

1 Development and testing of a micro wind tunnel for on-site wind erosion
2 simulations.

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15

16 **Abstract**

17 Wind erosion processes affect soil surfaces across all land uses worldwide. Understanding
18 the spatial and temporal scales of wind erosion is a challenging undertaking because these
19 processes are diverse and highly variable. Wind tunnels provide a useful tool as they can
20 be used to simulate erosion at small spatial scales. Portable wind tunnels are particularly
21 valued because erosion can be simulated on undisturbed soil surfaces in the field. There
22 has been a long history of use of large portable wind tunnels, with consensus that these
23 wind erosion simulation tools can meet real world aerodynamic criteria. However, one
24 consequence of striving to meet aerodynamic reality is that the size of the tunnels has
25 increased, making them logistically difficult to work with in the field and resulting in a
26 tendency to homogenise naturally complex soil surfaces. This homogenisation is at odds
27 with an increasing awareness of the importance that small scale processes have in wind
28 erosion. To address these logistical and surface homogenisation issues we present here
29 the development and testing of a micro wind tunnel (MWT) designed to simulate wind
30 erosion processes at high spatial resolution. The MWT is a duct-type design - 0.05 m tall
31 0.1 m wide and with a 1.0 m working section. The tunnel uses a centrifugal motor to suck
32 air through a flow-conditioning section, over the working section and then through a
33 sediment collection trap. Simulated wind velocities range from 5 to 18 m s⁻¹, with high
34 reproducibility. Wind speeds are laterally uniform and values of u_* at the tunnel bed
35 (calculated by measuring the pressure gradients within the MWT) are comparable with
36 those of larger tunnels in which logarithmic profiles can be developed. Saltation sediment
37 can be added. The tunnel can be deployed by a single person and operated on slopes
38 ranging from 0-10 degrees. Evidence is presented here that the MWT provides new and
39 useful understanding of the erodibility of rangelands, claypans and ore stockpiles.

40

41 *Keywords. Erodibility, Field studies, Dust, Methodology, Land use, rangelands, mine storage facilities.*

42

43 **1 Introduction**

44 Wind erosion is widespread across natural and anthropogenic surfaces and occurs
45 worldwide where wind speeds exceed the threshold velocity required to detach soil or
46 sediment particles and transport them. The susceptibility of a surface to wind erosion can
47 be measured in a variety of ways including field-based monitoring of wind regime and
48 sediment transport [1-2], using laboratory or field-based wind tunnels [3-5], portable wind
49 erosion facilities [6] and modelling [7-9]. Each approach has advantages and limitations [5]
50 and this paper focuses on the use of a field wind tunnel.

51 Despite the increasing variety of techniques available for studying wind erosion, wind
52 tunnels, which are one of the earliest approaches [10], are still very widely used. The
53 usefulness and validity of wind tunnels depends on them adequately simulating the natural
54 processes of wind and for this reason they have typically been constructed to be as large
55 as possible to minimize scaling effects [11]. Whilst fixed location, stationary wind tunnels
56 used for aeolian research can be very large, for example the Chinese Academy of Sciences
57 has a 38 m lab based tunnel [12], their limitation is that they are generally only used with
58 artificial soil surfaces. In contrast, portable wind tunnels typically have an open floor, and
59 can be moved around in the field to simulate wind erosion of surfaces *in situ*. Van Pelt et al.
60 [5] provide a useful review of portable wind tunnels used in wind erosion research and
61 highlight that although these tunnels are 'portable' they are often large (e.g. cross-section
62 up to 1 m² and length over 10 m) and require considerable logistical support for deployment.
63 Large portable tunnels also have the disadvantage of requiring space around the tunnel for
64 locating generators, trucks, trailers and ancillary equipment.

65 In many situations it is difficult and expensive to deploy such large wind tunnels in the field
66 due to physical limitations of; site access (e.g. unmade roads), steepness of slopes (e.g. on
67 mine spoils), and cost of labour required to rig and operate the tunnel. Also, on vegetated
68 field sites aerodynamic 'noise' is introduced because of difficulties in achieving a good seal
69 between the soil surface and the tunnel [13]. The working section beneath large tunnels
70 can also homogenise the effects of spatial variations in soil surfaces, such as changes in
71 sediment size and soil crust characteristics [14]. Some small portable wind tunnels have
72 been developed and successfully used in the field. For example the wind tunnel
73 constructed by Gillette [15] had a small cross section of 150 mm x 150 mm and length of 3
74 m and was used to determine threshold friction velocities on biological crusted soil surfaces
75 [16-17]. An alternative approach is the Portable In Situ Wind EROsion Lab (PI-SWERL).
76 The PI-SWERL differs from duct-type wind tunnels in that it uses rotating airflow within a
77 0.57 m diameter cylinder to generate shear stresses on the surface. Despite this
78 fundamental difference, the results from the PI-SWERL compare well with those from
79 conventional duct-type wind tunnels [18].

80 The present paper describes the development and testing of a new micro wind tunnel
81 (MWT) designed for field simulation of wind erosion on small plots. The MWT is a duct-type
82 design and is novel because it can be deployed by a single person on slopes ranging from
83 0-10 degrees. Three examples are provided to illustrate the application of the device
84 measuring the erodibility of rangeland and claypan soils, and of stockpiles at an iron ore
85 storage facility.

86

87 **2 Materials and Methods**

88 Numerous researchers have proposed practical and aerodynamic criteria to be met by the
89 design of portable wind tunnels [19, 20]. These design criteria are summarised by Maurer
90 et al. [13] as

- 91 • the tunnel must achieve wind speeds that reflect natural conditions;
- 92 • the tunnel should produce realistic aerodynamic flows within;
- 93 • the tunnel must be easy to transport, assemble and handle

