60.1 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.83 and 0.1 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 9,387 and 1,641 mg/kg for Sector A and Sector B respectively.

While the wind patterns for Episodes 1 and 2 were similar, the ambient lead concentrations in both Sector A and Sector B were higher than Episode 1. The lead-in-TSP level in Sector A was 36% higher in Episode 1 than in Episode 2. During this episode, Sector B wind direction was very similar to episode 1 placing the sampler downwind of residential north Broken Hill, and the ambient lead concentration was also very close to the site median. Sector A lead lead-in-TSP was the second highest. The winds in Sector A was mostly from the south during this episode; whereas winds were mostly south-south-east in episode 1. Episodes 1 and 2 showed that Sector A lead levels can be very high with a relatively low TSP concentration.

Episode 3 at Sewerage Pumping Station, 22 – 29 January 2020

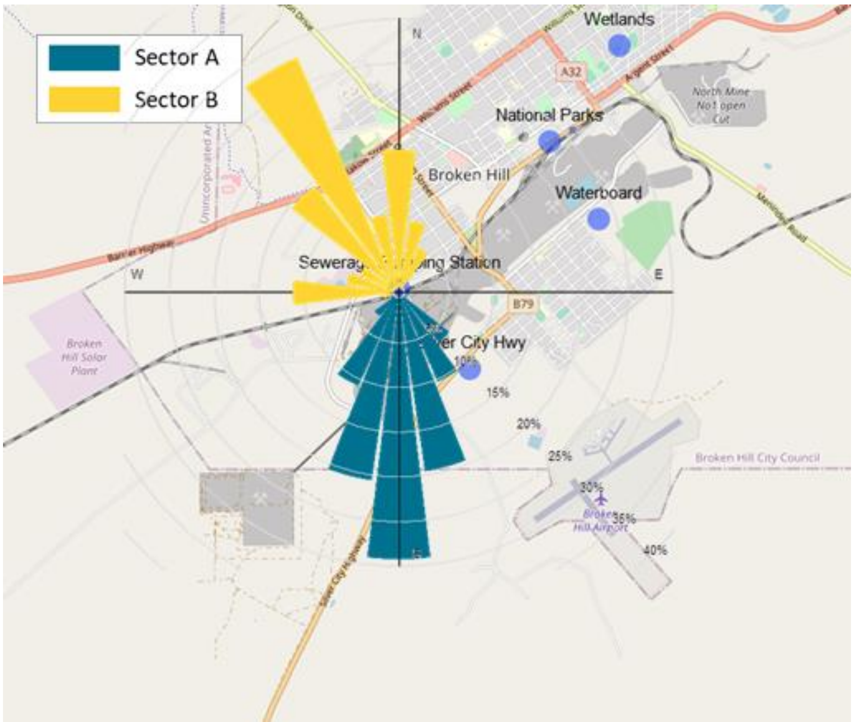

Figure 27 Wind direction coinciding with Sector A and Sector B at the Sewerage Pumping Station site during 22-29 January 2020.

This episode was selected considering the highest ambient lead and TSP concentrations in Sector B. Figure 27 shows that the Sector A winds were predominantly from the south-south-east to south-south- west which placed the sampler downwind of Perilya Southern Operations, similar to Episodes 1 and 2. The Sector B winds were predominantly from the north, north west and west. A dust storm was noted in the event log during this episode resulting in elevated dust and reduced visibility.

During this episode:

- Weekly average ambient TSP concentrations were 100 µg/m^3 and 7,185 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.41 and 1.31 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 4,069 and 182 mg/kg for Sector A and Sector B respectively.

The highest ambient lead concentration was recorded in Sector B during this episode, almost 18-times higher than that of the site median value, and more than three-times higher than in Sector A. Although there was no significant difference between wind patterns in Episodes 1, 2 and 3, the ambient lead concentration was significantly higher during Episode 3.

The strong northerly winds during the dust storm were likely to play a key role in the elevated ambient lead concentration in Sector B, as seen at the Wetlands site (Episode 3). Sector B winds were predominantly from the north-west placing the sampler downwind of residential areas to the north. It is highly likely that the lead-bearing TSP in Sector B that was deposited in the past was lifted by the north westerly winds during the dust storm event. However, the low lead-in-TSP in Sector B indicates the dilution of lead bearing dust by an influx of non-lead bearing dust during dust storm. Sector A was placed downwind of Perilya Southern Operations, indicating lead-bearing TSP in Sector A was likely from mining activities.

3.3.5 Results: Silver City Highway site

The Silver City Highway site is located 600 m south-east of Perilya Southern Operations (PSO). The complete wind roses in Figure 28 show that the winds were predominantly from the south west and north east, and the overall wind speed is relatively low compared to other sites because the sampling site is relatively sheltered. The wind sector for Sector A included the major source area (PSO), and the wind sector for Sector B included residential south Broken Hill and the non-mining regions to the south and south east of the monitoring site.

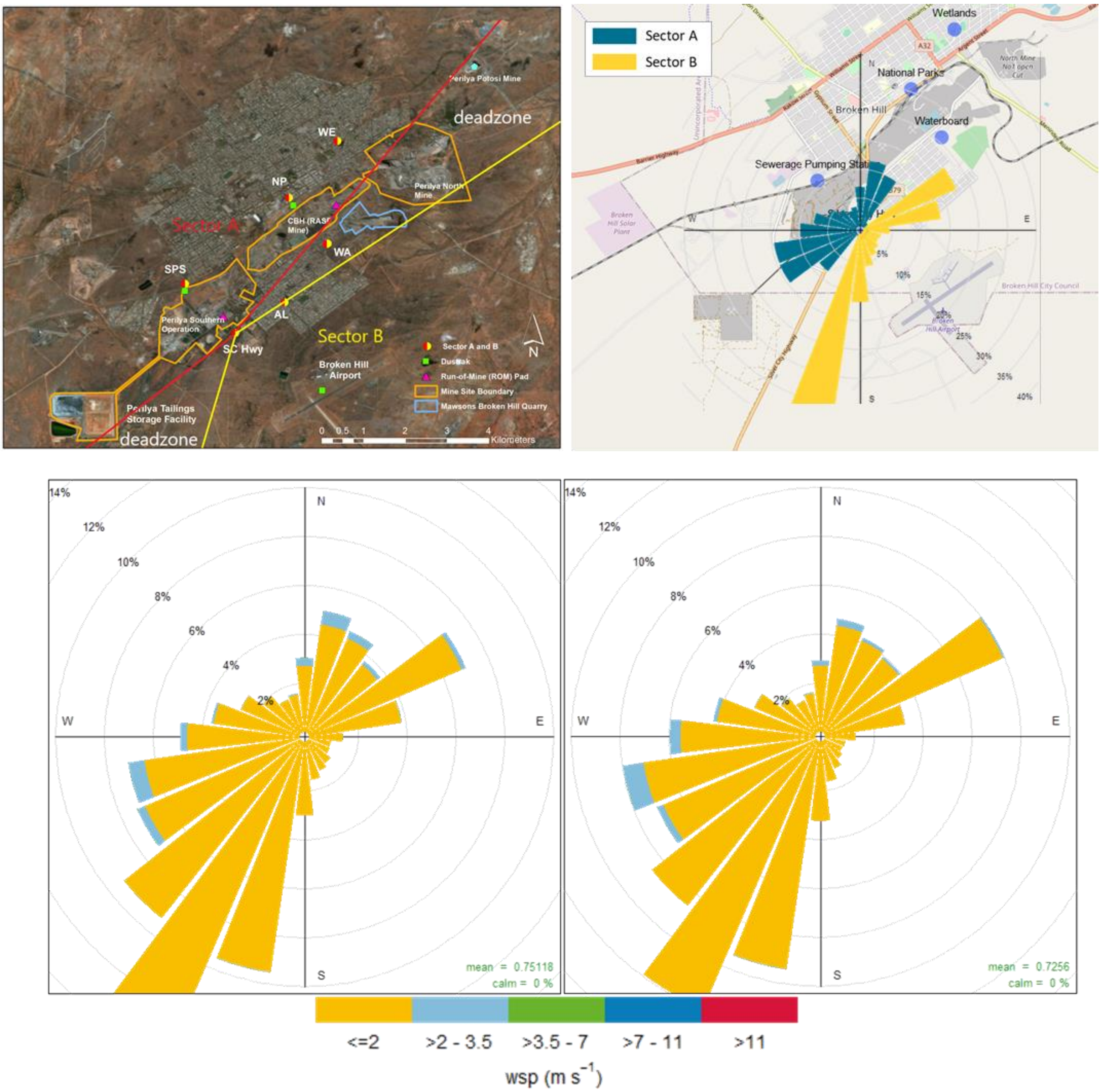

Figure 28 Silver City Highway site. Top panel: wind sampling sectors on the left; all wind directions coinciding with Sector A and B sampling on the right. Bottom panel: complete wind roses recorded by the Sector A (left) and Sector B (right) D-HVAS anemometers.

The total valid sampling days were 67 days for Sector A and 2.7 days for Sector B. As presented in Appendix A, the total number of valid filter samples were 47 for Sector A and 5 for Sector B. The total number of valid samples in Sector B was only a tenth that in Sector A. This was due to the very low wind speed from the north east and south west resulting in insufficient sampling times for most of the Sector B samples. That local winds are being steered by the LoL at this site. The Silver City Highway sampling site is an open area, but is surrounded by trees and shrubs (3-5 meters away). This may reduce windspeeds and alter the local wind direction at this site resulting in fewer samples (particularly for Sector B – the narrowed sampling sector also contributes to fewer valid samples). Therefore, the winds at this site may not represent the winds causing the raised dust.

