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A South Australian tailings storage facility: dust emissions study

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Abstract

A new copper-gold-silver mine has been developed approximately 160 km north of Port Augusta on the eastern margin of the Arcoona Plateau in South Australia, part of the traditional lands of the Kokatha people. The area is a rolling 'gibber plain'[†] surrounded by alluvial plains, stabilised dunes and salt playa such as Lake Torrens (Ngarndamukia).

Tailings from the mine are delivered as a salt-rich slurry to the tailings storage facility (TSF); a valley-fill impoundment located at the headwaters of the local creek. The fine tailings spread and as they settle, water rises to the slurry surface. As the tailings dry in the arid South Australian climate, dissolved mineral salts crystalise (effloresce) at the tailings surface, forming a durable crust that inhibits wind erosion of the fine tailings.

In 2023 BHP commissioned WSP to undertake a dust emissions study for the mine's TSF. The study deployed a Portable In Situ Wind Erosion Laboratory (PI-SWERL) to measure dust emissions fluxes directly, as a function of wind shear stress, from undisturbed dry tailings surfaces. These measurement data are then converted into dust emissions fluxes (i.e. $\mu g/m^2/s$) as a function of 10-m wind speeds (i.e. m/s).

The study included PI-SWERL measurements for various tailings types, the surrounding gibber plain, regional alluvial deposits and a salt playa. The study also included ancillary measurements of surface properties (e.g. moisture content and particle sizes). Our paper presents the PI-SWERL technique and results of the dust emissions study, and includes a discussion about what the study results mean in terms of local air quality, dust deposition and the long-term (> 100 years) wind erodibility of the mine's TSF.

Keywords: *tailings, tailings storage, mine closure, environmental impacts, dust, dust emissions, air quality, wind erosion, particle size*

1 Introduction

The copper-gold-silver mine (the operation) is located near Pernatty, South Australia. The mine is located on the traditional lands of the Kokatha people and represents one of Australia's largest copper reserves. An underground sublevel caving mining method is employed at the operation, and the expected mine life is approximately 20 years. The operation includes a valley-fill tailings storage facility (TSF) formed by a cross-valley embankment approximately 4.5 km down-valley from the head of the local creek.

The mine produces tailings as a wet slurry composed of mine tailings and brine. Tailings are delivered via a pipeline to the TSF. As they spread, the fine tailings settle ($d_p < 75\ \mu m$) and water rises to the slurry surface. As the tailings dry in the arid South Australian climate, dissolved mineral salts crystalise (effloresce) at the tailings surface, forming a durable crust that inhibits wind erosion of the fine tailings. The TSF is designed to

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[†] Also 'stoney downs', desert or cobble pavement.

store approximately 145 Mt of (dry) tailings after 20 years of emplacement and will have a final surface area of approximately 510 ha.

The current TSF strategy is an impounded valley-fill that leaves the tailings surface uncapped. It is considered unlikely that the tailings surface will support revegetation. This makes the tailings surface susceptible to enhanced soil erosion. Soil erosion includes both fluvial (water) and aeolian (wind) erosion. Which erosion process is dominant depends on local meteorology, the soil/tailings composition and the regional climate, which can vary over decadal and longer time scales.

1.1 Environmental setting

The operation sits within the Arcoona Plateau subregion (GAW4) of the Gawler bioregion (Federal Department of Climate Change, Energy, the Environment and Water [DCCEEW] 2000) and is located approximately 65 km east of Woomera, South Australia. The region is rich in biodiversity, with 419 native flora species, 54 fauna species and 112 bird species (including migratory varieties). Regional geologic features include:

- Flinders Ranges — the eastern study boundary is the Flinders Mountain Ranges, an ancient and once-large, deeply folded mountain range. The landscape between the Flinders Ranges and Lake Torrens contains alluvial fans and stabilised dunes overlain by solonised brown soils (Drexel & Preiss 1995) that support degraded woodlands, Acacia and chenopod shrublands (Government of South Australia 2009a)
- Lake Torrens (Kuyani: Ngarndamukia) — an ephemeral lake located within the Torrens Basin (GAW6), a north–south trending structural depression. During heavy rains the lake becomes brackish and muddy bottomed. The lake rarely breaches the hydrological divide at its southern end, making it a mostly closed evaporite basin that becomes a salt playa as the lake dries out
- Arcoona Plateau — the mine and the TSF are in the Arcoona Plateau subregion, a series of upland hills and plains that are the highest part of the regional Stuart Shelf geological structure that ends at the eastern shore of Lake Gairdner in the west (Drexel & Preiss 1995). Soils in this area are desert loams (Drexel & Preiss 1995) overlaid by a quartzite gibber pavement. The local environment at the mine and TSF supports saltbush low shrublands (Government of South Australia 2009b)
- Gawler Lakes — the lowlands west of the Arcoona Plateau are home to the calcareous plains and saline lakes of the Gawler Lakes subregion (GAW3), as well as sand sheets and dune fields characteristic of the Roxby subregion (GAW7). South Australian dunes have been active throughout the late Pleistocene (0.012 to 1.0 Mya) and contain paleosols indicative of periods of dune stability (Fujioka et al. 2009). Local dunes were last active 12,000 to 24,000 years ago during the last glacial maximum when environmental conditions were cold, arid and windy compared to the present day (Fitzsimmons et al. 2013). Dunes are of the ‘narrow crested linear’ typology (Wasson 1986; Wasson et al. 1988), and are currently stable and overlain by solonised brown soils supporting western myall woodlands and chenopod shrublands (Government of South Australia 2009b).

Figure 1 displays an aerial photo of the TSF in August 2023. The TSF area is located on a local topographical high near the head of a local creek. The creek drains into an arm of Lake Torrens. The TSF embankment is approximately 13.5 km from the creek outflow and 4.5 km from the head of the creek such that the embankment creates a valley-fill type TSF. Figure 2 shows locations sampled within the regional study area, including a local alluvial floodplain and the surface of Pernatty Lagoon.

