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Field testing, comparison, and discussion of five aeolian sand transport measuring devices operating on different measuring principles

Dirk Goossens[a,b,*], Corjan Nolet[c], Vicken Etyemezian[d], Leonardo Duarte-Campos[e], Gerben Bakker[f], Michel Riksen[c]

[a] Geography and Tourism Research Group, KU Leuven Department of Earth and Environmental Sciences, Geo-Institute, Celestijnenlaan 200 E, 3001 Leuven, Belgium
[b] ESAT/ELECTA KU Leuven & Energyville, Kasteelpark Arenberg 10, 3001 Leuven, Belgium
[c] Soil Physics and Land Management Group, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[d] Division of Atmospheric Sciences, Desert Research Institute, 755 E. Flamingo Rd., Las Vegas, NV 89119, USA
[e] Water Engineering and Management, Universiteit Twente, Post Office Box 217, 7500 AE Enschede, The Netherlands
[f] Soil, Water and Land Dynamics, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

Five types of sediment samplers designed to measure aeolian sand transport were tested during a wind erosion event on the Sand Motor, an area on the west coast of the Netherlands prone to severe wind erosion. Each of the samplers operates on a different principle. The MWAC (Modified Wilson And Cooke) is a passive segmented trap. The modified Leatherman sampler is a passive vertically integrating trap. The Saltiphone is an acoustic sampler that registers grain impacts on a microphone. The Wenglor sampler is an optical sensor that detects particles as they pass through a laser beam. The SANTRI (Standalone AeoliaN Transport Real-time Instrument) detects particles travelling through an infrared beam, but in different channels each associated with a particular grain size spectrum. A procedure is presented to transform the data output, which is different for each sampler, to a common standard so that the samplers can be objectively compared and their relative efficiency calculated. Results show that the efficiency of the samplers is comparable despite the differences in operating principle and the instrumental and environmental uncertainties associated to working with particle samplers in field conditions. The ability of the samplers to register the temporal evolution of a wind erosion event is investigated. The strengths and weaknesses of the samplers are discussed. Some problems inherent to optical sensors are looked at in more detail. Finally, suggestions are made for further improvement of the samplers.

1. Introduction

Since the introduction of the classic Bagnold trap (Bagnold, 1938), numerous devices have been developed to measure aeolian sand transport. They vary from very simple, passive traps to highly sophisticated electronic sensors. To measure the horizontal sand flux, passive vertically integrating samplers (Bagnold, 1938; Leatherman 1978, Davidson-Arnott and Bauer, 2009), passive segmented traps (WITSEG: Dong et al., 2004; MWAC: Wilson and Cooke, 1980; Kuntze et al., 1990; BSNE: Fryrear, 1986; BEST: Basaran et al., 2011), mesh-style traps for short-term deployments (Sherman et al., 2014), swinging traps (Hilton et al., 2017), and many other concepts have been applied. When the focus is on measuring sediment transport in real-time, one can use continuously-weighing sand traps (Lee, 1987; Janssen and Tetzlaff, 1991; Jackson, 1996; Bauer and Namikas, 1998) or electronic sensors with a high time resolution. The latter category of samplers has become very popular since the introduction of the Sensit (Gillette and Stockton, 1989; Stockton and Gillette, 1990), which uses a piezoelectric crystal that registers sand impacts. The Safire (Baas, 2004; Gillies et al., 2006, 2013; Lancaster et al., 2010) is a similar device that intends to be more economical. The Saltiphone (Spaan and van den Abeele, 1991) is an impact sensor that registers grain impacts on the membrane of a microphone. The Miniphone, introduced by Ellis et al. (2009), is a modified electret microphone that detects the impacts of individual grains.

Recently, several optical electronic devices have been developed that have proved to be very useful under field conditions. Mikami et al. (2005) experimented with, and continue to develop the sand particle counter (SPC). This instrument relies on laser light scattering to infer a particle size distribution for particles with diameters from 30 to 667 µm. Another optical device (Wenglor) has been tested by

* Corresponding author at: Geography and Tourism Research Group, KU Leuven Department of Earth and Environmental Sciences, Geo-Institute, Celestijnenlaan 200 E, 3001 Leuven, Belgium.
E-mail address: Dirk.Goossens@kuleuven.be (D. Goossens).