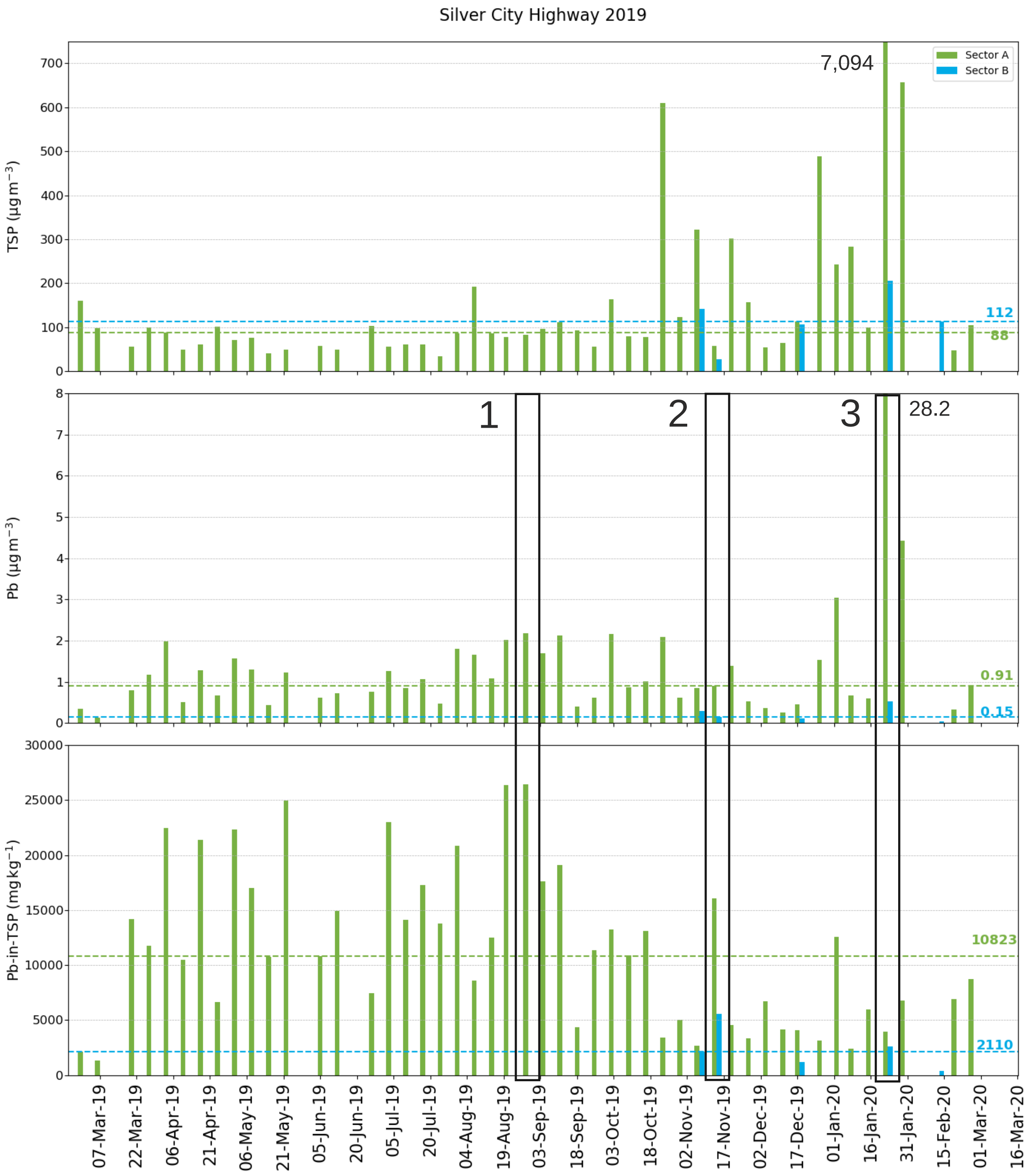

Figure 29 **Weekly TSP concentration, ambient lead concentration and lead-in-TSP mass fraction measured at Silver City Highway site. The dashed lines represent overall median concentration and the vertical boxes represent high lead episodes.**

The median ambient lead concentration and lead-in-TSP level were 0.91 µg/m^3 and 10,823 mg/kg, which were the highest Sector A lead levels among all sites. The median ambient lead concentration in Sector A was about five to eleven times higher compared to the other sites.

Although the median lead levels in Sector B were also high compared to the Sector B observations at all other sites, the comparison of the median values was biased by the small number (five) of valid filter Sector B samples.

The very high lead levels in Sector A would likely have an impact on residential areas of south Broken Hill. They are located downwind of the major mining activities, and therefore northerly and north easterly winds could transport lead bearing TSP into residential south Broken Hill. The deposited lead bearing TSP can then be subsequently resuspended by southerly winds hence producing occasional high Sector B lead levels. As described in the Section 3.2m the topsoil measurements of 2019 in the vicinity of the Silver City Highway site showed higher lead lead-in-soil close to the mining site and lower lead levels further out from mine. The 2019 interim report[5] also concluded that the higher lead-in-TSP levels than lead-in-soil was the likely effect of lead mining and processing activities.

The episode analyses below provide more specific information on the sources of lead measured at the Silver City Highway site.

Episode 1 at Silver City Highway, 20 – 28 August 2019

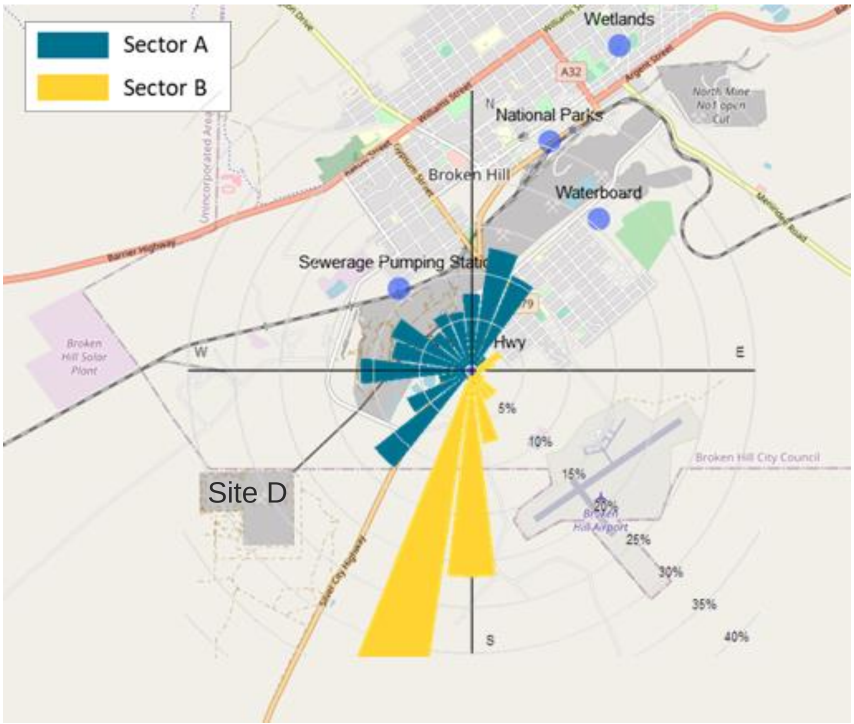

Figure 30 Wind direction coinciding with Sector A and Sector B at the Silver City Highway site during 20-28 August 2019.

This episode was selected considering the highest lead-in-TSP level in Sector A. Figure 30 shows that the Sector A winds were predominantly from the north east, north west, west and south west placing the station downwind of Perilya Southern Operations and the tailings dam at Site D. The Sector B winds were from the south-south west placing the station downwind of non-source areas. There were no valid Sector B lead data for this episode due to insufficient sampler run time.

5 2019 BHELS Interim Report, NSW DPIE, November 2019.

During this episode:

- Weekly average ambient TSP concentration was 76.8 µg/m^3 for Sector A.
- Weekly average ambient lead concentration was 2.02 µg/m^3 for Sector A.
- Highest weekly average lead-in-TSP level was 26,365 µg/m^3 for Sector A.

The weekly ambient lead concentration and lead-in-TSP level were more than two-times higher than the site median for Sector A. The station is located about 600 m from the mining operations at PSO, so it is the most likely source of lead bearing dust.

Episode 2 at Silver City Highway, 13 – 20 November 2019

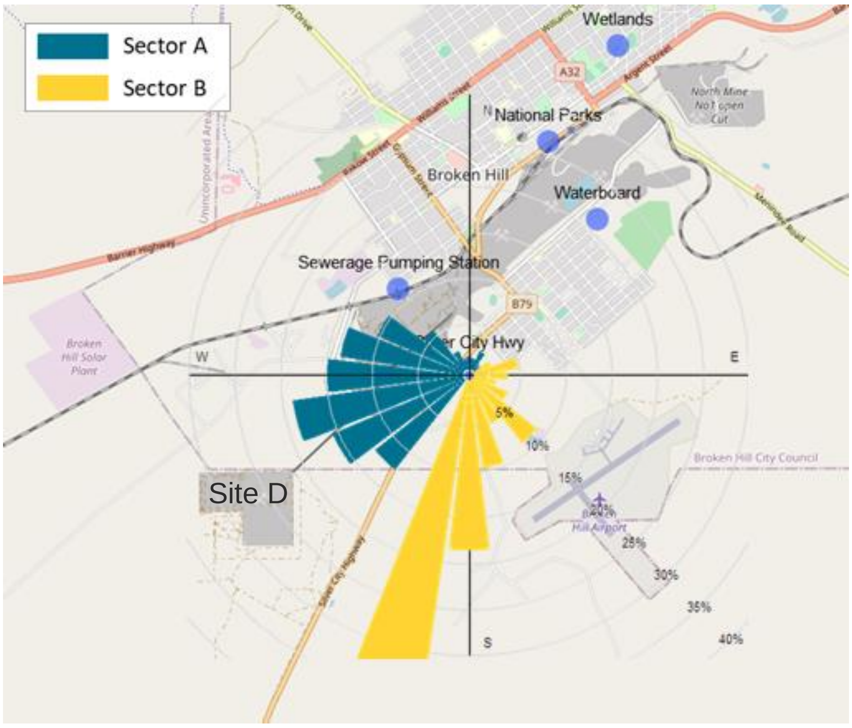

Figure 31 Wind direction coinciding with Sector A and Sector B at the Silver City Highway site during 13-20 November 2019.