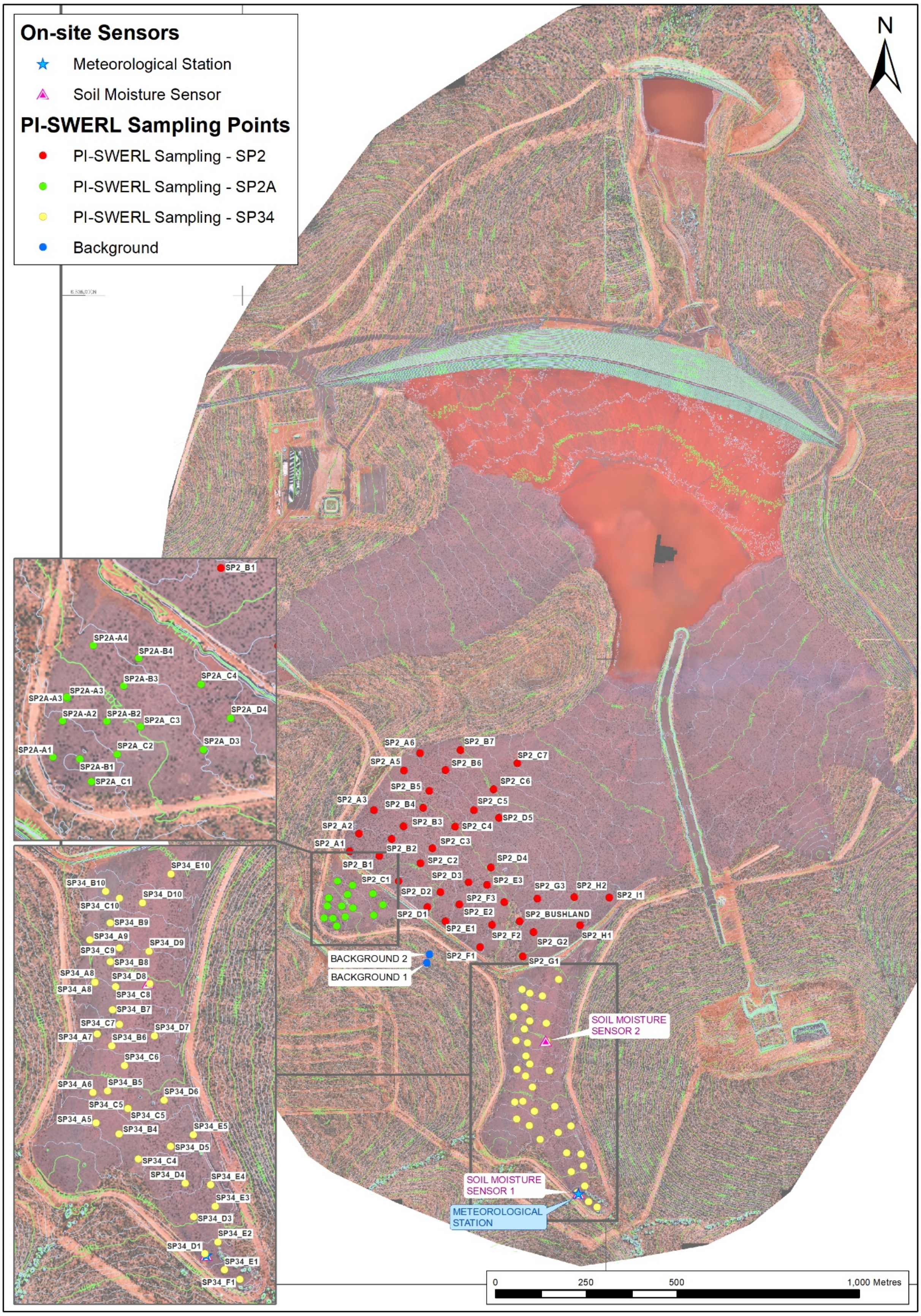


Figure 1 Tailings storage facility sampling locations at sampling point (SP) 2A (green), SP2 (red) and SP34 (yellow)

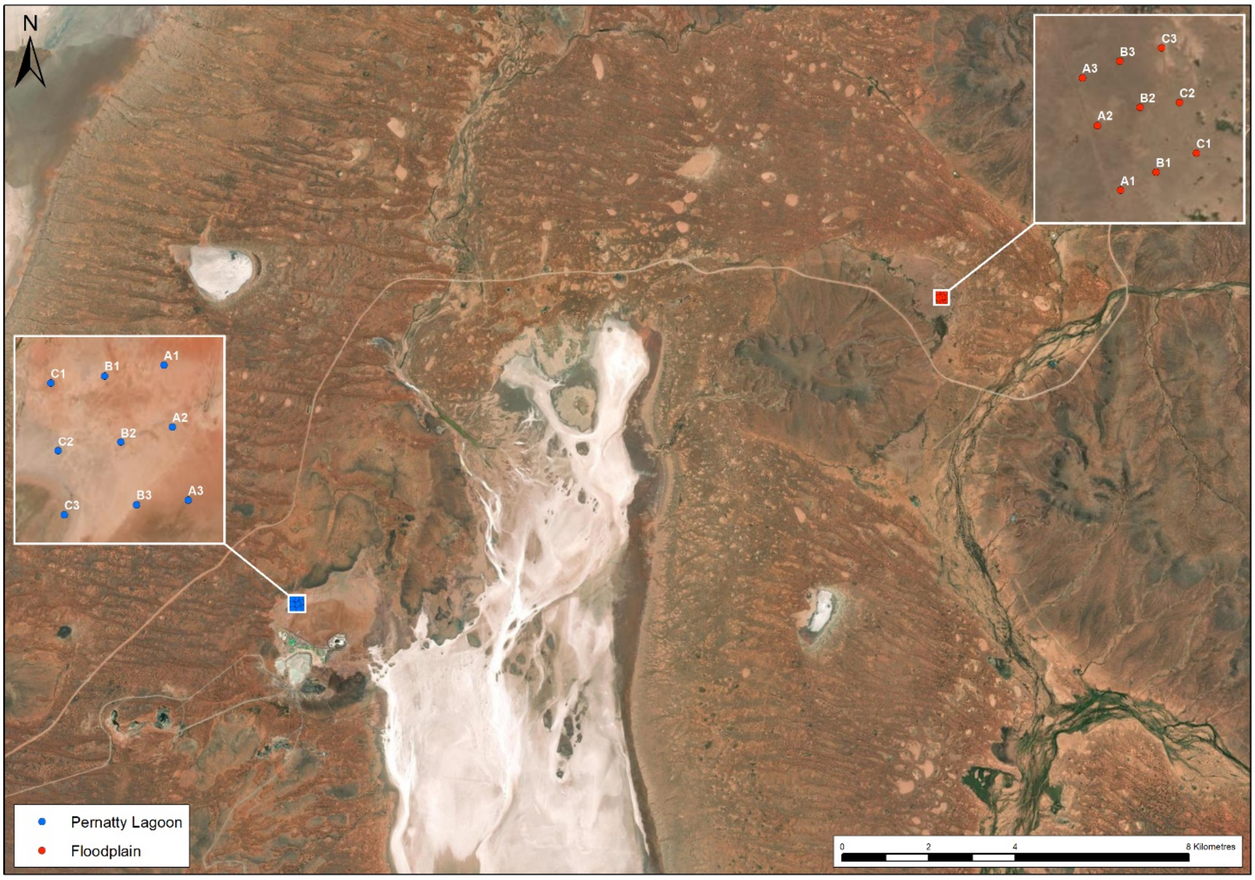


Figure 2 Floodplain and Pernatty Lagoon sampling locations, August 2024

1.2 Fluvial erosion

A landform evolution model (LEM) (SRK Consulting Australia [SRK] 2023) was created for the TSF and assumes a 3.5 m-thick mixture of colluvial and residual clay in the surrounding area. Results of the LEM indicated, over the 1,000-year time frame, that local soils will likely be eroded by precipitation, transported downstream and then deposited onto the TSF surface. This results in a reduction of the TSF basin's water-holding capacity over time, but overtopping of the embankment was deemed unlikely, even during extreme rainfall events (SRK 2023).