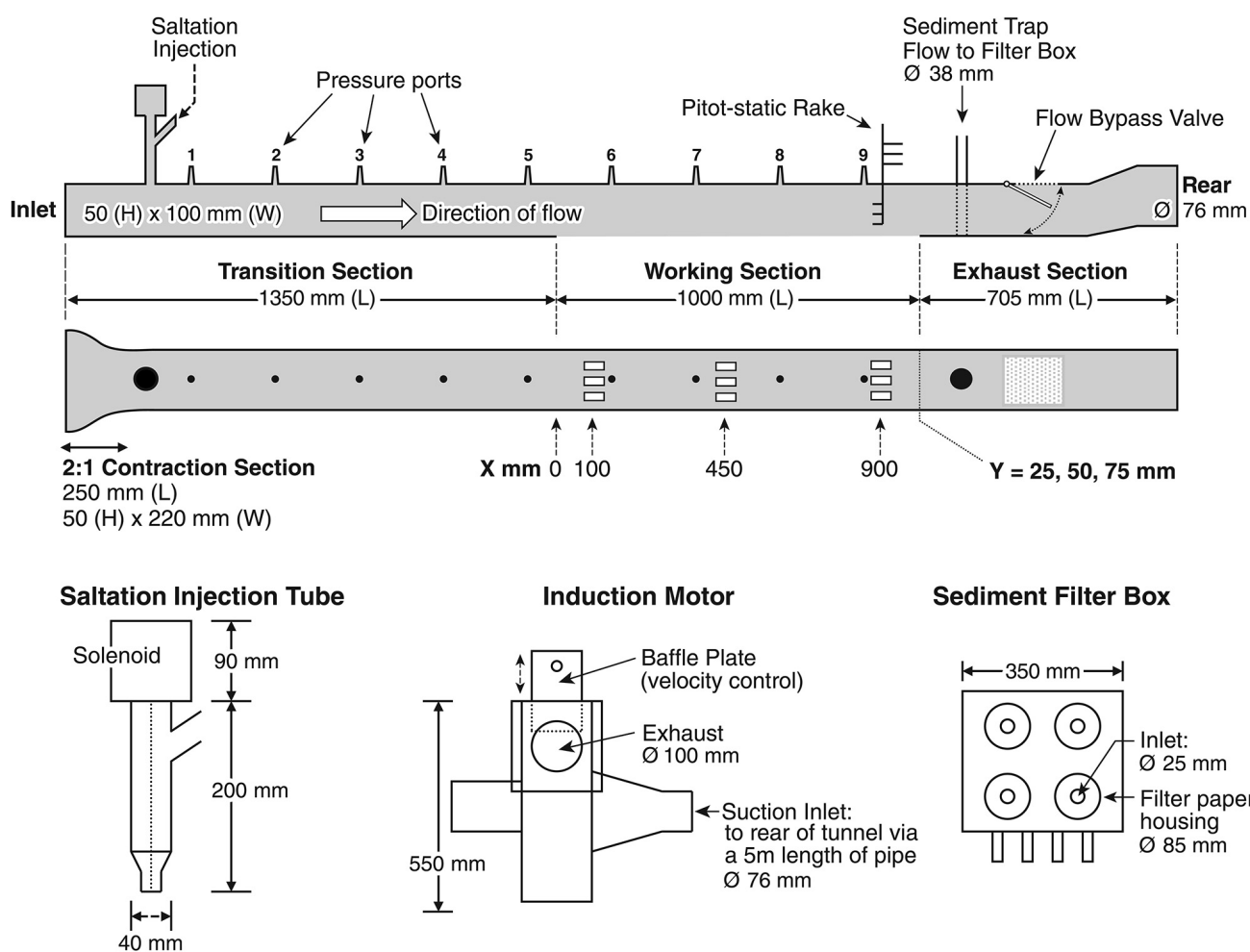
94 and the criteria have been recently reviewed by Van Pelt et al. [5]. In addition, for wind
95 erosion studies it is important that the full range of aeolian sediment transport processes
96 (creep, saltation, suspension) can occur, and that saltating grains can be introduced at the
97 upwind end of the working section to simulate the saltation impact process [20].

98

99 **2.1 Design and Construction**

100 The MWT has seven key components: a motor and tunnel wind velocity regulator, transition,
101 working and exhaust sections, sediment trap, saltation injection tube and wind speed
102 sensors (Figure 1). The motor is a 0.55 kW electric 240-volt induction motor that turns a
103 280 mm axial fan. The motor creates suction through the tunnel generating a velocity
104 range of 5-18 m s⁻¹. Wind velocity is controlled via a calibrated baffle plate on the motor
105 exhaust; complete blockage of the exhaust produces zero velocity whilst no blockage
106 allows maximum velocity. Air is drawn into the tunnel through an opening 220 x 50 mm
107 which contracts over 250 mm to a cross section 100 x 50 mm thus accelerating and
108 stabilising the airflow. This stabilisation and organisation of airflow continues through the
109 1100 mm long transition section (aluminium box tube) downwind of which is a 1000 mm
110 long working section. Within the working section the aluminium floor has been removed
111 allowing direct contact between the wind and the soil surface. The top of the working
112 section has a Perspex viewing window. Keyholes drilled in the top at distances of 100, 450
113 and 900 mm from the upwind end of the working section allow access for velocity
114 measurement instruments (1 mm Dwyer pitot-static tubes) and are sealed with silicone
115 plugs when not in use. Downwind of the working section is the 705 mm long exhaust
116 section in which tunnel wind velocity is measured, wind transported sediment is sub-
117 sampled via the sediment trap and the cross-section changes from rectangular to circular to

118 allow connection to the induction motor. A manually operated flow bypass valve within the
 119 exhaust section enables the operator to control when air is drawn through the tunnel. This
 120 avoids the ramp up / ramp down wind speeds associated with the motor being turned on/off
 121 being drawn across the tested surface. When the flow bypass valve is lowered, air is
 122 sucked from the roof within the exhaust section, avoiding flow over the working section.
 123 Once the motor has reached maximum revolution, the flow bypass valve can be raised
 124 redirecting suction (flow) to the tunnel inlet, ensuring desired wind speed is passed over the
 125 working section. The total tunnel footprint including all sections is 3050 mm x 120 mm. The
 126 generator and tunnel motor are connected via 5 m lengths of ducting (76 mm diameter) and
 127 can be positioned away from the operating tunnel. All equipment is contained in four boxes
 128 and transported (including the generator) in a standard box trailer (1800 x 1200 mm).



129

130 **Fig. 1 Schematic diagram of the Micro Wind Tunnel (MWT) displaying the three sections (transition, working**
 131 **and exhaust) and velocity measurement options (pressure ports and pitot-static rake) present. The flow bypass**
 132 **valve enables air to be drawn through the tunnel from the suction induction motor attached at the rear. Sediment**
 133 **transported in the tunnel is subsampled at the sediment trap and collected on filter papers housed in the sediment**
 134 **filter box.**

135

136 Due to the importance of saltation-impact entrainment in wind erosion of soils [20] saltation
 137 material can be added to the wind flow using a saltation injection tube. The injection tube is

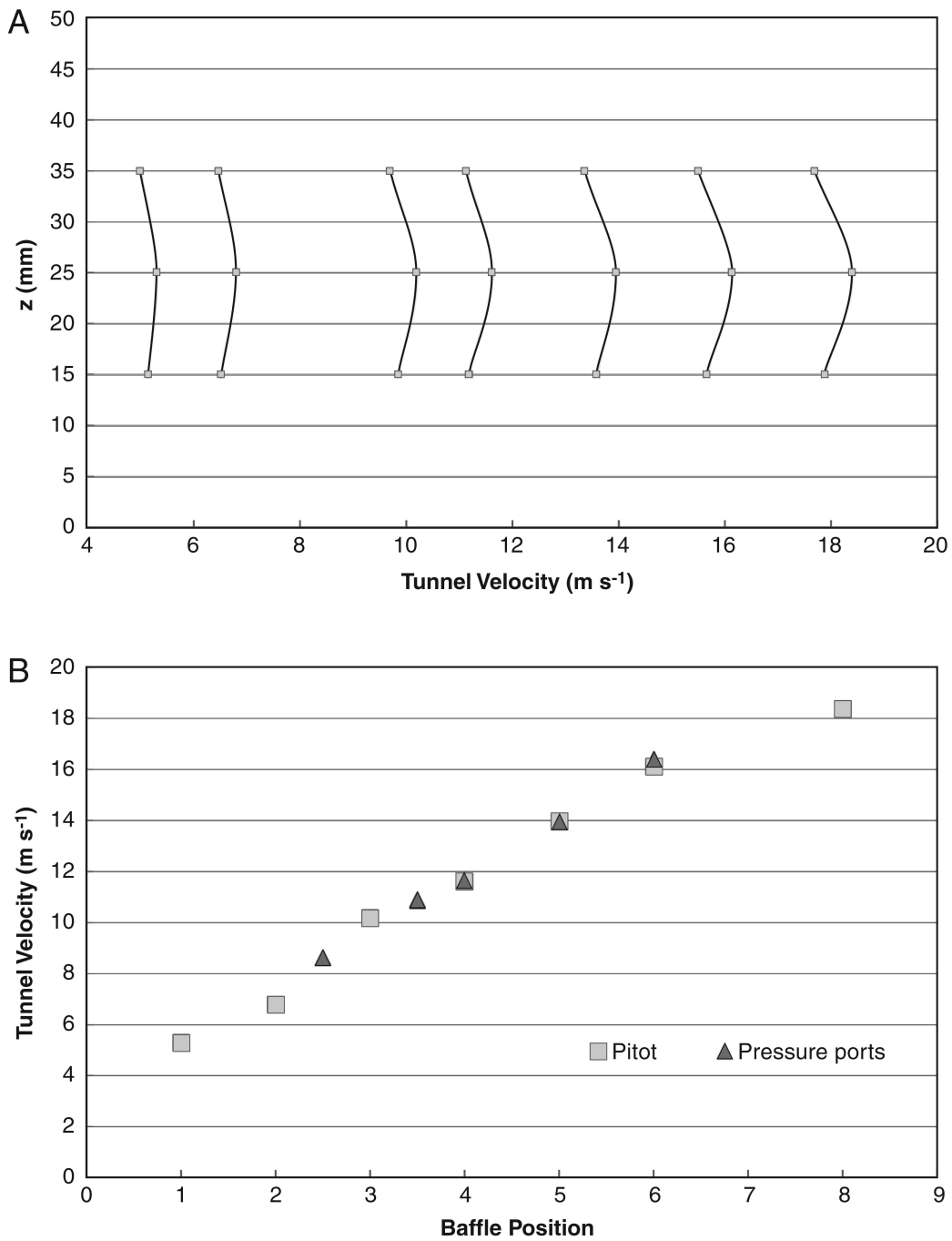
138 a 40 mm diameter acrylic tube, positioned at the upwind end of the transition section, which
139 narrows to 2 mm diameter at the base. The injection tube can be opened or sealed using a
140 tapered stainless-steel rod controlled using a solenoid that lifts the rod 10 mm vertically.
141 The solenoid can be activated at the same time as the bypass valve in order to synchronise
142 saltation injection with the start of tunnel flow. Transported sediment is collected via a
143 vertical slot sampler 10 mm wide and 50 mm high. This is located on the centre line of the
144 tunnel and is used to sub sample (10 %) of the sediment-laden tunnel airflow. Air from the
145 sediment sampler is drawn vertically through a 38 mm hose to the sediment filter box which
146 houses 125 mm-diameter glass-fibre filter papers with 0.1 μm pores.