This episode was selected considering the elevated lead-in-TSP levels in Sectors A and B, which had exceeded the site medians respectively. Figure 31 shows that the Sector A winds were predominantly from the west and north west and south west placing the station downwind of Perilya Southern Operations and the tailings dam at Site D. The Sector B winds were from the south, south-south west and south east, similar to episode 1, placing the station downwind of the non-source areas.

During this episode:

- Weekly average ambient TSP concentrations were 56.8 µg/m^3 and 27.7 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 0.91 and 0.15 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 16,070 and 5,555 mg/kg for Sector A and Sector B respectively.

The ambient lead concentration and lead-in-TSP levels in Sector A and Sector B were about the same level as the site median levels. The weekly average lead levels in Sector A were significantly higher than Sector B, about six-times higher for ambient lead concentration and about three-times higher for the lead-in-TSP. As the Sector A winds were mostly from the west to south west during this episode, the most likely source of lead-bearing TSP was the nearby mining operations at PSO.

Episode 3 at Silver City Highway, 22 – 29 January 2020

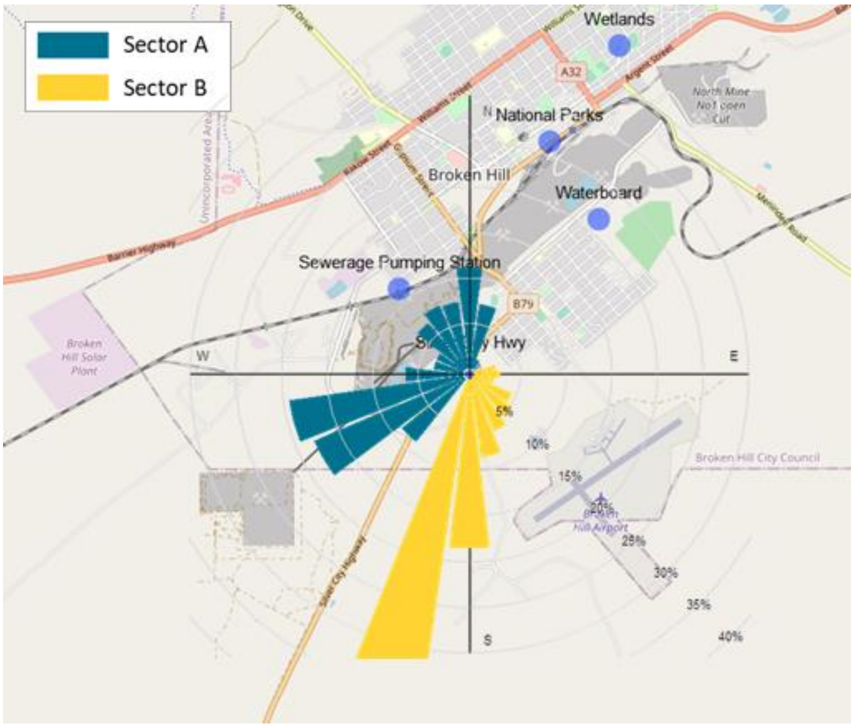

Figure 32 Wind direction coinciding with Sector A and Sector B at the Silver City Highway site during 22-29 January 2020.

This episode was selected considering the highest ambient lead and TSP concentrations recoded in Sector A. Figure 32 shows that the Sector A winds were predominantly from the south west, west south-west, north and north north-west placing the station downwind of Perilya Southern Operations and the tailings dam at Site D. The Sector B winds were from the south and south west, similar to Episodes 1 and 2, placing the station downwind of the non-source areas. A dust storm was noted in the event log during this episode resulting in elevated local dust and reduced visibility.

During this episode:

- Weekly average ambient TSP concentrations were 7,094 µg/m^3 and 206 µg/m^3 for Sector A and Sector B respectively.
- Weekly average ambient lead concentrations were 28.2 and 0.53 µg/m^3 for Sector A and Sector B respectively.
- Weekly average lead-in-TSP levels were 3,972 and 2,572 mg/kg for Sector A and Sector B respectively.

The weekly ambient lead concentration during this episode at Sector A was the highest measured over all sites during Year 3. The north, north west and south west winds placed Sector A sampler downwind of PSO and the tailings dam at Site D, which indicates that the likely source of lead-bearing TSP was associated with PSO. The ambient lead concentration in Sector B was also significantly elevated compared to the other sites. While the exact source of lead-bearing TSP in Sector B cannot be determined, it is plausible that the lead-rich TSP was likely deposited at some time (recently and historically) in residential south Broken Hill and is subsequently being resuspended (and mixed with other dust) and transported in a northerly direction.

The lead-in-TSP levels in both Sector A and B were significantly lower than Episodes 1 and 2. This result is likely due to the dust storm during this episode which transported a large quantity of non lead-bearing TSP into Sector A in particular, resulting in a reduction in lead mass fraction. The similar impacts of the dust storm on the lead-in-TSP were also observed at other sites.

4 Dust Deposition Results

The dust deposition gauges (DDGs) were installed at each site in March 2018. The non-directional DDGs collected coarse dust samples at each site. The collected dust samples were then analysed for total dust mass, total lead mass deposited, and lead content in the dust samples per month. While the D-HVAS measurements provided the primary measurements of lead content in dust, there was a possibility that the D-HVAS did not capture all the very coarse lead-bearing large dust particles and hence under-reported the lead mass. The DDGs therefore provided another independent measure of lead in TSP.

Figure 33 shows the monthly deposited dust levels measured by DDGs at each site. The deposited dust was generally below 5 g/m^2/month from February to October 2019, excepting a dust storm event in July 2019 and two dust storm events in August 2019. From October 2019 to February 2020, the Broken Hill region was impacted by frequent dust storms resulting in elevated dust deposition levels. All dust storm events during the monitoring period have been listed in Appendix B.

The highest dust deposition was recorded at the Wetlands site was 21.7 g/m^2/month in July 2019 and 14.5 g/m^2/month in February 2020. In general, elevated deposited dust (over 7.5 g/m^2/month) was recorded between January and March 2020 due to frequent dust storms and record-low rainfall.

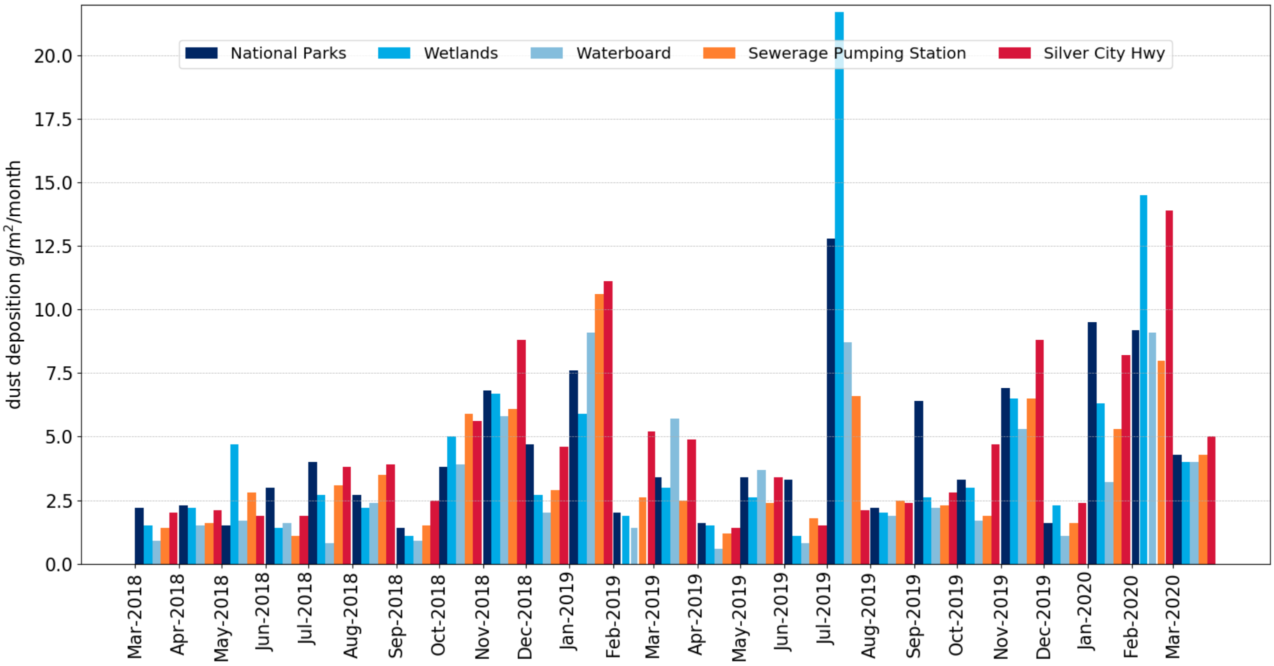

Figure 33 **Monthly dust deposition data for March 2018 to March 2020.**

Figure 34 shows the monthly deposited lead in the dust samples. Since the beginning of the monitoring campaign, the Silver City Highway site recorded the highest deposited lead for each month compared to all other sites. This trend of elevated lead levels at the Silver City Highway site continued in the Year 3 monitoring period, ranging between 0.002 grams Pb/m^2/month in December 2019 to 0.016 grams Pb/m^2/month in May 2019.