The LEM predicts erosion gulleys of 1 to 2 m depth could develop in the TSF over the 1,000-year time frame. The LEM also predicts greater erosion depths for existing soils, and that maximum TSF gulley depths will occur at the entry locations of the creek beds draining the present-day upstream catchment areas.

The LEM does not consider wind erosion, which is an important process in the semi-arid and arid landscapes of Australia (Ludwig et al. 1996; Breshears et al. 2003). The relatively susceptibility of local soils versus mine tailings to wind erosion, and the potential magnitude of dust emissions from these sources, were considered highly uncertain. This knowledge gap helped to motivate BHP and WSP to undertake this study.

1.3 Aeolian erosion

The wind erosion potential of soils and tailings depends on environmental factors and the physical attributes of the materials. Environmental factors include atmospheric temperature, pressure and relative humidity, wind speed and direction, and vegetation effects. Key physicochemical attributes of the tailings that affect their wind erosion potential include particle size and shape, density and moisture content.

Wind erosion potential for a given set of wind speeds critically depends on particle size. Particle size distributions must be approximated by adjusting for particle shape and density. In this assessment we will refer to particle aerodynamic diameter (d_{ae}), which is defined as the diameter representing a sphere of unit density. Geometric diameter (d_g) refers to the same unit sphere after correcting for particle density (ρ) but not shape.

Individual clay particles are small and considered fine dust ($PM_{2.5}$)[‡] and often occur as agglomerations (e.g. parna) that are weakly chemically bound to make them a coarser dust (PM_{10})[§]. Smooth high clay content surfaces can be resistant to wind erosion. However, they are often susceptible to wind erosion after fluvial erosion; especially if surfaces have been disturbed by forces that include mechanical grinding (e.g. road traffic) or chemical weathering. Due to their small size and plate-like shapes, clay- and silt-grade particles can be transported tens to thousands of kilometres (Hesse 1994; Marx et al. 2009).

Silts are highly erodible as coarse dust (PM_{10}, TSP[**]) and include particles between 2 and 75 micrometres (μm) in diameter. Individual particles larger than approximately 30 μm (i.e. coarse silt) do not remain suspended in the atmosphere for long (seconds to minutes). Loess is aeolian sediment dominated by silt-sized particles and it covers a significant portion of the Earth's surface. Muhs et al. (2014) state:

> *'Many loess sections consist of relatively thick deposits of mostly unaltered sediment with intercalated paleosols. Paleosols represent periods of landscape stability when loess deposition ceased or at least slowed significantly. Studies from several continents show that loess in most regions was deposited during glacial periods and paleosols formed during interglacial and interstadial periods'.*

Coarse silts (0.030 to 0.075 μm) and fine sand (0.075 to 0.420 μm) are subject to wind erosion. However, this process is dominated by saltation: the process by which particles move through a series of low bounces over the surface. Saltation contributes to abrasion: the mechanical breakdown of particles due to particle collisions. The amount and size of dust emitted by sandblasting and their dependence on soil properties and wind intensity are not well quantified (Marticorena 2014).

Figure 16.5a in Loess Records (Muhs et al. 2014) illustrates aeolian soils in Australia, including loess deposits and ocean areas with high dust deposition rates. Southern New South Wales and northern Victoria have prominent areas of soil derived from clayey loess (parna) deposited along the 'southeastern dust path' (Muhs et al. 2014). The fine-grained material that dominates Australian loess deposits is characterised by a high clay content, the presence of coarse silt-sized quartz, a strong red to yellow colour, and a variable presence of calcium carbonate. Muhs et al. (2014) go on to state:

> *'The current understanding of the genesis of Australian parna is that during arid and windy glacial periods of the Quaternary, fine-grained materials were winnowed from the sand hills, playas, and floodplains of what are now western New South Wales, northwestern Victoria, and eastern South Australia and deposited 300 to 500 km downwind as a blanket of sediment. A central tenet of this model is that while the transported material contained considerable clay-sized particles, it was transported in the form of silt-sized pellets accompanied by quartz companion grains'.*

Coarse sands, gravel and cobbles are not subject to wind erosion. However, after removal of loose soil and other surface material by the wind (i.e. deflation), coarse sands and cobbles can be left behind as stone pavements (also known as 'stony downs' or 'gibber plains'). The TSF is in a local valley within a rolling gibber plain and its surface is comprised of flat wind-worn quartzite cobbles that form an extensive pavement.

[‡] Suspended particulate matter with an aerodynamic diameter less than 2.5 micrometres

[§] Suspended particulate matter with an aerodynamic diameter less than 10.0 micrometres

[**] Total suspended particulate matter, i.e. those with aerodynamic diameter less than approximately 75 micrometres

Wind erosion of dust from this natural surface is currently very low, since the existing dust reservoir has been depleted over geologic time (0.012 to 2.58 My). The flat cobbles develop a desert patina and inhibit further wind erosion of the surficial soils. Underneath the cobble pavement, the soil, which is predominantly desert loam, is dry, friable and high in fines (dp < 0.075 mm). Thus, the local area has a high dust emissions potential if the surface pavement is disturbed (e.g. by road building or fluvial erosion).

2 Methods

2.1 Portable in situ wind erosion laboratory

Characterisation of the dust emissions fluxes on the surface of the tailings was undertaken using a DustQuant LLC PI-SWERL (portable in situ wind erosion laboratory) equipped with a TSI Dustrak DRX Aerosol Monitor 8583. A full description of this instrument and the technique can be found in Etyemezian et al. (2007; 2014).

The PI-SWERL is designed to directly measure the potential for wind erosion and dust emissions from exposed surfaces. The device uses an annular ring that rotates 60 mm above the soil test surface. Dust and sand are mobilised by the shear created by the rotating ring and the resultant dust concentrations within the chamber that encloses the annular ring are quantified. While the PI-SWERL does not realistically simulate natural wind erosion processes that are often driven by saltation, measurements with the device provide a robust index of wind erosion/dust emission potential up to and including the onset of saltation.

The methodology for PI-SWERL measurements onsite was as follows:

- At each test location the PI-SWERL was placed onto the level test surface. The instrument included a foam skirt that sealed against the test surface, a rotating blade that created a wind field and a DustTrak DRX instrument measuring size-resolved particulate matter concentrations (d_{ae} ~< 100 µm) in real time.
- PI-SWERL test measurements were collected over a period of 10–12 minutes, during which the PI-SWERL exposed the surface to steadily increasing wind shear stress.
- At each location, surface characteristics were recorded by the field staff.