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Hugenholtz and Barchyn (2011), Barchyn et al. (2014) and Duarte-Campos et al. (2017). Etyemezian et al. (2017) report on an optical gate sensor integrated into a setup called SANTRI (Standalone AeoliaN Transport Real-time Instrument). They argue that because the signal response of the sensor is proportional to the cross-sectional area of the grains travelling through the optical gate, it should be possible to estimate the particle size distribution.

Numerous papers have been published of studies testing and comparing sand transport measuring devices (Leatherman, 1978; Jones and Willetts, 1979; Arens and van der Lee, 1995; Nickling and McKenna Neuman, 1997; Goossens et al., 2000; Namikas, 2002; Li and Ni, 2003; Zobeck et al., 2003; Dong et al., 2004; Cabrera and Alonso, 2010; Tidjani et al., 2011; Poortinga et al., 2013, to mention only a few contributions). Perhaps the most fundamental methodological question that then arises is: Can we compare data that were obtained with samplers that operate on sometimes entirely different measuring principles? If so, how should the data be processed in each case to allow for objective comparison between samplers?

In this study we test a set of sand transport samplers that operate on diverse measuring principles and compare the results after the data have been processed towards a same standard so that they can be objectively compared. The test was performed on the Sand Motor, a nourishment of sand on the west coast of the Netherlands, an area that is prone to frequent wind erosion. The samplers included a passive, vertically integrating continuously-weighing trap, a passive segmented trap, an acoustic impact sensor, an optical electronic sensor, and a recently developed optical gate sensor with multiple channels each of which is sensitive to a particular grain size class. We present the methodology to objectively compare the data, discuss the strengths, weaknesses and applicability of each sampler, and provide suggestions for further improvement of the instruments.

2. Study area

The study was conducted on the Sand Motor (also called Sand Engine, Dutch: Zandmotor), a unique, approximately 1 km^2 large nourishment of sand with an initial volume of 21.5 million m^3 that was laid down for coastal protection on the west coast of the Netherlands near The Hague (Fig. 1). Its design stems from the philosophy of 'Building with Nature' (De Vriend and Van Koningsveld, 2012), a coastal management strategy that aims to provide coastal safety by utilizing natural processes. Through wave and wind action, the Sand Motor gradually releases its sand along the coastline, thereby reinforcing the beach and dunes against storm surges and sea level rise (Nolet et al., 2014; De Schipper et al., 2016). A net negative sediment balance is thus counteracted, while the coastal ecosystem is preserved (Stive et al., 2013).

The Sand Motor is located along a stretch of the Delfland coast and has a hook-shaped design (Fig. 1) that mirrors the natural onshore migration of an intertidal sandbar. The tide near The Hague is semi-diurnal with a spring-neap tidal amplitude around 1.5–2.0 m, generating alongshore currents with velocities up to 0.5 m s^{-1} (Luijendijk et al., 2017). Just after its construction in summer 2011 the Sand Motor had a surface area of about 128 ha, extending 2.5 km along the coastline and protruding 1 km into the sea. Natural processes have since then redistributed the sand at high rates (De Schipper et al., 2016). Fig. 1 provides a snapshot of the morphology of the Sand Motor during autumn 2015.

Climate in the Netherlands is temperate humid, with strong seasonal contrasts. The dominant wind direction is southwest, but during the wind erosion event analyzed in this study the wind blew offshore, coming from the east.

Annual average rainfall near The Hague is around 880 mm. During the wind erosion event analyzed here, no rain occurred.