In May 2019, the deposited lead at Silver City Highway was 0.016 grams Pb/m^2/month, which was on average 11.3 times more lead in deposited dust than the overall average of the other sites. While the deposited lead was higher in May 2019 at the Silver City Highway site, the deposited dust level was significantly lower than average in May 2019.

From September 2019 to March 2020, the National Parks site recorded the second-highest deposited lead after the Silver City Highway site, with the highest level of 0.01 grams Pb/m^2/month in January 2020. In September 2019, the deposited lead was 0.008 grams Pb/m^2/month at both the Silver City Highway and the National Parks site. The lowest monthly deposited lead recorded at the Waterboard site, which was on average seven-times lower than that of the Silver City Highway site.

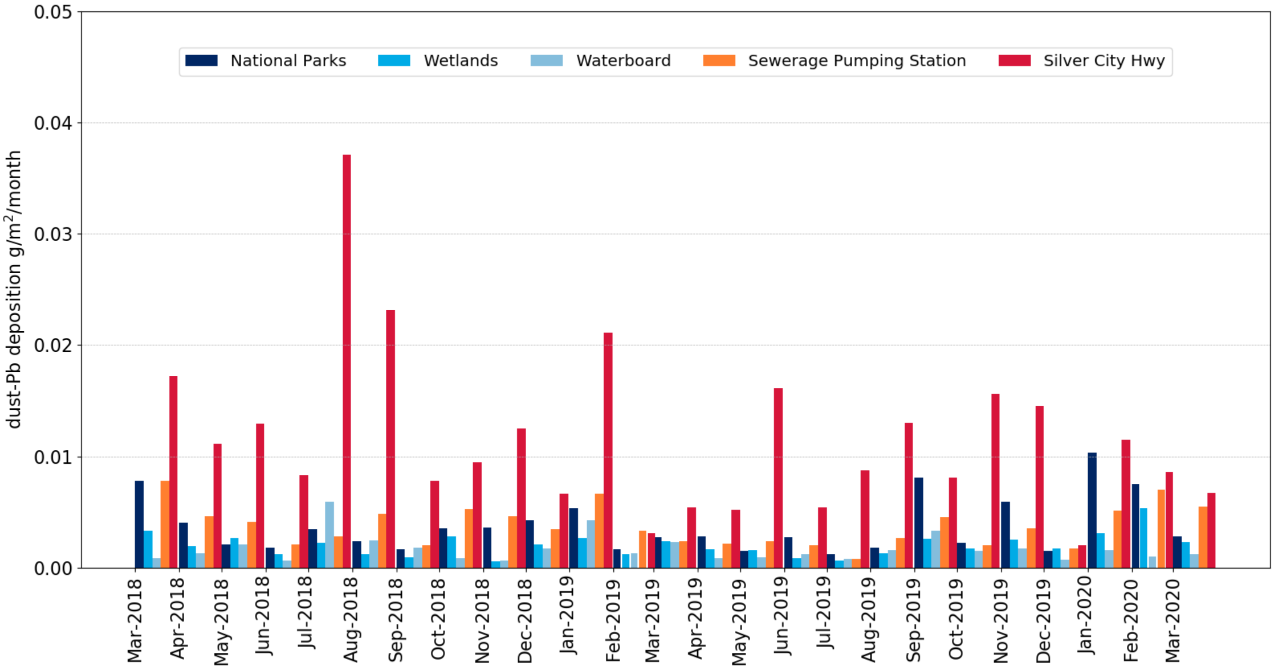

Figure 34 Monthly lead (Pb) in deposited dust for March 2018 to March 2020.

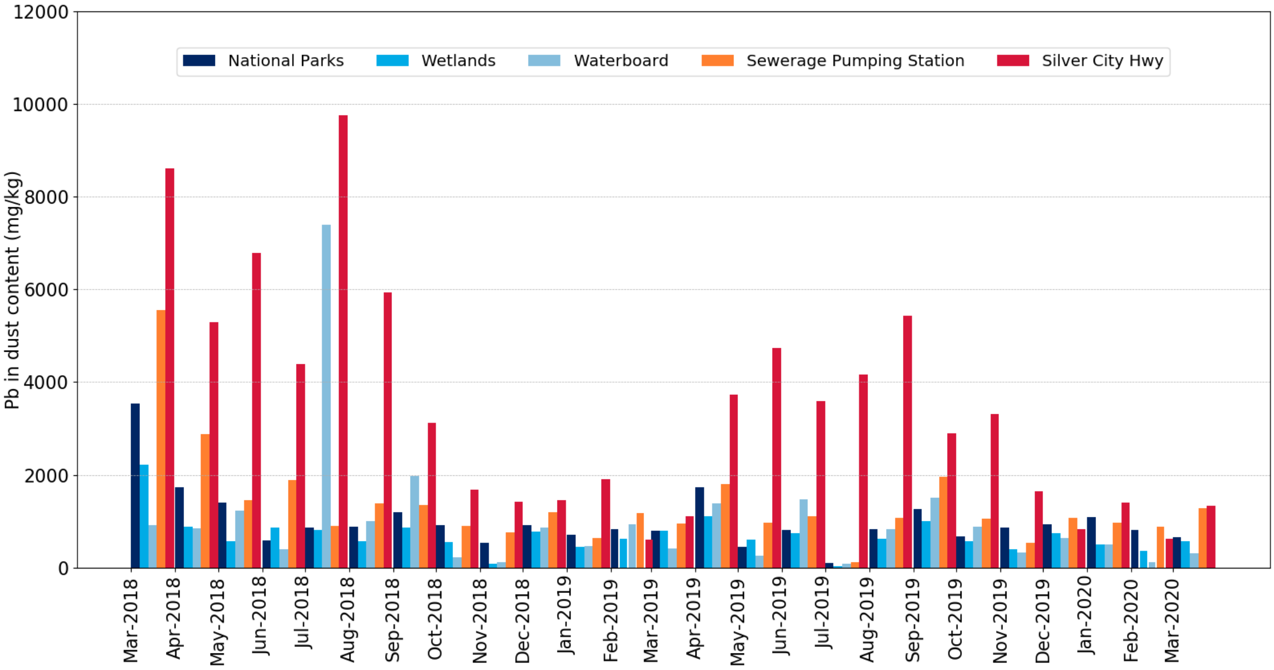

Figure 35 Monthly lead (Pb) in deposited dust by mass fraction for March 2018 to March 2020.

Figure 35 shows the monthly deposited lead mass as a fraction of the total deposited dust mass. As found in the deposited lead, the lead mass fraction was significantly higher at the Silver City Highway site compared to all other sites, ranging from 596 mg/kg to 5,425 mg/kg in Year 3. The maximum monthly deposited lead in Year 3 ranged from 1,113 mg/kg at the Wetlands site to 5,425 mg/kg at the Silver City Highway site.

The deposited lead was significantly lower in July 2019 and December 2019 – February 2020 for all sites except Silver City Highway, which coincided with high deposited dust. The high deposited dust tended to be associated with dust storms that bring in a greater proportion of lower Pb content dust. For instance, the highest monthly dust deposited in Year 3 was observed in July 2019 at the Wetlands site (21.7 g/m^2/month). The corresponding deposited lead (30 mg/kg) was the lowest. The deposited lead at the Wetlands site in July 2019 was almost 21 times lower than in August 2019 when there was no significant dust event.

5 Trends in TSP and lead levels between Years 1, 2 and 3

5.1 Number of valid sampling days

Table 4 shows the total number of valid sampling days per site and per sector for each sampling period. There is a significant variation in the number of valid sampling days due to the frequency of in-sector winds at each site. The National Parks, Wetlands, and Waterboard sites had more frequent in-sector winds and therefore higher numbers of sampling days, similar to those reported in the Year 2 report.

After the sector change in Year 2, the lowest number of valid sampling days was recorded in both sectors at the Silver City Highway site because the site is sheltered, resulting in less frequent in-sector winds and therefore low sampling volumes. Sector B sampling at the Silver City Highway site was particularly affected by the change in sampling sectors. The change was necessary to reduce contamination of non-source TSP in Sector B from TSP arising from mining sources. Although there were only a small number of valid Sector B samples in Year 3, these samples should be genuinely non-source samples.

The Wetlands site is also sheltered, reflecting the very low percentage of valid sampling days in Sector B in Year 2 (after the sector change) and Year 3.

Table 4 Number of valid sampling days during each sampling period and the percentage of the total sampling time.

BHELS Sampling Site	Sector	Number of valid sampling days (% of total)			
		Year 1[a]	Year 2[b]	Year 2[c]	Year 3[d]
National Parks (NP)	A	166 (45%)	141 (63%)	92 (53%)	171 (45%)
	B	144 (39%)	133 (59%)	40 (23%)	78 (21%)
Wetlands (WE)	A	33 (9%)	40 (18%)	77 (44%)	156 (41%)
	B	202 (55%)	172 (76%)	20 (11%)	39 (10%)
Waterboard (WA)	A	111 (30%)	66 (29%)	59 (34%)	130 (27%)
	B	-	-	70 (58%)*	175 (46%)
Sewerage Pumping Station (SPS)	A	15 (4%)	8 (4%)	60 (34%)	104 (28%)
	B	179 (49%)	152 (68%)	26 (15%)	52 (14%)
Silver City Hwy (SC Hwy)	A	19 (20%)[§]	65 (29%)	34 (19%)	67 (18%)
	B	26 (27%)[§]	68 (30%)	3 (2%)	3 (0.7%)

[a]: Year 1, data based on 365 days' sampling covering January 2017-January 2018, except at Silver City Highway; [b]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days' sampling); [c]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days' sampling); [d]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018 (120 days' sampling).