The process was then repeated at the next testing location.

2.2 Supporting measurements

2.2.1 Meteorological measurements

The operation includes an onsite meteorological station near the TSF which is installed at an elevation of 205 m. The meteorological measurements are collected at a height of approximately 3 m and include measurements of temperature, relative humidity and wind.

Data from the closest Bureau of Meteorology (BoM) station to the site were obtained to confirm that the wind measurements recorded onsite were representative and unaffected by local topography. The closest BoM station is at Woomera aerodrome (BoM station ID: 016001). This station is located at 31.16 south and 136.81 east at an elevation of 167 m and is approximately 65 km west of the operation. Woomera rainfall and hourly wind (direction and speed) data from May 2020 to February 2024 were compared to the onsite data.

2.2.2 Soil particle size and moisture

Soil particle size distributions and moisture content samples of approximately 0.5 to 1.0 kg of surficial tailings or natural soil were collected on a 200 x 200 mm area to a depth of 10 mm. A total of nine surficial samples were collected during the study. Specific sampling locations were evenly distributed across the tailings surface to capture the overall particle size distribution and moisture content. The soil and tailings samples collected onsite were analysed for particle size distributions and moisture content by WSP Australia’s Melbourne Geotechnical Laboratory (NATA Accreditation: 1961).

2.3 Field measurements

2.3.1 Portable in situ wind erosion laboratory measurement locations

PI-SWERL measurements were obtained during two seasons: summer (February) and winter (August) of 2023. Here we present the August 2023 results which were collected over:

- three separate tailings discharge points (i.e. spigots)
- a background gibber plains location near the TSF
- two natural analogue environments
    - Pernatty Lagoon
    - A natural local floodplain.

In consultation with BHP, tailings deposited from spigot 2A (SP2A), spigot 2 (SP2) and spigot 34 (SP34) were selected for evaluation during the study. These spigot locations were specifically chosen as the areas had previously deposited tailings (up to November 2023) and no physical disturbance (i.e. no addition of fresh tailings) was scheduled during the study period.

Local background PI-SWERL measurement locations were selected in the bushland surrounding the TSF in gibber plains areas not previously disturbed by mining activities. These sampling locations are identified along with the TSF sampling locations in Figure 1.

During the measurements in August 2023, access to two ‘natural’ (i.e. undisturbed) locations near the mine was organised by BHP. These natural locations are the Pernatty Lagoon and a natural floodplain accessible in Section 2 of the Western Access Road (Figure 2).

Specific PI-SWERL test locations were evenly distributed in a grid pattern across the tailings and natural locations (Figures 1 and 2). A total of 96 primary locations were selected to conduct PI-SWERL measurements on the tailings. Four locations in the natural bushland outside of the tailings deposition area were chosen to obtain the background measurements. In August 2023, 18 primary locations were selected on the Pernatty Lagoon and natural floodplain areas. A series of duplicate, triplicate and repeat tests were also undertaken as part of QA/QC measures.

Photos typical of each surface subgroup of PI-SWERL test locations are presented in Figure 3. The site photos illustrate the visual differences between test surfaces, which are related to their wind erosion potential.

SP2A **SP2**

SP34 **Onsite background ('gibber plain')**

Pernatty Lagoon **Flood plain**

Figure 3 Photos illustrating the range of surfaces tested as part of the August 2023 study

2.3.2 Data analysis

The PI-SWERL test measurements were analysed based on Etyemezian et al. (2007, 2014). The overall study was structured similarly to that of Watson et al. (2014), which quantified threshold friction velocities, dust emissions potential and other key parameters from a variety of surfaces including unpaved roads, overburden, mine and quarry stockpiles, and tailings embankments and surfaces.

The PI-SWERL reports an instant PM$_{10}$ measurement (µg/s) and the footprint of the PI-SWERL test area is used to convert this to a dust flux measurement (µg/m^2/s). The revolutions per minute (RPM) of the PI-SWERL annular blade are converted to a friction speed (µ*) assuming a surface roughness equivalent of silt-clay dry lakebed. The friction speed is then converted to fastest kilometre wind speed at 10 m using the equations described in the United States Environmental Protection Agency (EPA) AP-42 Chapter 13.2.5 — Industrial Wind Erosion (US EPA 2006). All PI-SWERL post-processing was completed using the RStudio software package. The key parameters that were assessed from the PI-SWERL measurements are:

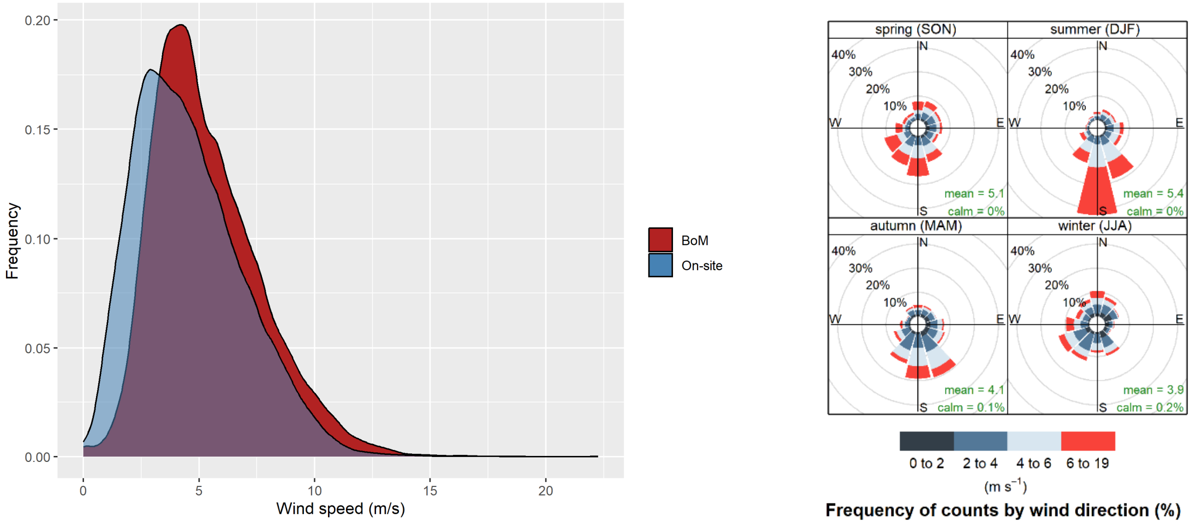
- PM_{10} threshold velocity = mean 10 m wind speed with a dust emissions rate > 1.0 mg/m2/s
- PM_{10} dust limited (Y/N) = whether dust emissions fluxes decrease (limited), are stable or increase (unlimited) while PI-SWERL RPMs are held constant after the onset of dust emissions
- Saltation (Y/N) = whether or not saltation of coarse silt or sand particles were observed after the onset of dust emissions, defined using the optical gate sensor (OGS) measurements which exceeded 10 counts for both sensors
- Saltation threshold velocity = mean 10 m wind speed corresponding to the onset of saltation. Where observed, the hypothesis is that dust 'limited' surfaces likely transition to 'unlimited' after the onset of saltation.