147 For any one run, wind speed within the tunnel can be measured simultaneously at three
148 different locations using pressure transducers connected to pitot-static tubes or roof
149 mounted pressure ports or a combination of the two. The 1 mm dynamic port Dwyer pitot-
150 static tubes can be positioned in a streamwise array at 100 mm, 450 mm and 900 mm from
151 the upwind end of the working section along the centre line. Alternatively, at each of these
152 locations, they can be arranged crosswise on the centre line and 25 mm from each wall (i.e.
153 3 equidistance measurements cross-flow). A pitot-static tube can also be located within the
154 sediment trap at the downwind end of the tunnel. The pressure ports are fitted inside the
155 tunnel, flush with the roofline, and located along the centre line at 300 mm intervals in the
156 transition section and 200 mm intervals in the working section (nine in total). The most
157 common field sampling configuration is one pressure transducer connected to a pitot tube
158 at 900 mm upwind at the cross sectional mid-point, one pressure transducer connected to a
159 pitot tube in the sediment sampler and the last pressure transducer connected to opposite
160 end roofline pressure ports (i.e. pressure port numbers one and nine). Where more than
161 three velocity measurements are required to characterise three dimensional flow structures,
162 the tunnel can be run multiple times at a fixed reference velocity with the pressure
163 transducers in different configurations. Data can be made dimensionless by relating all
164 measurements to a fixed reference point. Temperature of the tunnel airflow and barometric
165 air pressure are measured every second and averaged over 1 minute to enable the
166 calculation of air density.

167 **2.2 Airflow Measurements**

168 A range of tests were undertaken to characterise: a) the range of tunnel wind velocities
169 achieved within the tunnel, b) the uniformity of airflow and c) to develop an alternative
170 technique of calculating u_* other than from logarithmic velocity profiles.

171 Tunnel wind velocity is controlled by raising or lowering the baffle plate on the induction
172 motor exhaust (Figure 1). To determine the relationship between baffle position and tunnel
173 velocity the MWT was run as it would be in the field (i.e. with filters in place) but over a
174 smooth control surface (4 mm ABS plastic sheet, 'glassy' side up). Each baffle position was
175 replicated 19 times and the MWT was run for one minute per replicate. Wind speed was
176 measured using the pitot-static tubes and roof mounted pressure ports. Each baffle
177 position created a different wind speed ranging from 5-18 m s^{-1} with excellent reproducibility
178 (all standard errors lie within +/- 0.002 m s^{-1} of the mean value) (Figure 2).



179

180 Fig. 2 Airflow velocity (m s^{-1}) is determined by the position of the exhaust baffle. A) Velocity profiles measured
 181 with pitot-static tubes over a smooth test surface. Measurements made with a pitot rake at $x = 900$, $y = 50$, $z = 15$,
 182 25 and 35. SE included (19 reps/baffle position). B) Comparison of airflow velocities (m s^{-1}) measured using pitot-
 183 static tubes (squares) at $x = 900$, $y = 50$, $z = 25$ (SE included) and pressure port measurements at $x = 200$ and 900 ,
 184 $y = 50$, $z = 50$ (SE included). All testing conducted on the same smooth surface. All standard errors lie within \pm
 185 0.002 m s^{-1} of the mean values

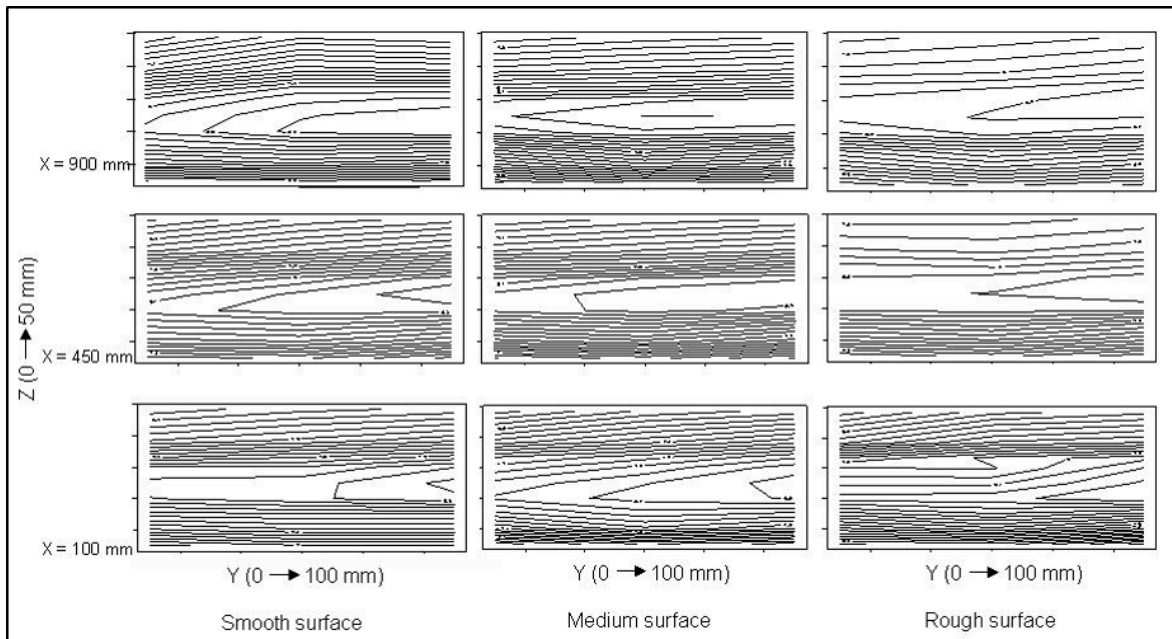
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187 Ideally a wind tunnel should produce uniform airflow across the tunnel and develop a
 188 logarithmic profile of wind velocity with height. To test these, with the baffle in position 2.5,
 189 wind speed was measured at 25 mm, 50 mm and 75 mm distance across the tunnel (y axis)

190 at 9 different heights (5, 10, 15, 20, 25, 30, 35, 40, 45 mm; z axis) and located at 100 mm,
 191 450 mm and 900 mm from the upwind end of the working section (x axis). This approach
 192 provides a grid of 27 velocity measurements at each downwind location and shows how
 193 cross-flow uniformity varies with distance down the working section. If all the
 194 measurements had been taken simultaneously the instrumentation would have blocked the
 195 airflow in the tunnel and set up secondary airflow patterns, so, given the uniformity of wind
 196 speeds indicated in Figure 2, measurements were taken at 3 locations at a time for the
 197 same baffle position and combined to create the data grid. These tests were repeated over
 198 three artificial surfaces, one smooth (ABS plastic as above), one of medium roughness (40
 199 grit sand paper), and one rough (10 mm diameter marbles protruding 2 mm above the test
 200 bed).