[§]Samplers installed 3 October 2017 (95 days' sampling in Year 1).

National Parks

The percentage of valid sampling days in Sector A was 45% in Year 3 which was the highest of all Sector A measurements across the other sites in Year 3. Sector B also had a similar percentage of valid sampling days to Year 2 (after the sector change). Before the sector change, the percentage of valid Sector B samples were relatively higher in Year 1 and Year 2 as the wind sector was 215°-65° which was broader than the wind sector 245-30° after the sector change.

The prevailing wind direction at National Parks site was from the south west and south east which coincided with the Sector A wind sector meaning high percentage (45%) of valid sampling days relative to the other sites in Year 3. Appendix A shows the total number of invalid TSP filter samples was 12 for Sector B and three for Sector A. The major reason of sample invalidation was low sampling time.

Wetlands

There was a relatively low number of valid Sector B sampling days at the Wetlands site, which is similar to those in Year 2 after the sector change. The Wetlands site had the second-highest valid Sector A sampling days (41%). Before the sector change in Year 1 and Year 2, the Sector B sampling area was wider (220°-145°) than after sector change (260°-30°) resulting in a higher number of valid sampling days before 29 August 2019.

The prevailing wind direction at the Wetlands site was southerly (Figure 13). Sector A, which samples these southerly winds, recorded a relatively high number of valid sampling days after the sector change in Year 2. The frequency of Sector B winds from the north and north west was very low resulting in the reduction of valid sampling days in Year 2 (after the sector change) and Year 3. Appendix A presents the total number of invalid TSP filter samples was 18 for Sector and one for Sector A. The main reason of sample invalidation was low sampling time, in particular in Sector B.

Waterboard

The percentage of valid sampling days was 27% for Sector A and 46% for Sector B in Year 3. The prevailing wind direction at the Waterboard site was from the south, south west and south east in Year 3 (Figure 18), which fell in the Sector B sampling sector hence the percentage of valid sampling days was much higher in Sector B than in Sector A, similar to Year 1 and Year 2 (after the sector change). The total number of invalid samples was five for Sector A and three for Sector B (two for low sampling duration and one for filter installation/collection error). The Sector B sampler at the Waterboard site was installed 23 October 2018, so there were no Sector B measurements in Year 1 and Year 2 (before the sector change).

Sewerage Pumping Station

The prevailing wind direction at Sewerage Pumping station is southerly (Figure 23). As a result, the total number of valid sampling days was 50% higher in Sector A compared to in Sector B in Year 3. A similar trend in the total valid sampling days was also observed in Year 2 (after the sector change). In Year 1 and Year 2 (before the sector change), the valid sampling days were significantly higher in Sector B because of the broader sampling arc. From 29 August 2018, the Sector B sampling area was reduced to cover the non-mining area in residential north Broken Hill and other non-mining areas, resulting in the lower number of valid sampling days. The total of 10 filter samples was invalidated in Sector B due to low sampling time in Year 3.

Silver City Highway

The wind direction was predominantly from the south west and north east, and the wind speed was mostly low (<= 2 m/s) (Figure 28). The monitoring site is located in a sheltered location. As a result, Sector A and Sector B had the lowest number of total valid sampling days compared to the other sites. The Sector B sampling sector was changed on 29 August 2018 to capture more TSP arising from the non-mining, residential areas in south Broken Hill and less from the mining areas. Since then most samples were invalidated at Sector B due to low sampling duration.

5.2 Trends in median TSP levels

Table 5 shows the median TSP concentration measured in Year 1 (2017), Year 2 (2018-19) and Year 3 (2019-20). In Year 3, the elevated TSP levels were observed between October 2019 and February 2020 due to frequent dust storms, as presented in Appendix B. Most of the dust storms were associated with strong winds from the north west and west. As a result, the sectors that were downwind of these wind directions during dust episodes received high levels of dust.

The median TSP levels across all sites were mostly of the order of 50 µg/m^3 or less in Year 1 and Year 2 (before the sector change), and there was an insignificant difference in median values between Sector A and Sector B in Year 1 and Year 2 (before the sector change), except Sewerage Pumping Station.

In Year 3, the median TSP levels were about 21% (Silver City Highway) to 46% (Wetlands) higher in Sector B than in Sector A, indicating the higher impact of elevated dust events in Sector B than in Sector A. The highest TSP level in Year 3 was at Silver City Highway, 88 µg/m^3 in Sector A and 112 in Sector B, which is similar to Year 2 (after the sector change). It is plausible that the high TSP concentrations in Sector A at the Silver City Highway site was a combined effect of the frequent dust storms in Year 3 and emissions from the nearby lead stockpile at PSO.

The TSP levels are expected to be higher in dry weather associated with very low rainfall. The total annual rainfall in Broken Hill was 68 mm in 2019, which is about 41% and 60% lower than in 2017 and 2018 respectively. The impact of low rainfall in 2019 was reflected in the elevated median TSP concentrations in Year 2 (after the sector change) and Year 3 (Table 5).

Table 5 Median values of measured TSP concentrations by sampling site and sampling periods.

BHELS Sampling Site	Sector	TSP (µg/m^3)			
		Year 1[a]	Year 2[b]	Year 2[c]	Year 3[d]
National Parks (NP)	A	44	45	69	54
	B	52	58	124	91
Wetlands (WE)	A	30	43	39	38
	B	28	42	107	71
Waterboard (WA)	A	33	35	78	45
	B	-	-	34*	26
Sewerage Pumping Station (SPS)	A	29	152	70	54
	B	34	50	130	78
Silver City Hwy (SC Hwy)	A	51§	63	105	88
	B	36§	40	85	112

[a]: Year 1, data based on 365 days' sampling except at Silver City Highway; [b]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days' sampling); [c]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days' sampling); [d]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018 (120 days' sampling).

§Samplers installed 3 October 2017 (95 days' sampling in Year 1).

National Parks

The median TSP level in Sector A was 54 µg/m^3 in Year 3, which is about 22% reduction than in Year 2 (after the sector change). Sector B level was 36% lower than in Year 2 after the sector change; however, 75% and 57% higher than in Year 1 and Year 2 before the sector change. The median TSP levels in Sector B were consistently higher than in Sector A, ranging between 15% in Year 1 to 44% in Year 2 after the sector change.

Wetlands

The median TSP levels were moderately lower than those measured at the National Parks site. Sector A and Sector B TSP levels were almost similar in Year 1 and Year 2 (before the sector change). The increase in TSP levels after the sector change were associated with frequent dust storms and elevated local dust levels. The Sector B TSP level in Year 3 was 71 µg/m^3 which is almost double than in Sector A. Sector B TSP level in Year 2 (after the sector change) was almost three times than in Sector A. The elevated Sector B TSP level was also observed at the National Park site.

Waterboard

In general, the lowest TSP levels (both in Sector A and Sector B) were recorded at the Waterboard site. In Year 3, the median TSP level in Sector B was 42% lower than in Sector A.

The Sector A TSP level in Year 3 was higher by 26% and 22% than in Year 1 and Year 2 (before the sector change) respectively. After the sector change in Year 2, the TSP level was 73% higher than in Year 3.

Sewerage Pumping Station

The Sector B median TSP level in Year 3 was 19% higher than in Sector A. The Sector A TSP level in Year 2 (before the sector change) was almost three times than in Year 3, which is primarily due to civil works near the site but likely intensified by the dry conditions.

Sector B TSP levels in Year 3 reduced by 40% compared to Year 2 (after the sector change). The median TSP level in Sector B was consistently higher than in Sector A in all monitoring period excepting in Year 2 before the sector change.

Silver City Highway

In Year 3, the highest Sector B TSP concentration was observed at the Silver City Highway site, which is 32% higher than in Year 2 (after the sector change). In Year 3 the median TSP levels in both Sector A and B were higher at Silver City Highway site compared to other sites. Although the site is in a sheltered location, the TSP concentration was elevated at this site compared to other sites. The most plausible reasons for higher median TSP at this site compared to other sites in Year 3 were a combined effect of the duration and direction of winds during dust storms and elevated particles from the nearby mining stockpile at PSO.

The median TSP level prior to the sector change was significantly lower. For instance, Sector A TSP level in Year 1 was about 73% lower than in Year 3, indicating an increase in dust level in Year 3 due to record low rainfall and frequent dust storms.

5.3 Trends in median ambient lead concentrations

Table 6 presents the ambient lead concentrations measured in 2017, 2018-2019, and 2019-2020, and Figure 36 presents the spatial distribution of median lead concentrations in all sampling period. In general, the median ambient lead concentrations in Sector B were mostly below 0.09 µg/m^3 at all sites and monitoring periods, except at Silver City Highway site (after the sector change). The median ambient lead concentrations in Sector A were 0.1–0.18 µg/m^3 at all sites excepting to those were at the Wetlands and Silver City Highway sites. Wetlands site was the furthest away from the mining activities compared to other sites, which was the most likely reason for the lowest Sector A lead concentrations (0.08 µg/m^3) in all monitoring periods. The median ambient lead at Silver City Highway was the highest in both sectors, in particular in Year 2 (after the sector change) and in Year 3.