3 Results

3.1 Meteorology

The BoM rainfall classification for the local area is arid, with mean annual rainfall of less than 500 mm. The other key meteorological parameter is 10 m wind speed because it represents the state variable from which we calculate the wind erosion of tailings.

A frequency histogram of onsite wind speed measurements is consistent with, but slightly lower than, the BoM station at Woomera (Figure 4). The seasonal wind direction trends observed onsite were broadly consistent with the BoM data at Woomera and are also plotted in Figure 4.



(a) (b)

Figure 4 (a) Histogram of Woomera wind speeds compared to onsite station observations (b) and seasonal wind roses for Woomera

3.2 Soil moisture

Tailings are emplaced as a wet slurry high in dissolved salts and are not prone to wind erosion while wet. As the tailings dry, a salt crust forms that is predicted to inhibit wind erosion of the mineral component of the tailings. It is also reasonable to assume that the salt crust may inhibit evaporation from the tailings and/or tailings may retain a relatively high moisture content despite the arid site conditions. Onsite observations confirmed the presence of the salt crust and that recent (< 2 years) tailings remained moist to wet.

Soil surface samples were acquired for soil moisture and particle size distribution analysis, and the results are summarised in Table 1. The dry densities of each sample are determined gravimetrically as part of the size distribution analysis (see next section).

The volume of voids that are water-filled can be estimated by taking the ratio of the volume of water-filled space and the volume of solids (Vw/Vs). A robust estimate of the material's void ratio, or volume of water and air-filled spaces versus volume of solids (Vv/Vs), is needed to compute saturation. Table 1 includes estimates based on the observed soil types and knowledge of the material in situ.

The soil moisture results indicate that tailings materials are dense (ρ = 3.4 t/m3) compared to local lagoon and floodplain soils (all ~2.8 t/m3) as well as dry sodium chloride salt (2.2 t/m3). Higher particle density lowers the tailings wind-erosion potential.

Tailings and the lagoon materials were both observed to have high water saturations (85 to 100%), indicating they both can retain significant moisture under arid conditions. Local soils and the floodplain materials were dry to very dry (< 10–20%) and indicate that the background soils and floodplain materials are more likely to experience desiccation and wind erosion than tailings will.

Table 1 In situ soil moisture and bulk density information

Sample no	Location	MC (wt%)	Dry density (t/m^3)	Vw/Vs	Void ratio (est)	Saturation (est)	Descriptor
10	Floodplain	6.10%	2.83	0.18	1.00	18%	Clay, high plasticity
11	Floodplain	6.60%	2.86	0.20	1.00	20%	Clay, high plasticity
12	Lagoon	20.40%	2.76	0.71	0.70	101%	Sandy clay, low plasticity
13	Lagoon	18.30%	2.75	0.62	0.70	88%	Sandy clay, low plasticity
14	SP2	16.50%	3.30	0.65	0.70	93%	Inorganic clay, low plasticity
15	SP2	16.20%	3.39	0.66	0.70	94%	Inorganic clay, low plasticity
16	SP2A	15.00%	3.34	0.59	0.70	84%	Inorganic clay, low plasticity
17	SP34	17.50%	3.23	0.69	0.70	98%	Inorganic clay, low plasticity
18	SP34	15.00%	3.42	0.60	0.70	86%	Inorganic clay, low plasticity
Tailings average		**16%**	**3.34**	**0.64**	**0.70**	**91%**	

3.3 Soil particle size distributions

Surficial samples of tailings and (background) local materials were collected to evaluate their particle size distributions. Samples were collected over an approximately 200 x 200 mm area to a depth of approximately 10 mm. Figure 5[††] and Table 2 present particle size distribution information for each area. Local background samples were collected from beneath the surface cobbles (i.e. cobbles were removed). As expected, local soils contain high proportions of silt, sand and gravel. Where surficial cobbles are disturbed, the high proportion of fines (> 50%) means these soils will likely be subject to wind erosion.

[††] Here particle size distributions are plotted in a $dM/d_{\log}d_g$ versus $\log(d_g)$ format such that the area under each curve is equivalent to the total mass of all particles.

Surface materials at Pernatty Lagoon are similar to the local background soils (BKG) except that the gravel component is not present at Pernatty Lagoon. This results in a sandy-silt type classification for this soil. This material will also be subject to wind erosion since it contains relatively high proportions of fines (55%).

The background soils and Pernatty Lagoon material differ significantly from the surface materials found in the floodplain area. Floodplain soils were subject to fluvial transport, which has sorted the material. The result is a surface dominated by clay-grade material and a total fines content of 94%. These surfaces will be highly erodible and would be predicted to produce large quantities of dust at relatively low wind speeds.

The particle size distributions for the tailings material were relatively uniform, consistent with their methods of production, i.e. mechanical crushing/grinding in a ball mill. The tailings contain a very high proportion of fines (81%) which means that they also have a relatively high dust emissions potential.

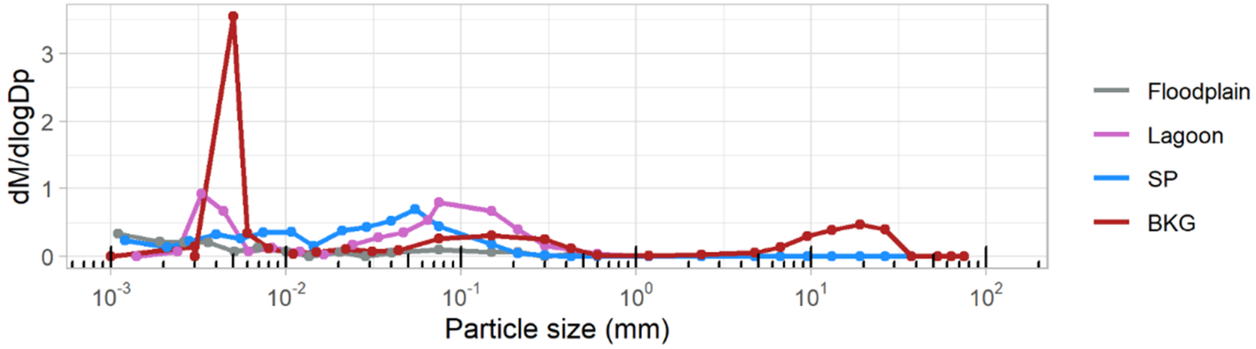


Figure 5 Mean particle size distribution for different sampling locations. Note SP is the mean of SP2, SP2A and SP34 test areas