201 All surfaces within the tunnel are sources of drag, and the cross-sectional contour plots
 202 indicate that changes in floor roughness create the greatest changes in the flow symmetry
 203 (Figure 3). As floor roughness increases, flow lines compress near the floor surface. Figure
 204 3 also indicates there is a slight surface imperfection in the top left hand corner where the
 205 Perspex working section ceiling is affixed. This has changed the flow symmetry slightly with
 206 slower flow along the left side. Despite this, the flow in the tunnel reflects what would be
 207 expected in a rectangular duct which is a fully developed flow. The length of the tunnel
 208 means this fully developed flow is also turbulent in nature and there is no logarithmic
 209 velocity profile as expected in larger wind tunnels.

210



211

212 **Fig. 3 Contour plots of airflow velocity (0.2 m s^{-1} intervals) for smooth, medium and rough test surfaces showing**
 213 **the cross-sectional profile of the tunnel at 100, 450 and 900 mm from the upwind end of the working section.**
 214 **Airflow direction is away from the reader**

215

216 As the MWT is a duct with a fully developed flow the shear stress and the friction velocity
 217 are calculated by measuring the pressure gradient not by the traditional approach of using
 218 logarithmic velocity profiles [5, 15, 19, 20]. Pressure drop along the length of a duct is well
 219 understood within fluid mechanics [21, 22]. The approach taken here is to partition the
 220 contribution that an open floor (one wall of the duct) has on the total duct pressure
 221 gradients in order to calculate the shear stress and the friction velocity on that surface. The
 222 following describes the approach taken.

223 Internal flow within a duct is constrained by bounding walls and the viscous effect which
 224 permeates the entire flow. Inviscid flow enters the duct and viscous boundary layers flow
 225 downstream retarding the axial flow $u(y,z)$ at the wall, thereby accelerating the centre of the
 226 flow to maintain the incompressible continuity requirement [21].

$$Q = \int_A u(y,z) dA = \text{constant}$$

227
 228 (1)

229 Where Q is volume flow, $u(y,z)$ is flow velocity and A is cross sectional area. At a finite
 230 distance from the entrance the boundary layers merge and the inviscid core disappears.
 231 The duct flow then is entirely viscous and the axial velocity adjusts until it is fully developed.
 232 The distance (x) downstream that this occurs is referred to as the entrance length (L_e).
 233 Downstream of $x \geq L_e$ the velocity profile $u(y,z)$ is constant, wall shear is constant and
 234 pressure drops linearly with x for either laminar or turbulent flow. Dimensional analysis
 235 indicates the Reynolds number (Re_e) is the only parameter affecting entrance length L_e . Re_m
 236 is the Reynolds number for the MWT and calculated by

$$237 \quad Re_m = \frac{\rho U}{\nu} D_h \quad (2)$$

$$238 \quad = \omega D_h \quad (3)$$

239 where U is the average flow velocity, ρ is the density of air, ν is the viscosity of air, D_h is the
 240 hydraulic diameter, and ω is the scaled flow velocity. In a rectangular duct, the hydraulic
 241 diameter is determined as

$$242 \quad D_h = \frac{2 \times \text{area}}{\text{width} + \text{height}} \quad (4)$$

243

244 The MWT has Reynolds numbers ranging from $26,500 < Re_m < 80,000$ (i.e. fully turbulent
 245 flow) [22]. In ducts with turbulent flows, the boundary layers grow faster and L_e is relatively
 246 short:

$$247 \quad \frac{L_e}{D_h} \approx 4.4 Re_m^{\frac{1}{6}} \quad (5)$$

248 Therefore whilst the MWT does not support a log profile, the entrance length (L_e) effect is
 249 restricted within the transition section of the tunnel leaving the fully developed flow region to
 250 occur within the working section (Figure 1). This is important because it is in the working
 251 section that a developed velocity profile $u(y, z)$ needs to occur if changes in surface
 252 roughness are to be determined.

253 In larger wind tunnels the surface roughness is calculated from the wind profile. However,
 254 the micro wind tunnel does not support a log profile, thus an alternative technique for
 255 calculating u_* , the friction velocity, is required. The friction velocity (u_*) is frequently used to
 256 measure the wind speed required to initiate sediment movement.

257 The integral momentum method [23 in 24] is used here to calculate u_* . This paper shows
 258 that the friction velocity can be determined by measuring pressure gradients and using
 259 integral momentum balance. Theoretically, in a fully developed duct flow, the integral
 260 momentum balance is:

$$261 \quad \int_p \rho u_*^2 dP = -A \frac{dp}{dx} \quad (6)$$

262 where u_* is the friction velocity, ρ is air density, ρu_*^2 is the drag on the surface of the duct, P
 263 is the perimeter of the duct, dP is increment of the perimeter, A is the cross-sectional area
 264 of the duct and $\frac{dp}{dx}$ is the stream-wise pressure gradient. Therefore, in a rectangular duct of
 265 height Z and breadth Y :

$$266 \quad 2(Y + Z)u_{*\alpha}^2 = -\frac{YZ}{\rho} \frac{dp}{dx} \quad (7)$$

267 where $u_{*\alpha}$ is an area-weighted average friction velocity for all surfaces around the tunnel
 268 circumference. The turbulence and secondary flow within the duct as documented by
 269 Schetz and Allen [22] act to equalise the shear stress across the perimeter of the duct.
 270 Thus, it is possible to partition the friction velocity to the various surfaces, hence the floor
 271 contributes a length Y to this average and the sides and roof together contribute a length
 272 $(2Z + Y)$. Consequently:

$$273 \quad 2(Y + Z)u_{*\alpha}^2 = Y u_{*f}^2 + (2Z + Y)u_{*s}^2 \quad (8)$$

275 where u_{*f} is the friction velocity for the rough floor and u_{*s} is the friction velocity for the
 276 smooth sides and roof. Equating Equations 7 and 8 gives:

$$277 \quad Y u_{*f}^2 + (2Z + Y)u_{*s}^2 = -\frac{YZ}{\rho} \frac{dp}{dx} \quad (9)$$

278 Determining the friction velocity for the rough floor (u_{*f}) can therefore be inferred from
 279 measurements of the pressure gradient ($\frac{dp}{dx}$) by re-arranging Equation 8 as:

280

$$281 \quad u_{*f}^2 = - \left(\frac{2Z}{Y} + 1 \right) u_{*s}^2 - \frac{Z}{\rho} \frac{dp}{dx} \quad (10)$$