Overall the median ambient lead concentrations across all sites indicate that the Sector A lead level is about 25% and 18-35% higher in Year 3 than in Year 1 and Year 2 respectively. The Silver City Highway site was the most dominant contributor to the overall lead levels during each monitoring period.

Table 6 Median values of measured ambient lead concentrations by sampling site and sampling period.

BHELS Sampling Site	Sector	TSP-Pb (µg/m^3)			
		Year 1	**Year 2[a]**	**Year 2[b]**	**Year 3[c]**
National Parks (NP)	A	0.12	0.11	0.15	0.14
	B	0.08	0.06	0.09	0.09
Wetlands (WE)	A	0.08	0.08	0.08	0.08
	B	0.03	0.04	0.04	0.04
Waterboard (WA)	A	0.13	0.13	0.18	0.15
	B*	-	-	0.02	0.02
Sewerage Pumping Station (SPS)	A	0.16	0.10	0.14	0.18
	B	0.06	0.08	0.05	0.08
Silver City Hwy (SC Hwy)	A	0.58	0.50	0.63	0.91
	B	0.06	0.08	0.37	0.15

[a]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days); [b]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days); [c]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018

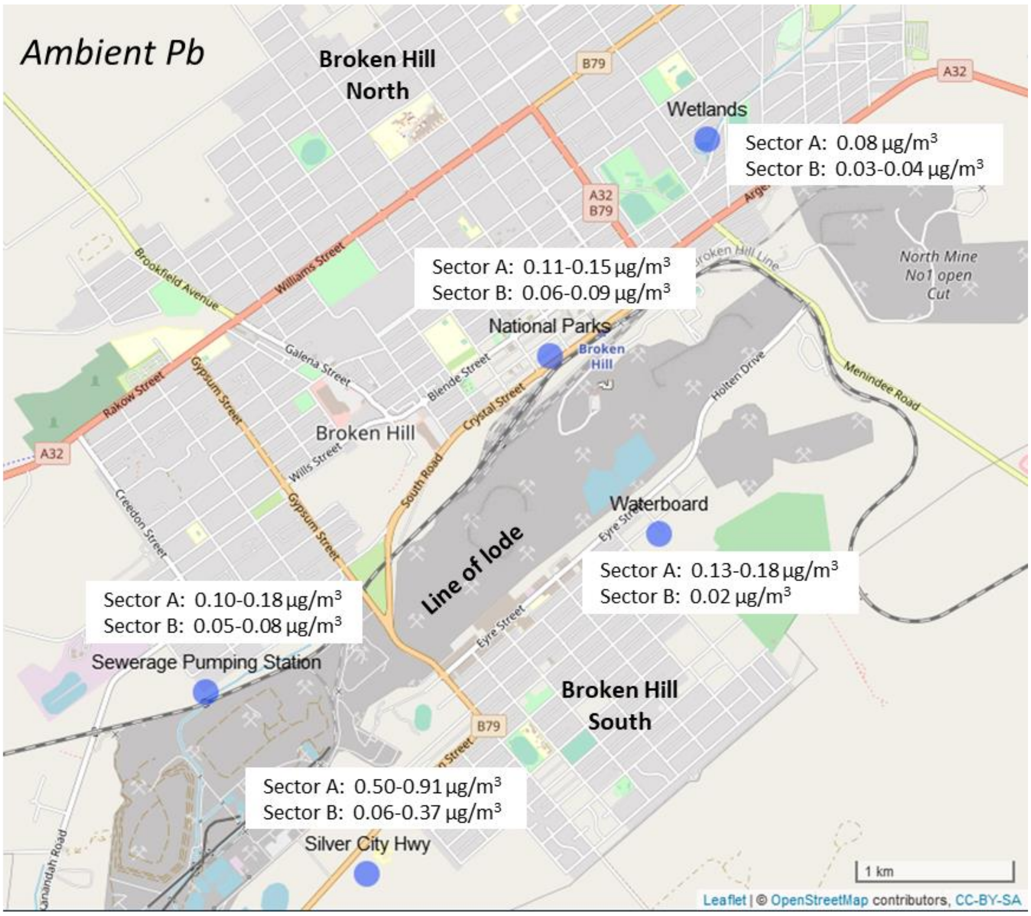

Figure 36 Spatial distribution of median ambient lead concentration measured in all sampling period.

National Parks

In Year 3, the median ambient lead concentrations in Sector A and Sector B were 0.14 and 0.09 µg/m^3 respectively, which are comparable to the reported levels in Year 1 (Sector A: 0.12 µg/m^3 and Sector B 0.08 µg/m^3) and Years 2 (Sector A: 0.11-0.15 and Sector B 0.06-0.09). The median lead concentration in Sector B ranged between 0.06–0.09 µg/m^3 during all monitoring period from Year 1 to Year 3.

Wetlands

The median ambient lead concentrations at the Wetlands site were very consistent during all monitoring periods and they were generally low compared to the other sites. Sector A concentration was 0.08 µg/m^3 across all four-sampling periods. The Sector B concentration was 0.04 µg/m^3 in the three sampling periods in Year 2 and Year 3, and the median lead level was slightly lower (0.03 µg/m^3) in Year 1. The reason for the low lead levels at Wetlands site was due to site location 1.4 km north east of the LoL and therefore the LoL terrain features have less influence at the Wetlands site compared to other sites. The site is more influenced by the regional south-south south-west winds.

Waterboard

The median ambient lead concentrations in Sector A and Sector B were 0.15 and 0.02 µg/m^3 respectively. The median Sector A lead concentration was the same (0.13 µg/m^3) during the two consecutive sampling periods in Year 1 and Year 2 (before the sector change). After the sector change in Year 2, the median Sector A lead level increased by 38%. In Year 3, the median lead concentration decreased by 18% compared to Year 2 (after the sector change).The Sector B measurement commenced after the sector change in Year 2, and the median lead concentrations were identical (0.02 µg/m^3) in both Years 2 and 3.

The Waterboard Sector A sampler is about 1 km south of the Line of Lode and south-east of the Rasp Mine. Therefore, the relatively high median lead concentrations in Sector A are likely associated with the mining operation. Sector B monitors lead-bearing TSP transported by southerly winds from south Broken Hill, where there is no lead mining, resulting in a substantially lower median lead concentration.

Sewerage Pumping Station

The median ambient lead concentrations in Sector A were higher by 12.5%, 80%, and 28% in Year 3 compared to Year 1, Year 2 (before sector change), and Year 2 (after sector change), respectively. The median lead concentrations in Sector A at Sewerage Pumping Station, National Parks, and Waterboard sites were within the range of 0.10 – 0.18 µg/m^3 across all monitoring periods. The median lead concentrations in Sector B were similar across the four monitoring periods from Year 1 to Year 3, ranging between 0.05 and 0.08 µg/m^3.

Silver City Highway

The highest median lead concentration was 0.91 µg/m^3 measured in Sector A in Year 3. It was the highest out of all monitoring sites, sectors, and monitoring periods. The Sector A ambient lead concentration in Year 3 was 57%, 82%, and 44% higher than in Year 1, Year 2 (before the sector change), and Year 2 (after the sector change), respectively.

The median ambient lead concentrations were significantly higher in Sector B after the sector change in Year 2. Compared to the Sector B lead concentrations in Year 1, the level was more than double in Year 3 and over six-times the levels in Year 2 (after sector change). However, Sector B recorded only five valid samples in both Year 2 (after the sector change) and Year 3. Sector B recorded few valid samples (e.g., 3 days in Year 2 and 2.7 days in Year 3) due to the low wind speed/low frequency of winds from the north east and south west resulting in insufficient sampling times for most of the Sector B samples. So the median values are likely to be biased. These few days of Sector B data show relatively high ambient lead concentration. That local winds are being steered by the LoL at this site. The Silver City Highway sampling site is an open area, but is surrounded by trees and shrubs (3-5 meters away). This may reduce windspeeds and alter the local wind direction at this site resulting in fewer samples (particularly for Sector B.

5.4 Trends in median lead-in-TSP

Table 7 presents the lead-in-TSP (mg/kg) levels measured in 2017, 2018-2019, and 2019-2020, and Figure 37 presents the spatial distribution of median lead-in-TSP levels in all sampling period. The trend across all sites was a general increase in lead-in-TSP levels in Year 3 compared to Year 2, and a general decrease in lead levels in Year 3 compared to Year 1. Sector A Pb-in-TSP values in Year 3 are consistently higher than Sector B values by a factor of 2 to 5. The highest lead-in-TSP levels were consistently measured at the Silver City Highway site in both sectors.

The lead-in-TSP levels were lower during days with elevated dust compared to days with low TSP levels. The decrease in lead mass in these TSP samples was likely due to an increase in non-lead bearing dust diluting the lead content.

Table 7 Median values of measured ambient lead-in-TSP levels by sampling site and sampling period.

BHELS Sampling Site	Sector	TSP-Pb (mg/kg)			
		Year 1	Year 2[a]	Year 2[b]	Year 3[c]
National Parks (NP)	A	2,670	2,504	2,024	2,361
	B	1,680	1,134	996	1,349
Wetlands (WE)	A	2,370	1,591	1,713	2,298
	B	1,080	832	482	565
Waterboard (WA)	A	3,850	3,320	2,098	2,654
	B*	-	-	196	654
Sewerage Pumping Station (SPS)	A	4,780	1,244	1,840	3,538
	B	1,550	1,374	462	894
Silver City Hwy (SC Hwy)	A	9,110	8,140	6,416	10,823
	B	2,170	2,135	1,981	2,110

[a]: before the sector change covering 16 Jan 2018-29 August 2018 (225 days); [b]: after the sector change covering 29 August 2018 to 20 Feb 2019 (175 days); [c]: Year 3 data based on 378 days' sampling covering 27 Feb 2019 to 10 March 2020.