Table 2 Mean soil gradings for tailing dam samples

Location	Clay (< 2 µm)	Silt (2–75 µm)	Sand (0.075–2 mm)	Gravel (2–60 mm)	Cobble (60–200 mm)
Background	5.7%	44%	24%	27%	0.0%
Floodplain	79%	15%	5.7%	0.0%	0.0%
Pernatty Lagoon	14%	41%	45%	0.0%	0.0%
SP2	23%	59%	18%	0.0%	0.0%
SP2A	21%	58%	21%	0.0%	0.0%
SP34	25%	57%	18%	0.0%	0.0%
Tailings average	**23%**	**58%**	**19%**	**0%**	**0%**

3.4 Portable in situ wind erosion laboratory measurements

The PI-SWERL measurements at SP2A, SP2 and SP34 were subdivided based on visual observations during the field measurements. These subgroups were created to help determine whether there are differences in dust emissions based on visual differences in tailings or their post-depositional history.

The SP2 ‘mixed’ location had local soils mixed with tailings and the SP34 ‘run-off’ location had local soils deposited onto tailings. This is consistent with the LEM (SRK 2023), which predicts that erosion of the local landscape will lead to local soils depositing onto tailings. Two locations outside of the tailings deposition area were chosen for local background (BK) measurements. Measurements were also taken offsite at the floodplain and Pernatty Lagoon. Like the local background areas, measurements at regional locations were undertaken so that their dust emissions potential could be compared to that of the tailings surface.

PI-SWERL measurements are summarised in Table 3 and illustrated in Figures 6 to 8. Natural floodplain materials have the lowest PM_{10} emissions thresholds and the highest PM_{10} emissions fluxes at all wind speeds. This is consistent with these materials being fine-grained and dry. Dry lagoon surfaces had PM_{10} threshold velocities lower than wet lagoon surfaces and emissions rates ~10x higher at 15 m/s wind speeds.

For all tailings locations, undisturbed tailings had PM_{10} threshold velocities higher than the threshold velocities for scoured tailings. Dust emissions rates from the scoured surfaces begin to exceed emissions rates from the undisturbed surfaces at wind speeds greater than 10–15 m/s. For the scoured or disturbed areas of the tailings, the measured PM_{10} threshold velocities were > 13 m/s.

Tailings affected by natural materials had higher PM_{10} emission fluxes (Figure 7) compared to the other tailing areas (Figure 8). The PM_{10} thresholds were lower for SP2 mixed compared to the SP34 run-off area (4.8 and 13 m/s). For both areas, the PM_{10} emissions fluxes exceed 500 µg/m2/s between wind speeds of 15–20 m/s. Wind speeds above 15 m/s (< 0.1%) occur very infrequently at the site, and the dust emissions at the SP2 mixed and SP34 run-off area are more similar to those of natural local material than for tailings.

Despite surface cracks, tailings with salt crusts were not prone to saltation. Saltation was only observed at background locations near the TSF, the floodplain, and disturbed SP2A and SP34 tailings. The onset of saltation can lead to the surface dust reservoir becoming unlimited. At sites with saltation, the OGS counts for both sensors were observed to exceed the 10 particles/s threshold. Table 3 shows that the threshold velocity for saltation of coarse silt and sand (dp > 0.100 mm) is higher than for PM_{10} emissions at the same location.

Table 3 Summary table of portable in situ wind erosion laboratory measurements

		PM_{10}			Saltation	
Tailings area	**Subgroup**	**N**	**Threshold velocity (m/s)**	**Dust limited?**	**observed**	**Threshold velocity (m/s)**
Background	**BK1 — Sandy**	2	8.9	Y	Y	16.3
	BK2 — Rocky	2	8.9	Y	Y	12.7
Floodplain	**n/a**	11	1.5	Y	Y	23
Lagoon	**Dry**	2	13	Y	N	–
	Wet	9	22	Y	N	–
SP2	**Undisturbed**	37	23	Y	N	–
	Scoured	6	9.0	Y	N	–
	Mixed	2	4.8	Y	N	–
SP2A	**Undisturbed**	6	16	Y	Maybe	–
	Scoured	8	16	N	Y	23.1
	Excavator	2	13	N	Y	15.1
SP34	**Undisturbed**	29	9.0	Y	Y	–
	Scoured	11	12	Y	N	–
	Run-off	1	13	Y	Y	15.1