282

283 Now u_{*s} can be determined by noting that when $u_{*f} = u_{*s}$, Equation 8 becomes:

$$284 \quad 2(Z + Y)u_{*a}^2 = (2Z + 2Y)u_{*s}^2 \quad (11)$$

285 Equating Equations 7 and 11 gives:

$$286 \quad u_{*s}^2 = - \frac{YZ}{2(Z+Y)\rho} \frac{dp}{dx} \Big|_s \quad (12)$$

287 Where $\frac{dp}{dx} \Big|_s$ denotes the pressure gradient when all four surfaces are smooth. Hence, u_{*f}
 288 can be related to current pressure gradient ($\frac{dp}{dx}$) and the smooth pressure gradient ($\frac{dp}{dx} \Big|_s$) by:

$$289 \quad u_{*f}^2 = - \frac{Z}{\rho} \left[\frac{dp}{dx} - \frac{(2Z+Y)}{2(Z+Y)} \frac{dp}{dx} \Big|_s \right] \quad (13)$$

290 Finally, the surface roughness (Z_0) can be estimated from the central flow characteristics of
 291 the duct:

$$292 \quad Z_0 \approx \frac{25 \times 10^{-3}}{\exp\left(\frac{k u_c}{u_{*f}}\right)} \quad (14)$$

293 where u_c is the measured velocity in the centre of the duct ($z = 25$ mm) and $k =$ von
 294 Karman's constant (0.4).

295 These theoretical workings were tested by measuring the pressure gradient for the
 296 transition and working sections of the tunnel over three test surfaces (under both transition
 297 and working sections). These three surfaces are; smooth (4 mm ABS plastic, 'glassy' side
 298 up), medium (213 micron sand spray-glued to PVC) and rough (bubble-wrap with bubble 10
 299 mm diameter, 5 mm high). Results in Table 1 show that as the test surface roughness
 300 increased, so did u_{*f} , indicating that the pressure gradient method is sensitive to scaling
 301 issues within the MWT. This increases confidence that drag coefficient can be partitioned.

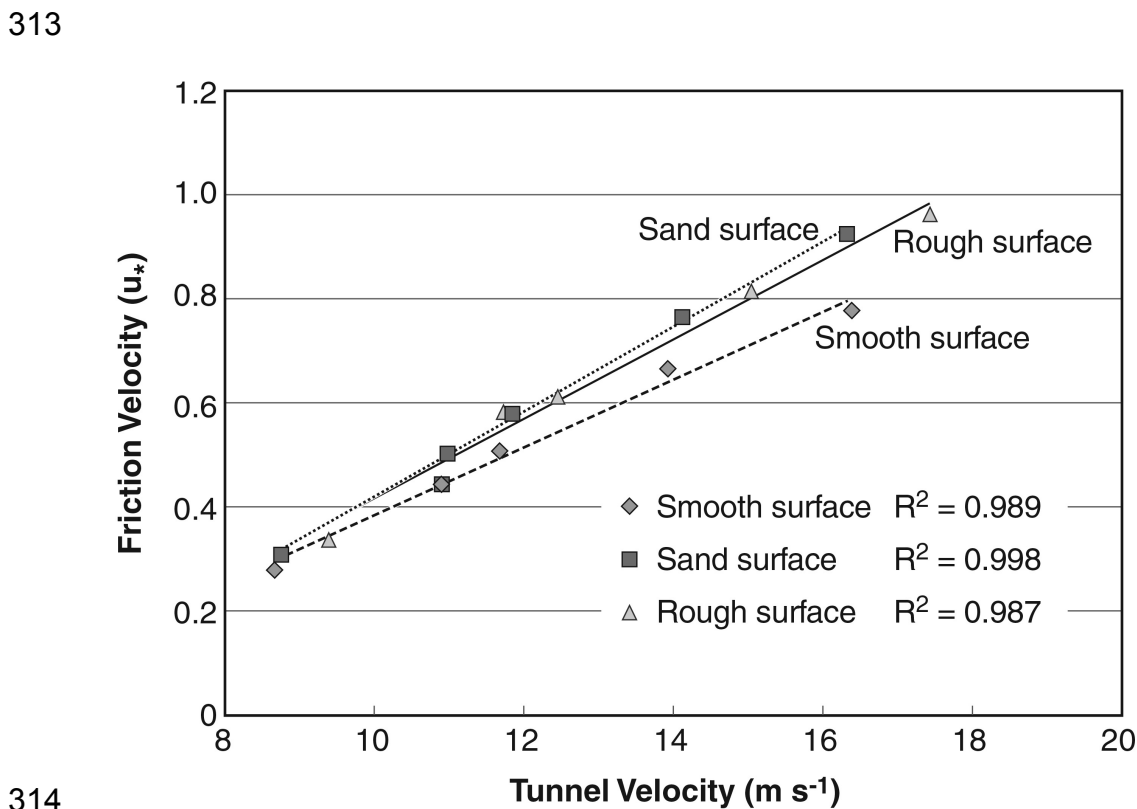
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303

304 Table 1 Flow descriptors for the MWT calculated using the pressure gradient method (Raupach et al. 2006) for
 305 the flow on the tunnel floor. Wind speeds measured using the roof mounted pressure ports (pressure port
 306 measurements at $x = 200$ and 900 , $y = 50$, $z = 50$).

Tunnel speed $m s^{-1}$	Test surface	Coefficient of drag (unitless)	u_* ($m s^{-1}$)	z_o (mm)
6.8	Smooth	0.0023	0.32	0.006
6.8	Medium	0.0034	0.40	0.026
6.8	rough	0.0059	0.52	0.139
11.6	Smooth	0.0021	0.54	0.004
11.6	Medium	0.0034	0.68	0.027
11.6	rough	0.0056	0.86	0.117

307
 308 The data in Table 1 compare well with u_* values of $0.35 m s^{-1}$ ($U=6.8 m s^{-1}$) and $0.72 m s^{-1}$
 309 ($U=11.6 m s^{-1}$) obtained by Shao and Raupach [25] who tested on a bed of $200 \mu m$ sand
 310 using a large portable wind tunnel. This result suggests that the MWT produces
 311 comparable surface drag for the wind speeds in the tunnel. Figure 4 shows the relationship
 312 between tunnel velocity and friction velocity for the MWT.