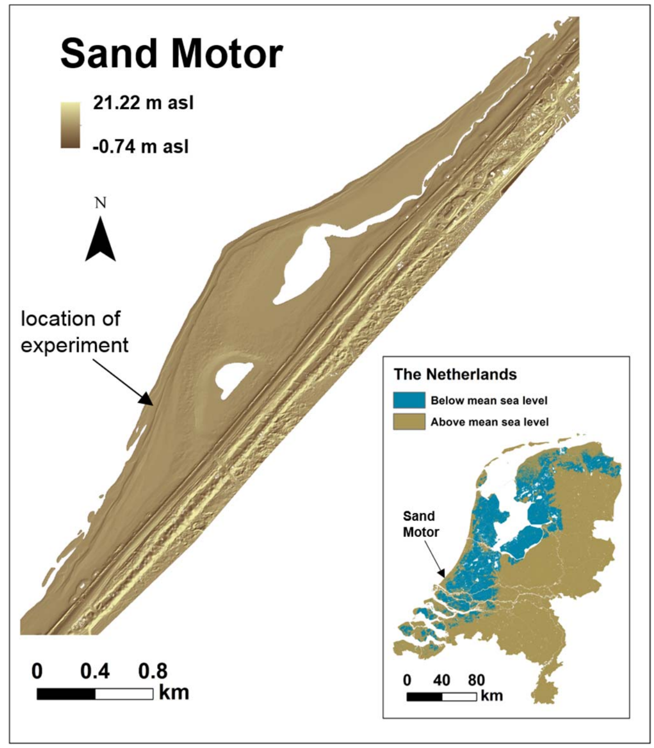

Fig. 1. Location of the experimental site on the Sand Motor along the Dutch coast. The inset map of the Netherlands illustrates the importance of coastal defense as large parts of the country are below mean sea level. The map of the Sand Motor was derived from airborne lidar during a flight in October 2015.

3. Description of samplers

3.1. MWAC sampler

The MWAC sampler is based on an original concept developed by Wilson and Cooke (1980). The sampler consists of a plastic bottle to which an inlet tube and an outlet tube have been added (Fig. 2). The bottle serves as the settling chamber for the wind-transported grains. In the original version the bottle was installed vertically, with the inlet oriented to the wind. Sand entering the bottle deposits due to the pressure drop created by the difference in diameter between the bottle and the inlet and outlet tubes. The clean air then discharges from the bottle via the outlet. The initial concept was later slightly modified by Kuntze et al. (1990), who attached the bottle in a horizontal position to a vertical mast. A wind vane ensures that the inlet faces the wind. Attaching several bottles at different levels to the mast can measure vertical flux profiles (Sterk, 1993). In this study, the MWAC was tested with the bottles oriented in the horizontal position. Sediment was collected at 7 heights above the ground, at approximately 8, 15, 22, 30, 50, 75, and 100 cm.

3.2. Saltiphone

The Saltiphone is an acoustic sensor that records the impacts of saltating particles on a sensitive microphone submerged in the saltation layer. Preliminary versions of the sensor have been tested by van der Linden (1985). The final version, which is shown in Fig. 3a, was described by Spaan and van den Abeele (1991). A technical scheme is given in Fig. 3b. The instrument consists of a microphone containing a sensitive membrane 10 mm in diameter, which is installed in the middle of a stainless-steel tube 130 mm long and 50 mm in diameter. The tube protects the microphone against severe weather conditions. To keep the microphone's membrane perpendicular to the wind at all times, two vanes are attached to the back of the tube. The tube itself is mounted on