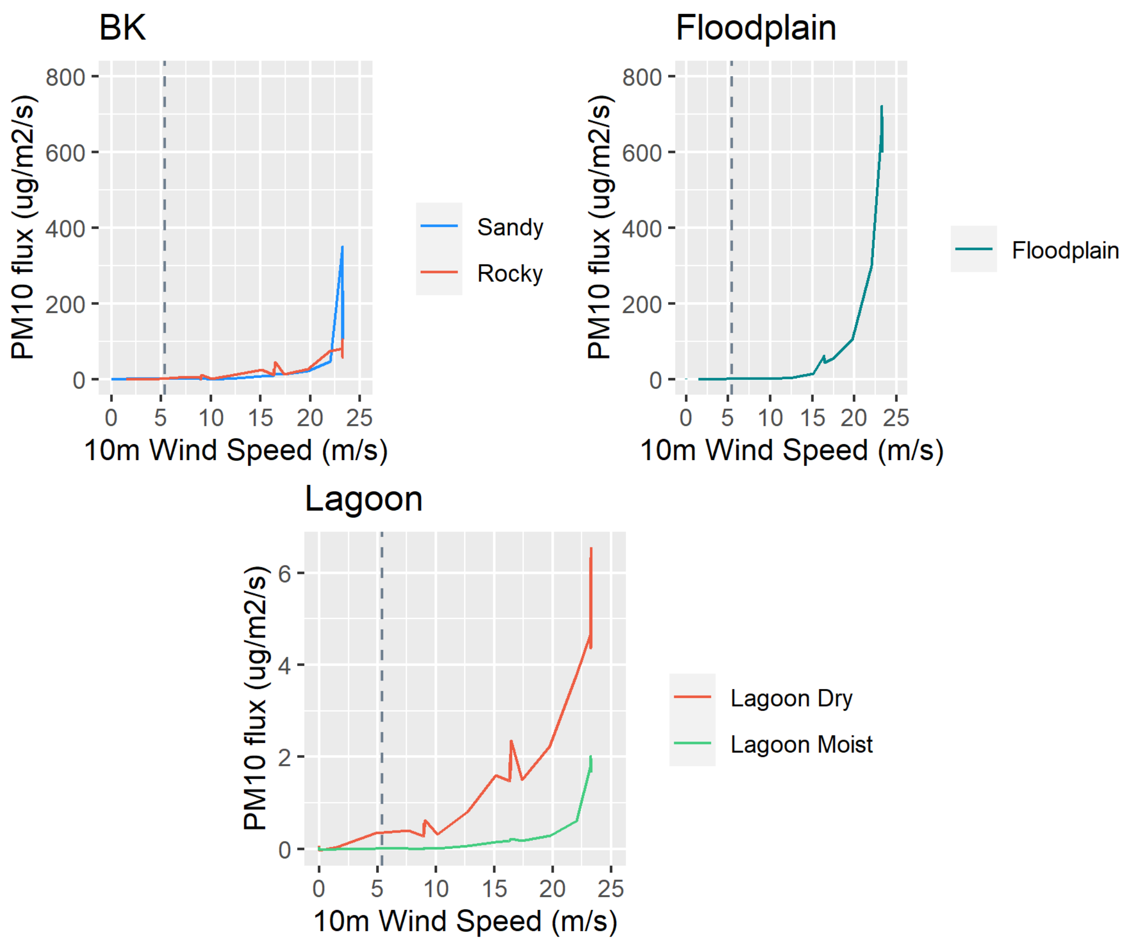


Figure 6 PM₁₀ emission fluxes (μg/m²/s) as a function of 'fastest mile' (gust) wind speed (m/s) for the August background locations. For reference, the 5.4 m/s threshold velocity assumed in the Environmental Impact Assessment is shown as a dashed line. Note the different y-axis scales

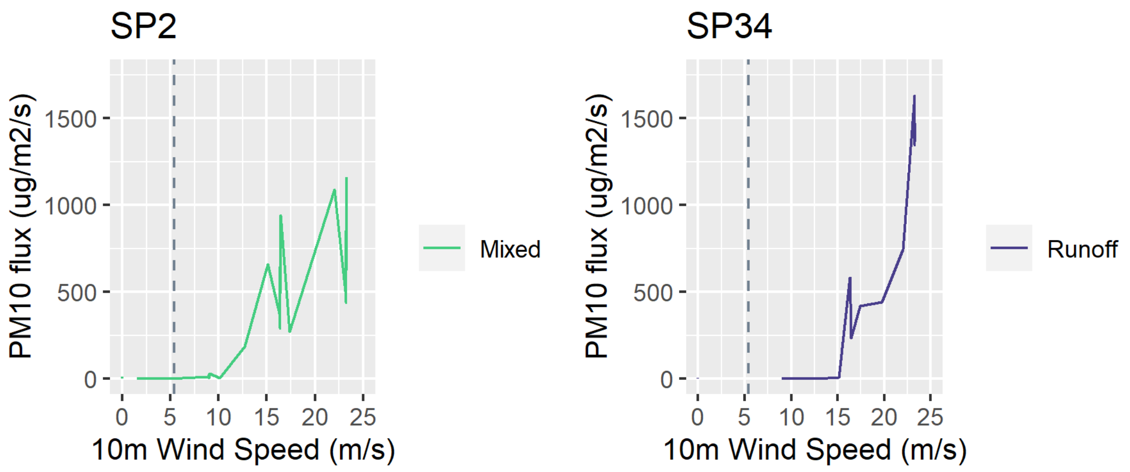


Figure 7 PM₁₀ emission fluxes (μg/m²/s) as a function of 'fastest mile' (gust) wind speed (m/s) for the August tailings locations affected by natural material. For reference, the 5.4 m/s threshold velocity assumed in the Environmental Impact Assessment is shown as a dashed line

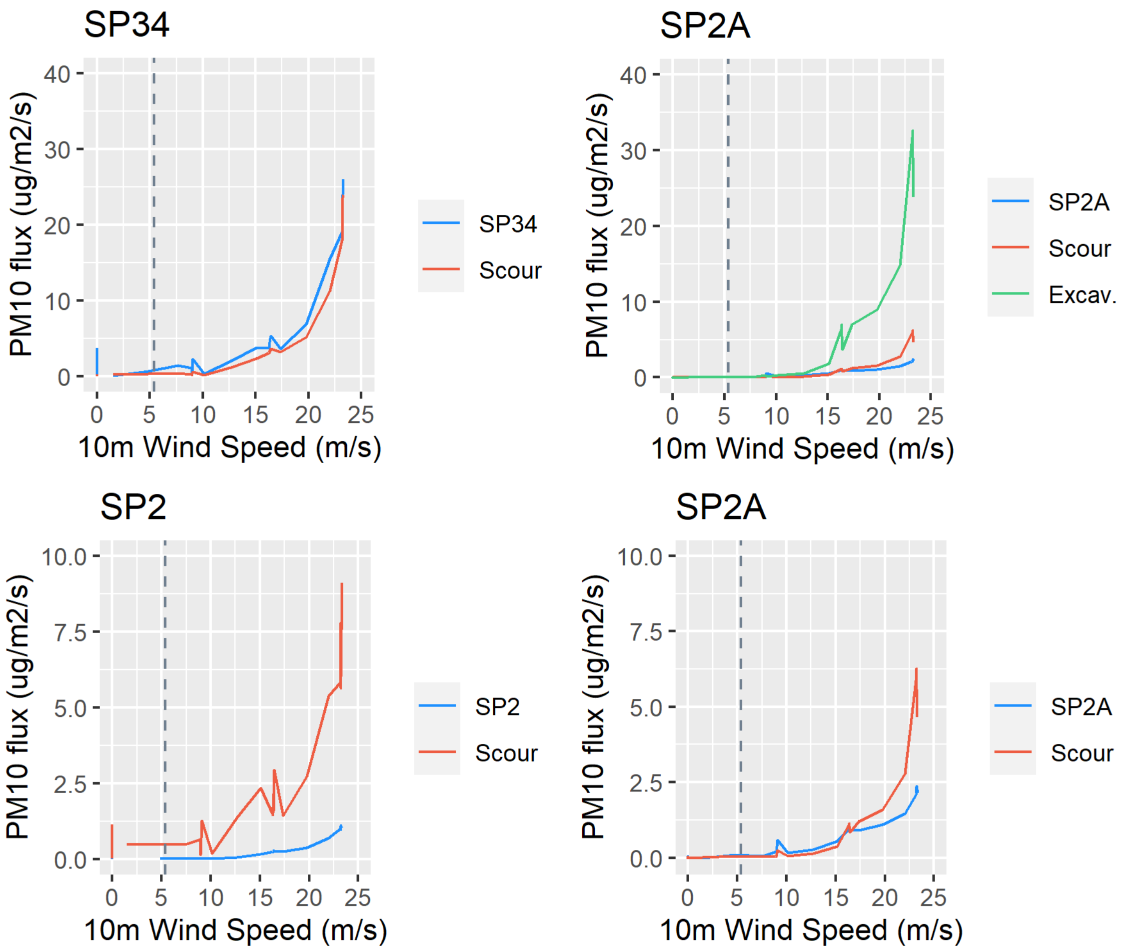


Figure 8 **PM_{10} emissions fluxes (μg/m^2/s) as a function of 'fastest mile' (gust) wind speed (m/s) for the August Tailings locations. For reference, the 5.4 m/s threshold velocity assumed in the Environmental Impact Assessment is shown as a dashed line. Note the different y-axis scales**

4 Discussion

The risk of long-term fluvial (water) erosion of tailings was evaluated in a separate study (SRK 2023). The relatively susceptibility of the mine tailings to wind erosion was highly uncertain and motivated the present work. The overall goal of the dust emissions study is to determine whether the uncovered tailings in the TSF are at risk of wind erosion over the long-term (> 100 years) in the arid environment of South Australia. While contaminants in tailings dust could be a concern (e.g. heavy metals or radionuclides), this study focuses exclusively on the physical aspects of aeolian erosion and did not measure tailings, dust or salt chemistry.