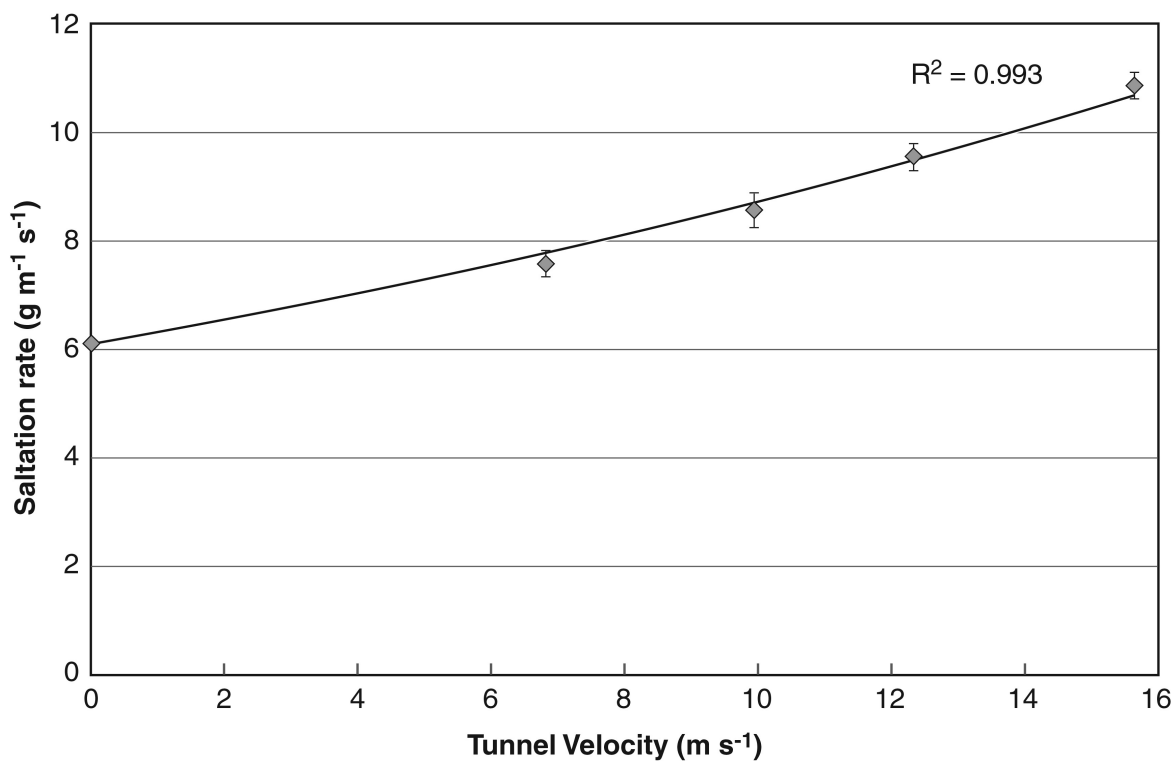
314
 315 Fig. 4 Relationships between the tunnel velocity and u_* for each of the three tested surfaces (smooth ($z < 0.01 mm$),
 316 medium ($z \sim 0.1 mm$) and rough ($z \sim 2 mm$)). Wind speeds measured using the roof mounted pressure ports
 317 (pressure port measurements at $x = 200$ and 900 , $y = 50$, $z = 50$). All standard errors lie within ± 0.002 of the
 318 mean values

320

321 2.3 Saltation injection, collection efficiency and operation procedures

322 Saltation injection is used in a wind tunnel to achieve saturated saltation flow. In the field
323 saturated saltation will develop over much longer distances than can be reproduced in the
324 working sections of portable wind tunnels [20, 25]. Saltation sands should therefore be
325 delivered at a flux rate sufficient to produce saltation rates observed in the field, and have
326 known physical properties (size, chemical composition).

327 Commercially available sand with a unimodal size of 213 microns and 99 % quartz content
328 is used in the MWT saltation injection system. Without the tunnel operating (tunnel velocity
329 = 0 ms⁻¹) the saltation flux rate is 6.1±0.1 g m⁻¹s⁻¹. As the tunnel airflow velocity increases
330 (tunnel velocity = 5–16.1 ms⁻¹) so too does the saltation flux rate, ranging from 7.5-10.8 g
331 m⁻¹s⁻¹ (Figure 5). Saltation flux rates are slightly higher than those reported by Pietersma et
332 al. [26] who had an adjustable saltation feed rate of 0.25-6.6 g m⁻¹s⁻¹, but lower than Van
333 Pelt et al., [5] who had an adjustable saltation feed rate of 10-30 g m⁻¹s⁻¹. The range of
334 saltation flux rates for the MWT is within the variability reported for other wind tunnels and
335 therefore differences considered inconsequential.



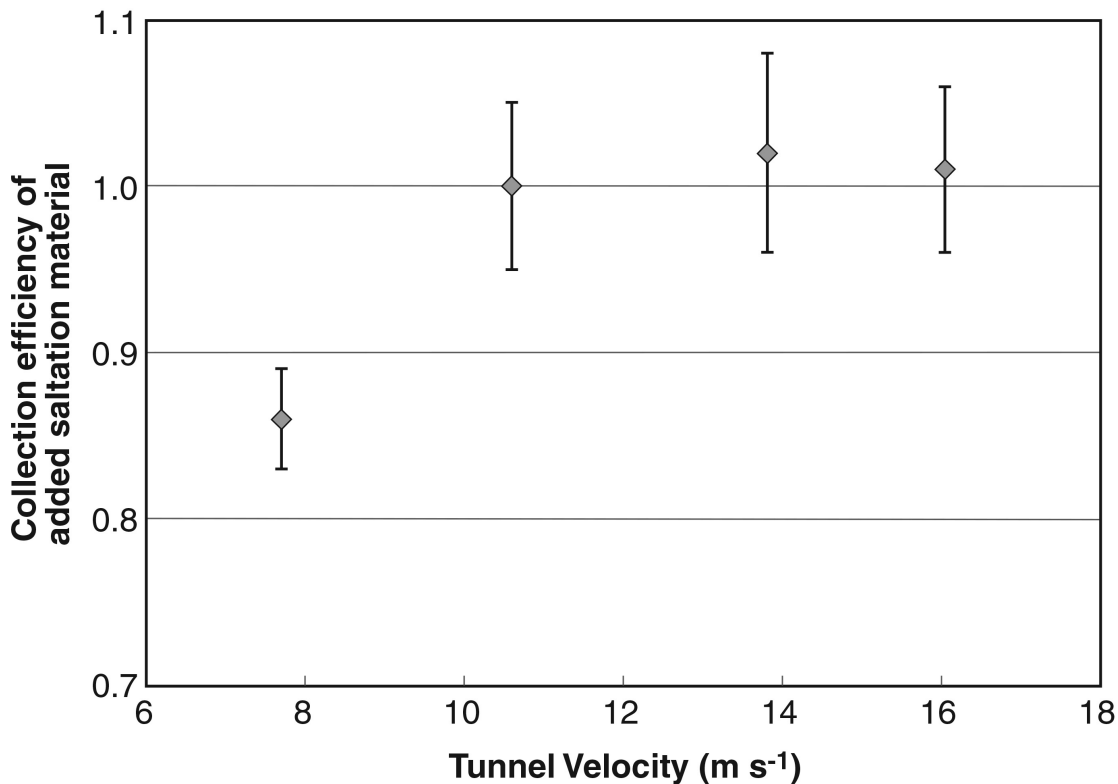
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337 Fig. 5 Saltation flux rate is 6.1 g m⁻¹s⁻¹ with no tunnel flow but increases (7.5-10.8 g m⁻¹s⁻¹) as tunnel velocity
338 increases. Each velocity was replicated five times measured using pitot-static tubes at x = 900, y = 50, z = 25 and
339 all standard errors lie within +/- 0.07 of the mean values

340

341 The collection efficiency of the sediment sampler was tested by adding a known amount of
342 saltation sand. The sampler inlet has a cross-section of 10 x 50 mm representing 10 % of

343 the cross-sectional area of the tunnel. For four wind speeds (each repeated five times) 30
 344 g of saltation sand was added via the saltation injection system at the start of the one
 345 minute run (using a smooth test bed). Assuming that the sediment sampler is 100 %
 346 efficient, 3 g of sediment should be collected at the end of each run. The ratio of collected
 347 sediment to that expected shows that on the smooth test surface, the sampling efficiency
 348 was greater than 95 % for wind speeds higher than 10 ms^{-1} but dropped to 85 % at lower
 349 wind speeds (Figure 6). A change in trapping efficiency with wind speed is commonly
 350 observed in semi-isokinetic samplers [27]. On rough surfaces the expectation is that
 351 sediment will be trapped by roughness elements reducing the amount of sediment reaching
 352 the sampler. Understanding the trap efficiency means that the storage potential of different
 353 surfaces can be estimated [24].