*Waterboard sector B sampler installed 23 October 2018

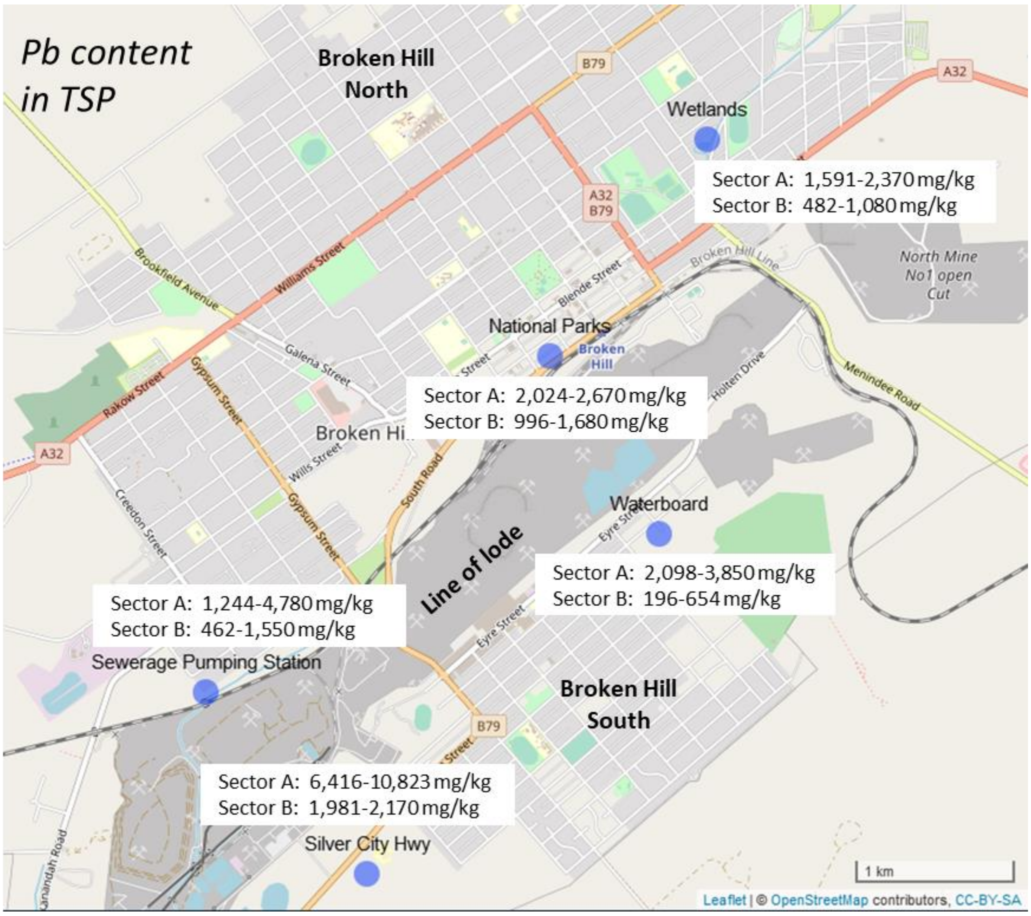

Figure 37 Spatial distribution of median lead-in-TSP measured in all sampling period.

National Parks

The Sector A median lead-in-TSP levels in Year 3 was about 17% higher than in Year 2 (after the sector change), 6% lower than in Year 2 (before the sector change), and 11% lower than in Year 1.

The median lead-in-TSP in Sector B was approximately half of the lead-in-TSP levels in Sector A. In Sector B, the median lead-in-TSP levels were also higher by 19% and 36% in Year 3 than in before and after the sector change in Year 2, respectively. The Sector B median lead-in-TSP was about 20% lower in Year 3 than in Year 1.

In general, the lead-in-TSP levels in Sector B were relatively higher at the National Parks site during the last two monitoring periods compared to the Sector B results at all other sites, except the Silver City Highway site.

Wetlands

The Year 3 lead-in-TSP level in Sector A was higher by 44% and 34% compared to the Year 2 results before and after the sector change. Relative to Year 1, the Sector B lead-in-TSP level was similar to Year 3.

In Year 3, the Sector A median lead-in-TSP level was almost four-times higher relative to the level in Sector B. In general, the lead-in-TSP levels were lower in Sector B relative to Year 1 and Year 2 before the sector change. However, a slight increase (17%) in the median lead-in-TSP level was observed in Year 3 compared to Year 2 after the sector change.

Waterboard

The Sector A median lead-in-TSP level was higher by 26% in Year 3 compared to Year 2 after the sector change. However, the lead-in-TSP level in Sector A was lower by 31% and 20% in Year 3 than in Year 1 and Year 2 before the sector change, respectively.

The Sector B measurements were established from Year 2 from 29 August 2018. The Sector B median lead-in-TSP level in Year 3 was 654 mg/kg which is over three times higher than in Year 2. Nevertheless, the Sector B median concentration at Waterboard site was the lowest in Year 2 and the second lowest in Year 3 after Wetlands site. Compared to the lead-in-TSP in Sector A, the lead levels in Sector B were over four times lower in Year 3, which is similar to the Wetlands site.

The Sector B captured lead bearing TSP from the residential South Broken Hill region, so the measured lead-in-TSP concentrations were a good indicator of the expected lead-in-TSP levels in the residential areas nearby waterboard site. It highly likely that the deposition pattern is not even in these residential areas, as described in Section 3.2, rather a lead concentration gradients would be expected depending on how close a residential area is to a mine or the Line of Lode, and the direction of prevailing winds in a residential area.

Whereas, Sector A was downwind of the LoL and associated mining activities at the nearby Rasp Mine. Therefore, the elevated lead-in-TSP in Sector A was expected to be higher than in Sector B.

Sewerage Pumping Station

The Year 3 Sector A lead-in-TSP level was the second highest after Silver City Highway. The Sector A median lead-in-TSP level was almost 92% higher than in Year 2 after sector change, but lower by 26% compared to Year 1.

Similar to Sector A, the Sector B lead-in-TSP level in Year 3 was also higher by 93% compared to Year 2 after the sector change. In Year 3, the lead level in Sector B was 42% lower than in Year 1. After the change in the wind sector in Year 2, the overall median lead-in-TSP level was lower in Sector B than in Year 1 and Year 2 before the sector change.

Silver City Highway

The lead-in-TSP level in Sector A was 10,823 mg/kg in Year 3, which was the highest measured across all sites and all monitoring periods. The Sector A lead-in-TSP level was higher by 68% in Year 3 than in Year 2 after sector change. Also, the Sector A level was 19% and 33% higher in Year 3 than in Year 1 and Year 2 before the sector change.

The median lead-in-TSP levels in Sector B were similar across all monitoring periods, ranging between 1,981 to 2,170 mg/kg. It should be noted that there was very limited valid sample data in Sector B during last two monitoring periods in Years 2 and 3. This was due to the low number of valid sampling days, as explained in Section 5.3.5. The very low sample sizes may have biased the Sector B median values.

6 Conclusions

This report presents the results of Year 3 (2019-2020) of the BHELS and compares these results with the results of Year 2 (2018-2019) and Year 1 (2017-2018) of the study. In this study, TSP monitoring by D-HVAS and DDGs has been conducted at five sites, and two detailed reports have been produced to analyse the results and likely lead sources.

Sector A results indicate that the majority of lead rich TSP was likely from the vicinity of the mining activities as expected. The Sector B results suggest the existence of lead rich TSP in residential north and south Broken Hill. While the lead levels were lower in Sector B than in Sector A as expected, the significant variation in Sector B median concentrations was observed across all monitoring periods. For instance, the Sector B median ambient lead concentrations ranged between 0.02–0.37 µg/m^3, suggesting strong lead concentration gradients depending on how close a residential area is to a mine or the Line of Lode, and the direction of prevailing winds in a residential area. Therefore, it is expected that even larger variations across the north and south Broken Hill residential areas. It is likely that the lead rich TPS was deposited at some time (recently and historically) in north and south Broken Hill (Sector B and non-mining source areas) and was subsequently being resuspended and mixed with other dust.

In Year 3, the median ambient lead concentrations and lead-in-TSP levels were consistently higher in Sector A (mining source areas) at each site than in Sector B (non-mining source areas), which is similar to the results in Years 1 and 2 reports. The Sector B results indicate the presence of lead bearing dusts in non-mining, residential areas in Broken Hill. The episode analysis finds that on a finer time scale (weekly) lead levels were higher occasionally in Sector B than in Sector A (e.g, Episode 3 at National Parks, 8 – 15 January 2020).

The median lead levels calculated for each site, sector, and monitoring period found that the highest lead level was 0.91 µg/m^3 in Sector A at Silver City Highway during Year 3. The median ambient lead levels in Sector B were generally low (less than 0.09 µg/m^3) in all monitoring periods, except Silver City Highway (0.06 – 0.37 µg/m^3). It should be noted that the small number of valid Sector B samples at the Silver City Highway site could have biased the median concentrations.

Since the beginning of the BHELS, the lowest ambient lead concentrations in Sector A were recorded at the Wetlands site, as the site is the furthest away from the major mining sources compared to the rest of the sites. The median ambient lead concentrations across all sites and sampling periods indicate that the Sector A lead levels were about three times higher than in Sector B. The highest lead levels were measured at the Silver City Highway site (in both Sector A and Sector B), indicating the higher lead levels in the western part of south Broken Hill which is downwind of mining activities at the PSO site.