4.1 Comparison of tailings to local soils

Based on a threshold dust emissions flux of 1.0 μg/m^2/s, the dust emissions study shows undisturbed tailings have PM_{10} threshold velocities of 9.0–23 m/s. This emissions threshold exceeds the conservative (i.e. low) estimate of 5.4 m/s used in the original air quality impact assessment for the operation (dashed lines in Figures 6 to 8). This confirms dust emissions in the environmental impact assessment were conservatively estimated.

The PI-SWERL measurements indicated that the local wind speed threshold for wind erosion of soils underlying the gibber plain is approximately 9 m/s**.** Importantly, this threshold is below threshold wind velocity for both undisturbed (9.0–23 m/s) and scoured (9.0–16 m/s) tailings. Based on these observations, it is reasonable to assume that post-closure the long-term dust deposition from the local environment to the TSF surface may be more important than dust deposition from the tailings to the local environment.

In other words, tailings can be eroded by wind but the onset of these emissions occurs later (i.e. at higher wind speeds), and the amount of dust produced will be much less than other dust sources found in the local and regional environment. It will be important for future studies to consider the possibility that surface dust on the tailings may be dominated by local dust derived from alluvial material rather than dust derived from the (mineral) tailings. Determining the geochemical fingerprint of source materials (i.e. local soils versus tailings) may be required to correctly apportion future windblown dust to its source(s).

4.2 Comparison to run-off and floodplain materials

The regional environment includes alluvial fans, ephemeral ponds and lakes, and dunes formed over geologic timescales. Offshore marine sediments and loess deposits in Victoria, New South Wales and South Australia are formed from the deposition of fine materials deflated from this source region in South Australia (Hesse 1994; Muhs et al. 2014). During the current interglacial period these dunes are further stabilised by vegetation.

The ancillary measurements at a local floodplain show these materials are high in fine (i.e. < 0.075 mm), clay- and silt-grade particles. The floodplain material does not retain moisture, and appeared dry and friable during testing. Among all surfaces tested with the PI-SWERL, floodplain materials had the lowest threshold wind velocity (1.5 m/s) as they undergo saltation and were dust unlimited. At 15 to 20 m/s wind speeds, emissions fluxes of 50 to 200 $\mu g/m^2/s$ were recorded. We conclude that, among all surfaces tested, local alluvial deposits (i.e. floodplains) have the highest regional dust emissions potential and dust emissions fluxes**.**

We also measured dust emissions from tailings affected by run-off during recent rains. Composed mostly of alluvially deposited local soil, this surface had a similar wind speed threshold to disturbed tailings (13 m/s) but became dust unlimited and was prone to saltation. This is consistent with LEM predictions and highlights that local soils deposited onto tailings could be a source of airborne dust over the long-term.

4.3 Comparison to salt playa

The regional environment around the operation includes ephemeral lakes such as Ngarndamukia and Pernatty Lagoon. During (infrequent) heavy rains, these lakes become brackish and muddy bottomed. These lakes only rarely breach their confining hydrological divides, forming a mostly closed evaporite basin. As the lakes dry out they become salt playa and a potential source of windblown salt and/or mineral dust.

The TSF design creates a similar man-made structure where run-off from the head of the creek is directed onto the TSF. Water is prevented from moving further downstream to Lake Torrens by the TSF embankment. Since the tailings are covered by a layer of salt evaporite it is reasonable to assume that during heavy rains the tailings may also experience periods where a shallow muddy (tailings) lake could form. Since the TSF sub-basin is closed the surface water will evaporate, so it is also reasonable to assume that the shallow tailings lake will again become a type of man-made salt playa.

Undisturbed tailings retain their moisture, but some scoured tailings appeared drier in small, localised patches. The threshold wind velocities measured at Pernatty Lagoon under wet (22 m/s) and dry (13 m/s) conditions were similar to those measured at undisturbed (9.0–23 m/s) and scoured (9.0–16 m/s) tailings. This indicates that the present TSF emissions are similar to emissions from other salt playa in the region.

Field observations indicated that, in general, particulate matter emissions were highest for the freshest tailings, i.e. SP34 > SP2 > SP2A. We hypothesise that the majority of ‘dust’ emissions measured from the TSF are likely salt crystals, not mineral grains. Future studies should consider collecting particulate matter on filters to confirm whether particle composition is dominated by insoluble minerals or soluble salts. We note that wind erosion of salts crystals from the TSF surface is not likely an environmental risk since the surface area of the final TSF (~510 to 550 ha) is small (< 0.1%) compared to Lake Torrens (574,500 ha) and other salt playa found in the Gawler Lakes subregion (e.g. Lake Gairdner and Pernatty Lagoon).

5 Conclusion

BHP and WSP undertook a dust emissions study for the TSF at a mine in South Australia. The study's goals were to quantify dust emissions from exposed tailings surfaces and to evaluate their potential for long-term (> 100 years) wind erosion. Using a portable in situ wind erosion laboratory (PI-SWERL), dust emissions were quantified for tailings surfaces of varying ages as well as natural surfaces characteristic of the local and regional environment.

The PI-SWERL proved to be an effective tool for directly measuring the wind speed dependence of particulate matter emissions from mine tailings. Ancillary data from the study show that the mine tailings are fine-grained similarly to local and regional soils. Although disturbed tailings were more susceptible to wind erosion, tailings surfaces overall were less susceptible to wind erosion than local soils or alluvial deposits.

Higher wind speed thresholds and lower dust emissions rates from TSF surfaces are attributed to the formation of a salt crust and the tendency for tailings to remain moist, even two years after they were emplaced. In the present relatively warm, wet interglacial period, we conclude that the long-term wind erosion potential of the TSF is very low to negligible, the onset of emissions is later, and the magnitude of emissions is lower than emissions from other local and regional surfaces (e.g. alluvial plains and salt playa).

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