354

355 **Fig. 6** Collection efficiency of the sediment sampler indicates that over a smooth test surface the tunnel is very
 356 efficient at collecting the expected 10 % sediment flow released in the tunnel at wind speeds greater than 10 m s^{-1} .
 357 The tunnel under samples at tunnel velocities less than 8 m s^{-1} (baffle position 2). Each velocity was replicated five
 358 times measured using pitot-static tubes within the tunnel flow at $x = 900$, $y = 50$, $z = 25$ and sediment trap line. All
 359 standard errors lie within ± 0.05 of the mean values

360

361 Operating the MWT uses two approaches to saltation impact. The first approach relies on
 362 any naturally-available, loose, erodible material to act as a saltation source. Wind-removed
 363 sediment is collected on 125 mm-diameter glass-fibre filter paper with 0.1 μm pores, and
 364 weighed. Sediment flux (Q) ($\text{g m}^{-1}\text{s}^{-1}$) with no added saltation material is calculated as:

365
$$Q = \frac{mass}{[0.01m^2 \times 60s]} \quad (10)$$

366 The second approach uses the addition of saltation material as described above to initiate
367 the breakdown and removal of fine sediments through abrasion process. Saltation induced
368 sediment flux (Q_{Si}) ($g\ m^{-1}s^{-1}$) is calculated as:

369
$$Q_{Si} = \frac{[mass - 3g]}{[0.01m^2 \times 60s]} \quad (11)$$

370 where mass is the weight (g) of sediment collected on the filter paper and $0.01m^2$ is the
371 footprint of the MWT working area. This equation assumes that all the sediment introduced
372 at the upwind end reaches the sediment sampler at the downwind end. This is a reasonable
373 assumption for a smooth surface with no storage capacity. As highlighted above rough
374 surfaces can trap sediments and there is potential to use the MWT to increase the
375 understanding of this however it will not be explored further in this paper. To identify the
376 susceptibility of a surface to abrasion, the ratio of $Q_{Si} : Q$ is used to describe the saltation
377 entrainment ratio, quantifying how much more sediment was lost with the addition of
378 saltation sand. The higher the number the greater impact of the saltation sands.

379

380 The use of a range of wind speeds on all surfaces provides an indication of how sediment
381 flux changes with wind speed. Comparison between the surfaces requires a standard wind
382 speed to act as a default comparison. The chosen wind speed was $u = 9\ m\ s^{-1}$ as this
383 typically causes sediment entrainment in the field [28, 29].

384

385 **2.4 Summary of development and calibration**

386 The MWT has been shown to produce velocities ranging from 5 to $18\ m\ s^{-1}$ with high
387 reproducibility. Wind velocities are laterally uniform ($\pm 0.2\ m\ s^{-1}$) and values of u_x at the
388 tunnel bed (calculated using the integral momentum method) are comparable with those
389 from larger tunnels where logarithmic, profiles can be developed [25,5]. To account for the
390 variability in the saltation feed rate as velocity increases, known amounts of saltation
391 sediment were used for all runs. A high collection efficiency ($>85\ %$) was reported across a
392 range of tunnel velocities. The MWT therefore achieves the three fundamental wind tunnel
393 design criteria proposed by Maurer et al., [13] of, producing wind speeds and aerodynamic
394 flows that reflect natural conditions, along with being easy to transport, assemble and
395 operate.

396

397

398

399 **3 Research Applications of the MWT**

400 The second half of this paper provides three contrasting examples of where the MWT has
401 been used in field research in order to illustrate the practicality of its use.

402

403 3.1 Wind erosion of rangeland soils

404 A field study was undertaken in semi-arid rangelands near Longreach, Queensland,
405 Australia to assess the impact of different stocking pressures from cattle and sheep grazing
406 on soil erodibility to wind [30]. Wind erosion simulations were conducted along a grazing
407 gradient (from high to low) leading away from a stock watering point; following the design of
408 Pickup [31]. Field experiments were conducted on two soil types, a cracking clay soil
409 (23°36'44.8"S; 143°17'46.9"E) and a sandy loam (30°27'14.7"S; 141°44'32.4"E).

410 Both sites were vegetated with annual and perennial grasses. As the focus of the study
411 was upon soil erodibility (rather than the protection to soils afforded by vegetation) it was
412 important to exclude grasses from the wind tunnel simulation sites. The MWT was highly
413 suitable to this application because its small footprint could fit between the grass clumps
414 (Fig. 7). This project would not have been feasible with a conventional field wind tunnel,
415 because grasses could not have been excluded from the large working section of such a
416 tunnel.



417

418 **Fig. 7 The micro wind tunnel was highly suitable to deployment in a grassed rangeland site because its small**
419 **footprint could fit between grass clumps**

420 Sediment flux was measured along the grazing gradient using the MWT, but only two points
 421 along this transect are reported here. The highest stocking rate and soil surface
 422 disturbance zone was closest to the watering point and a low stocking rate and disturbance
 423 zone was 2000 m from the watering point.

424

425 **Table 2 Measured sediment flux ($\text{g/m}^2/\text{s}$) at two disturbance zones on two soil types using one MWT wind speed, U**
 426 **$= 9 \text{ m s}^{-1}$. Q is sediment flux with only wind blowing across soil surface. Q_{Sl} is the sediment flux with saltation**
 427 **sediment added to the tunnel runs**

	Sediment flux ($\text{g/m}^2/\text{s}$)			
	Clay site		Sandy loam site	
	High disturbance zone	Low disturbance zone	High disturbance zone	Low disturbance zone
Without saltation added (Q)	3.35	0.04	9.59	2.64
With saltation added (Q_{Sl})	5.66	0.31	13.47	3.39
Saltation entrainment ratio ($Q_{\text{Sl}} : Q$)	x 1.7	x 7.8	x 1.4	x 1.3

428

429 Three results of the MWT simulations are shown in Table 2.

430 1. Overall wind erosion rates, measured as sediment fluxes (Q), are higher on sandy loam
 431 soils than clay soils; confirming the widely reported result that increasing the sand content
 432 of soils increases their erodibility [32].

433 2. Disturbance of soil surfaces increases sediment fluxes on both soils but the relative
 434 impact is much greater on the clay soil than on the sandy loam soils. This suggests that
 435 clay soils are more vulnerable to increased stocking rates than sandy soils.

436 3. If saltation sands are present in the windflow sediment fluxes are increased to a much
 437 greater extent on clay soils (x 1.7 to x 7.8) than sandy loam soils (x 1.3 to x 1.4); confirming
 438 the earlier result that the presence of sands increases soil erodibility.

439 This study provides new and useful understanding of changes in soil erodibility in response
 440 to variations of grazing pressure. The results suggest that spatial variations of soil surface
 441 disturbance induced by grazing pressure have a direct impact on soil erodibility to wind.
 442 The MWT played a crucial role in this project because its small footprint enabled the
 443 positioning of the tunnel between grass clumps; thus testing the soil surface conditions
 444 avoiding the complicating effects of vegetation upon wind erosion.

445 3.2 Wind erosion on alluvial claypans

446 A field study was undertaken on a claypan on the Diamantina River floodplain, Queensland.
 447 Claypans as a single unit (covering from 1 – 100s square kilometres in size) are known to
 448 be dust source hotspots [32, 33]. However claypans do not comprise uniform surfaces and
 449 instead are characterised by a complex mosaic of surface crust types. The aim of this study

450 was to determine the relative erodibility of each crust type. The erodibility of individual crust
 451 types is poorly understood in part because most large portable wind tunnels cover a range
 452 of crust types in a single run, thereby homogenising the results. Field experiments were
 453 conducted on three crust types; structural, depositional and biological as defined by
 454 Valentin and Bresson [34] and Thomas and Dougill [35]. The MWT was used both without
 455 and with saltation added.