The median lead-in-TSP level at Silver City Highway was 10,823 mg/kg in Year 3, which was the highest measured across all sites, sectors and monitoring periods. The trend in overall lead-in-TSP levels across all sites was a general increase in Year 3 compared to Year 2, and a general decrease in lead levels at all sites (except Silver City Highway) in Year 3 compared to Year 1.

As shown in Figure 7, the lead masses for each site and sector indicate that the highest lead mass was measured at the Silver City Highway in Sector A, which coincided with the high ambient lead concentrations and lead-in-TSP levels. The results indicate that the most likely source of the high lead levels in Sector A at Silver City Highway was the nearby mining operation at PSO, which includes a Run-of-Mine (ROM) stockpile.

The monthly DDG results showed that the deposited dust was generally below 5 g/m^2/month from February 2019 to October 2019, excepting a dust storm event in July 2019 and two dust storm events in August 2019. The Broken Hill region was impacted by frequent dust storms resulting in elevated dust deposition occurred from October 2019 to February 2020. The monthly DDG results showed that the highest lead levels in deposited dust were recorded at Silver City Highway. For instance, in May 2019, the deposited lead level at Silver City Highway was 0.016 grams lead/m^2/month, which was on average 11.3 times more lead in deposited dust than average of the other sites.

7 Recommendations

Given the consistency of the lead measurements over the past three years, the future of the continuous monitoring program needs to be considered. It is recommended that a monitoring network be implemented that is compliant with the Ambient Air Quality National Environment Protection Measure (AAQ NEPM)[6]. This network will assess community exposure and allow comparison with the health standard for lead.

AAQ NEPM compliant sampling requires sampling and analysis of TSP and lead for 24 hours every sixth day (i.e., 1 day in 6). The NEPM goal for lead is 0.5 µg/m^3 based on the mean of lead concentrations over a calendar year. The network would make use of the instruments purchased for the BHELS study and would only require on-going operational and analysis costs.

[6] National Environment Protection (Ambient Air Quality) Measure as amended, National Environment Protection Council, 7 July 2003, Canberra. https://www.legislation.gov.au/Details/C2004H03935 - refer Schedule 2, Standards and Goals.

Appendix A Data Completeness

National Parks (NP)	Sampling	
	Sector A	Sector B
Total # TSP Samples	**55**	**55**
D-HVAS failure	0	0
Low sample duration	1	10
Lab data not reported	0	0
Flow rate out of range	0	0
Filter installation/collection errors	2	2
Filter damaged during sample collection	0	0
HVAS wind sensor/test failure	0	0
Total invalidated	**3**	**12**
Total valid	**52**	**43**

Wetlands (WE)	Sampling	
	Sector A	Sector B
Total # TSP Samples	**55**	**56**
D-HVAS failure	0	0
Low sample duration	0	15
Lab data not reported	0	0
Flow rate out of range	0	0
Filter installation/collection errors	1	3
Filter damaged during sample collection	0	0
HVAS wind sensor/test failure	0	0
Total invalidated	**1**	**18**
Total valid	**54**	**38**

Waterboard (WA)	Sampling	
	Sector A	Sector B
Total # TSP Samples	**56**	**56**
D-HVAS failure	0	0
Low sample duration	2	2
Lab data not reported	0	0
Flow rate out of range	0	0
Filter installation/collection errors	3	1
Filter damaged during sample collection	0	0
HVAS wind sensor/test failure	0	0
Total invalidated	**5**	**3**
Total valid	**51**	**53**

Sewerage Pumping Station (SPS)	Sampling	
	Sector A	Sector B
Total # TSP Samples	**56**	**56**
D-HVAS failure	0	0
Low sample duration	2	10
Lab data not reported	0	0
Flow rate out of range	0	0
Filter installation/collection errors	3	3
Filter damaged during sample collection	1	0
HVAS wind sensor/test failure	0	0
Total invalidated	**6**	**13**
Total valid	**50**	**43**

Silver City Hwy (SC Hwy)	Sampling	
	Sector A	Sector B
Total # TSP Samples	**55**	**54**
D-HVAS failure	0	0
Low sample duration	6	49
Lab data not reported	0	0
Flow rate out of range	2	0
Filter installation/collection errors	0	0
Filter damaged during sample collection	0	0
HVAS wind sensor/test failure	0	0
Total invalidated	**8**	**49**
Total valid	**47**	**5**

Appendix B Dust Events

Date	Location	Nearest BHELS Sampling Site	Approx. times and duration	Event
5/3/19	Broken Hill and surrounds	All sites	From about 14:45 for about 2 hours	Mild dust storm associated with strong NW winds
29/6/19	Broken Hill and surrounds	All sites	Mid afternoon	Mild dust storm associated with strong WNW - W winds
12/7/19	Broken Hill and surrounds	All sites, especially southern	14:20 – 15:40	Dust haze, especially to south of city. Strong westerly winds.
8-10/8/2019	Broken Hill and surrounds	All sites	Mid afternoon 8th – 10th August	Strong north-westerly winds, especially on 8th; local raised dust on outskirts of town, mild dust storm afternoon of 8th.
18/8/2019	Broken Hill and surrounds	All sites	From about 13:00-19:00	Strong westerly winds, mild dust storm
6/9/2019	Broken Hill and surrounds	All sites	From about 10:00 for several hours	Strong westerly winds. Raised dust and dust haze from about 10:00, mild dust storm from about 11:30, moderate dust storm from around 16:30 – 17:45, mild from around 17:45
3/10/19	Broken Hill and surrounds	All sites	Most of afternoon	High dust haze associated with strong North – North-westerly winds.
24/10/19	Broken Hill and surrounds	All sites	From about 1 pm onwards for several hours	Mild dust storm, winds from N-NE.
1/11/19	Broken Hill and surrounds	All sites	From about 11 am onwards for several hours	Dust haze from ~ 11 am, mild dust storm from ~ 12 pm, winds from N-NNE, 30 – 50 kmph.
6/11/19	Broken Hill and surrounds	All sites	From about 2 pm onwards for several hours	Mild dust storm associated with strong WNW winds

Date	Location	Nearest BHELS Sampling Site	Approx. times and duration	Event
8/11/2019	Broken Hill and surrounds	All sites	From about 10 am onwards for several hours	High level dust haze assoc with strong WNW winds
21/11/19	Broken Hill and surrounds	All sites	From about 9 am onwards for several hours	High level dust haze assoc with strong N winds – dust haze from ~ 9 am, mild dust storm ~ 10 am – 12:00, high level dust haze from ~ 1:00, dust storm again from ~ 3pm
29/11/19	Broken Hill and surrounds	All sites	From about 19:45 for a couple of hours	Dust storm on back of strong southerly winds
1/12/19	Broken Hill and surrounds	All sites	From about 16:00 for several hours	Dust haze / mild dust storm associated with strong westerly winds
9/12/19	Broken Hill and surrounds	All sites	From about 20:30 for about an hour	Dust haze / mild dust storm associated with strong South-Westerly - Southerly winds
19/12/19	Broken Hill and surrounds	All sites	All day	High level haze, believe smoke haze
20/12/19	Broken Hill and surrounds	All sites	All day	High level haze, believe smoke haze. Brief dust storm in evening for around half an hour or so.
21/12/19	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze.
30/12/19	Broken Hill and surrounds	All sites	From about 18:45	Dust storm from about 18:45 with strong WNW winds; mild dust storm by 20:30
31/12/19	Broken Hill and surrounds	All sites	All day	Hazy all day, smells strongly of smoke; South winds
1/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
2/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze

Date	Location	Nearest BHELS Sampling Site	Approx. times and duration	Event
3/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
4/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
5/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
6/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
7/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
8/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
9/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, believe smoke haze
10/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, quite heavy from around 12 o'clock with SW wind. Mild dust storm from about 17:30 associated with strong SSW wind.
11/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day, SW wind
13/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day
14/1/20	Broken Hill and surrounds	All sites	All day	Hazy all day
15/1/20	Broken Hill and surrounds	All sites	All day	Slight haze until mid afternoon.
22/1/20	Broken Hill and surrounds	All sites	From mid morning until about 22:30	Strong northerly winds. Locally raised dust from about 9:30 am, light dust haze from about 11 am and dust storm from about 1 pm, which lasted for several hours. Visibility reduced to less than 200m (ie less than a city block) for some of the afternoon.

Date	Location	Nearest BHELS Sampling Site	Approx. times and duration	Event
23/1/20	Broken Hill and surrounds	All sites	From mid afternoon for several hours	Light, high level dust haze visible all around city. Moderate Westerly wind.
31/1/20	Broken Hill and surrounds	All sites	From about 10 am for several hours	From about 10:00 am, locally raised dust being kicked up from bare soil on back of strong NNW winds. From about 11:30, dust haze visible all way around town. From about 14:30, mild dust storm.
1/2/20	Broken Hill and surrounds	All sites	From about 10:30 am for several hours	From about 10:30, mild dust storm for several hours associated with strong NW winds.
7/2/20	Broken Hill and surrounds	All sites	From about 17:00 for ~ 20 minutes	Brief mild dust storm ahead of SSE winds and light shower.
8/2/20	Broken Hill and surrounds	All sites	From about 19:00 for couple of hours	Mild dust storm ahead of SSE winds.
18/2/20	Broken Hill and surrounds	All sites	From about 10:30 for most of the day.	Light dust haze visible all around city; moderate SW winds