456 Across the claypan, the sediment flux varied considerably (at $u = 9 \text{ m s}^{-1}$), with biological
 457 crust surfaces yielding a higher sediment flux (Q) than the depositional and structural crusts
 458 (Table 3). Sediment flux with saltation added (Q_{SI}) is again higher from the biological crusts
 459 than the structural and depositional (Table 3). At first sight, these results appear to be
 460 inconsistent with other published studies [16,17] which conclude that biological crusts
 461 provide greater protection to soils than physically crusted or depositional surfaces. In
 462 reality the results probably reflect the capacity of biological crusts to store loose sediment
 463 and release it when wind speeds increase. The proportional increase in sediment flux with
 464 the addition of saltation sands ($Q_{SI} : Q$) is much less for biological crusts (x 5.6) than
 465 depositional and structural crusts (x14 and x 16 respectively), indicating that biological
 466 crusts are more protective of soils in a saltation impact environment. This result reinforces
 467 the earlier interpretation; that the relatively high overall sediment fluxes from biological
 468 crusted surfaces reflect their capacity to store loose sediment and release it when wind
 469 speeds increase.

470 This result also supports the conclusions from the study by Hupy [36] which showed that
 471 the spatial positioning of different surface types can have an important influence upon
 472 overall wind erosion rates from a claypan. Hupy [36] found that storage zones of saltation
 473 sands, such as the biological crusted regions, provided a source of abrasion material for
 474 downwind sites.

475 **Table 3 Measured sediment flux ($\text{g/m}^2/\text{s}$) at three surface crust types using one MWT wind speed, $U = 9 \text{ m s}^{-1}$**

	Sediment flux ($\text{g/m}^2/\text{s}$)		
	Structural crust	Depositional crust	Biological crust
Without saltation added (Q)	0.109	0.316	1.117
With saltation added (Q_{SI})	1.766	4.371	6.196
Saltation entrainment ratio ($Q_{SI} : Q$)	x 16	x 14	x 5.6

476

477 This study provides new and useful understanding of the changes in soil erodibility across a
 478 heterogenous claypan surface. The results suggest that spatial variations of crust types
 479 have a direct impact on erodibility and that both the abundance and spatial distribution of
 480 the crust types have an effect of the overall sediment flux of a claypan as a whole. The use
 481 of the MWT was crucial to the collection of this sediment flux data as its small nature and
 482 portability enabled the testing of discrete crust types. Larger field tunnels would have
 483 measured the response of either a range of crust types, and/or the patchy vegetation which
 484 is commonly associated with the biological crusts on claypans.

485

486 3.3 Erodibility of iron ore sediments

487 A field study was undertaken to assess the relative erodibility of different iron ore sediments
 488 within an iron ore port facility in Western Australia. The iron ore storage facility involved
 489 receiving, sorting, stacking, transporting via conveyors and ship loading several different
 490 ore products. This diverse range of products and material handling activities produced
 491 considerable fugitive dust which can have negative impacts upon local communities. The
 492 term fugitive dust refers to dust which is mechanically entrained [37] and may be wind-
 493 eroded at mine sites, ore storage areas and mine rehabilitation areas [38, 39]. One
 494 measure of the fugitive dust potential of an ore deposit is the surface sediment fluxes
 495 resulting from increased wind speeds. Identifying the key sources of dust is an important
 496 precursor to applying appropriate dust mitigation strategies. The MWT was used to
 497 measure the wind erodibility of different iron ore deposits. MWT measurements were
 498 carried out on two iron ore stockpiles and two local ore deposits; on roadsides and beneath
 499 the conveyor belts (Table 4).

500

501 **Table 4. Measured sediment flux ($\text{g/m}^2/\text{s}$) at two iron ore sites and two deposited sediment sites using one MWT**
 502 **wind speed, $U = 9 \text{ m s}^{-1}$**

	Sediment flux ($\text{g/m}^2/\text{s}$)			
	Iron Ore surfaces		Deposited sediments	
	Stockpile 1	Stockpile 2	Deposits on road	Deposits below conveyor
Without saltation added (Q)	1.41	0.01	78.13	4.35
With saltation added (Q_{SI})	2.65	0.49	159.08	32.93
Saltation entrainment ratio ($Q_{\text{SI}} : Q$)	x 1.9	x 49.0	x 2.0	x 7.5

503

504 The highest overall sediment fluxes were recorded on the local ore deposits (on road and
 505 under conveyor) and the lowest from the two stockpile ores (Table 4). The very high fluxes
 506 on the local ore deposits arose because they were relatively fine dust deposits ($< 50 \mu\text{m}$),
 507 with low compaction. These deposits were therefore a major potential source of fugitive
 508 dusts. The sediment fluxes with saltation material in the airflow (Q_{SI}) were increased on all
 509 sites. While the proportional increase in sediment flux ($Q_{\text{SI}} : Q$) was greatest on the
 510 stockpile 2, the absolute sediment flux was much lower than on the local deposits. The
 511 large range in sediment fluxes between sites highlights the complexity of managing fugitive
 512 dust emissions at mine sites and iron ore storage areas and the need to adopt a range of
 513 different dust mitigation strategies.

514

515 The MWT proved to be very well suited to the practical demands of operating at this
516 industrial site; where equipment access and operation was difficult, especially on inclined
517 stockpile surfaces and beneath conveyor belts.

518

519 **3.4 Summary of applications of the micro wind tunnel**

520 The MWT has proved to be a valuable tool for assessing small scale soil erodibility issues.
521 The use of the MWT across a range of surfaces provides new and useful understanding of
522 the erodibility of rangelands, claypans and ore stockpiles. There are 3 key attributes of the
523 MWT. First, nimbleness, second flexibility, third operability. The MWT “nimbleness” in
524 getting in and around grass clumps which are a common feature of many rangelands and
525 difficult to measure with larger tunnels provides a true practical advantage. The tunnel is
526 “flexible” in being easily deployed across diverse terrains and in constricted industrial
527 settings. Truck or trailer mounted portable wind tunnels are well suited to large open
528 agricultural paddocks, therefore to apply these tools in a spatially restricted environment
529 often means the test surfaces have to be disturbed and brought to the tunnel, thus altering
530 their natural erodibility properties. Another important feature of the MWT is its “operability”.
531 This tunnel can be used, packed up and transported by one person. Larger portable tunnels
532 require multiple people and often heavy lifting aids to assemble and pack the equipment.

533

534 **4 Conclusion**

535 The micro wind tunnel (MWT) is a small, portable wind tunnel, operable by one person.
536 The MWT produces airflow velocities ranging from 5 to 18 m s⁻¹ with high reproducibility.
537 The velocity profiles show an orderly progression downwind, and the across tunnel contour
538 plots showed a good air speed distribution. Unlike larger wind tunnels, the dimensions of
539 the MWT limit the form of velocity distribution in the working section, but it is these duct like
540 dimensions that enable the shear stress within to be determined from the pressure drop.
541 Through measuring the pressure gradients enables the measurement of drag coefficient
542 and allows the calculation of both sensible u_* and surface-roughness measures in the
543 MWT. Saltation feed into the airflow is at the optimal rate of 6.1 g m⁻¹s⁻¹ and collection
544 efficiency is high.

545 The utility of the MWT is demonstrated from wind erosion studies on rangelands and
546 alluvial claypans, and at an iron ore storage facility. The rangeland study highlights the
547 ease of use of the MWT on surfaces with complex patterns of tufted pasture grasses. At
548 the claypan site the small footprint of the MWT allowed wind erosion simulations to be
549 conducted on different discrete surface crust types. At the iron ore storage facility the MWT
550 proved to be very well suited to the practical demands of operating at an industrial site;
551 where equipment access and operation were difficult; on inclined stockpile surfaces and
552 beneath conveyor belts. The MWT is therefore a valuable wind erosion simulation tool
553 which very well supplements larger portable field wind tunnels.

554

555

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562

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