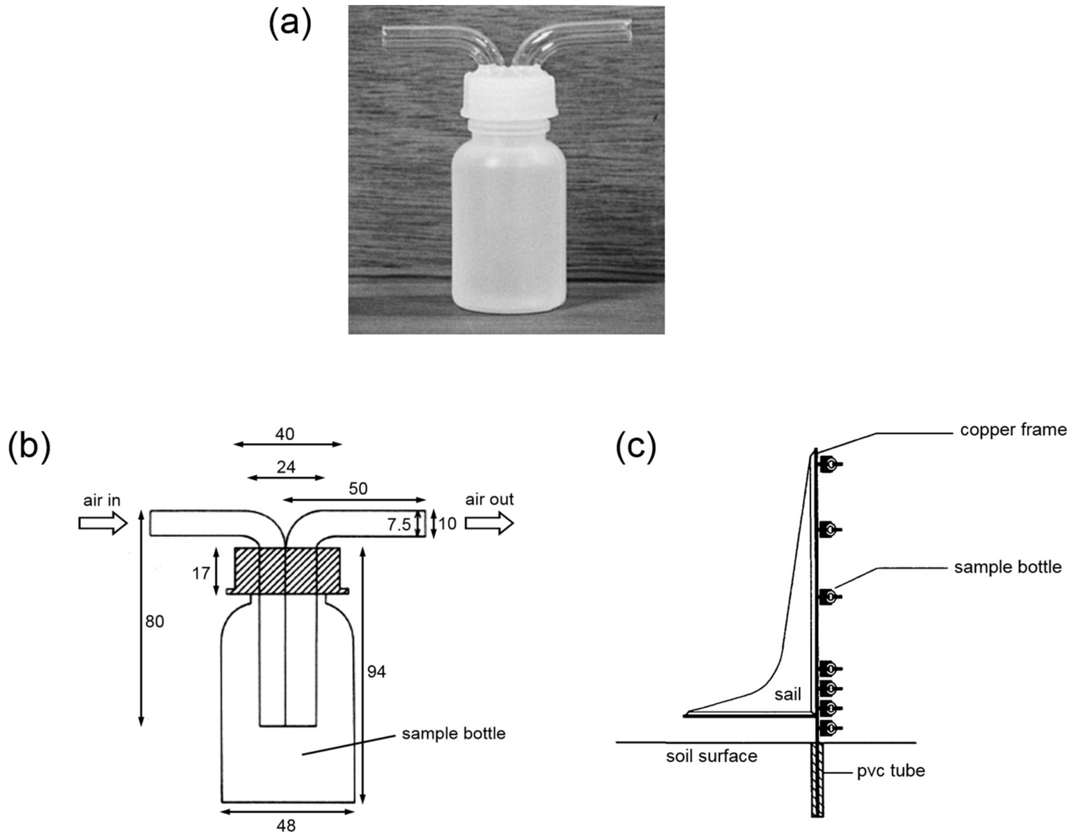

Fig. 2. Photograph and schematic of the MWAC sampler (all units in mm).

a ball bearing attached to a 500-mm-long stainless-steel pin pressed vertically into the soil. Saltating sand particles that enter the tube bounce against the microphone. For sufficiently large grains, the impact energy is high enough to vibrate the membrane. The impacts are recorded on a data logger connected to the instrument. The low-frequency tones caused by rain and by the wind itself are removed from the signal so that only the high-frequency tones of the impacting sand grains are retained. This makes it possible to register the total number of impacts on the membrane. Experiments by Bakkum (1994) have shown that the impact energy of suspended dust particles is too low to vibrate the membrane. This means that the Saltiphone detects only saltating sand.

Apart from the digital pulse output that is translated into number of counts, the Saltiphone also has an analogue voltage output that can provide information on the intensity of the grain impacts (Poortinga et al., 2013). In this study we used the digital output to compare with the other sand samplers.

3.3. Wenglor

The Wenglor is an optical sensor that can be used as an optical particle counter. A picture is shown in Fig. 4. A laser beam is used to detect the particles in transport. To guarantee an optimal alignment of the optical system, the light transmitter and light receiver are integrated into a single housing, which reduces interconnection errors significantly. The light receiver converts the amount of light into an analogue voltage level. The analogue voltage decreases if the received light intensity decreases. Particles travelling through the light beam will affect the intensity of the beam. The measured analogue signal is compared to a user-adjustable offset voltage. If the measured voltage drops below the offset value, as occurs during interruption of the light beam by a particle, then the digital output signal of the instrument is switched to OFF. A correct value of offset is important to ensuring that particle counts are reliable. This implies that an erroneous offset voltage will result in unreliable counts. To avoid this, the offset can be calibrated by the user by pushing the offset button during operation. Given the rather harsh environmental conditions on the Sand Motor during the experiment, we decided to perform a calibration of the offset (minimal teach-in mode) at least once a day after cleaning the lenses of both the light transmitter and light receiver.

Several versions of the Wenglor gate sensor are in use in aeolian sand transport research, such as the YH03PCT8 (30 mm fork width) and the YH08PCT8 (80 mm fork width). In the Sand Motor experiment we used the YH05PCT8 version (50 mm fork width) to find a balance between avoiding grain saturation during high wind speeds and missing particles during low wind speeds. The light beam diameter is 0.6 mm. The smallest detectable particle is 40 µm according to the manufacturer, but a study by Duarte-Campos et al. (2017) suggests that this is too optimistic. Verifying the signal interruptions by direct high-speed camera observations, they found that the smallest detectable particle is 210 µm. In the Sand Motor experiment reported in this article, the counts were logged every 30 s.

3.4. SANTRI

The SANTRI platform used in the Sand Motor experiment is depicted in Fig. 5. Starting from the top of the figure, a solar panel is oriented horizontally and fastened to a water resistant electrical enclosure. The enclosure contains a 12-volt, lead-acid battery that in conjunction with the solar panel and a charge regulator is intended to provide the necessary power to operate the instrument. The entire enclosure is mounted on a shaft that is free to rotate. An attached wind fin 42.6 cm in length causes the enclosure to orient itself in alignment with the wind direction. Also mounted on the wind fin is a 3-cup anemometer. A digital compass in the enclosure provides information about the ambient wind direction. Humidity and temperature are also measured.

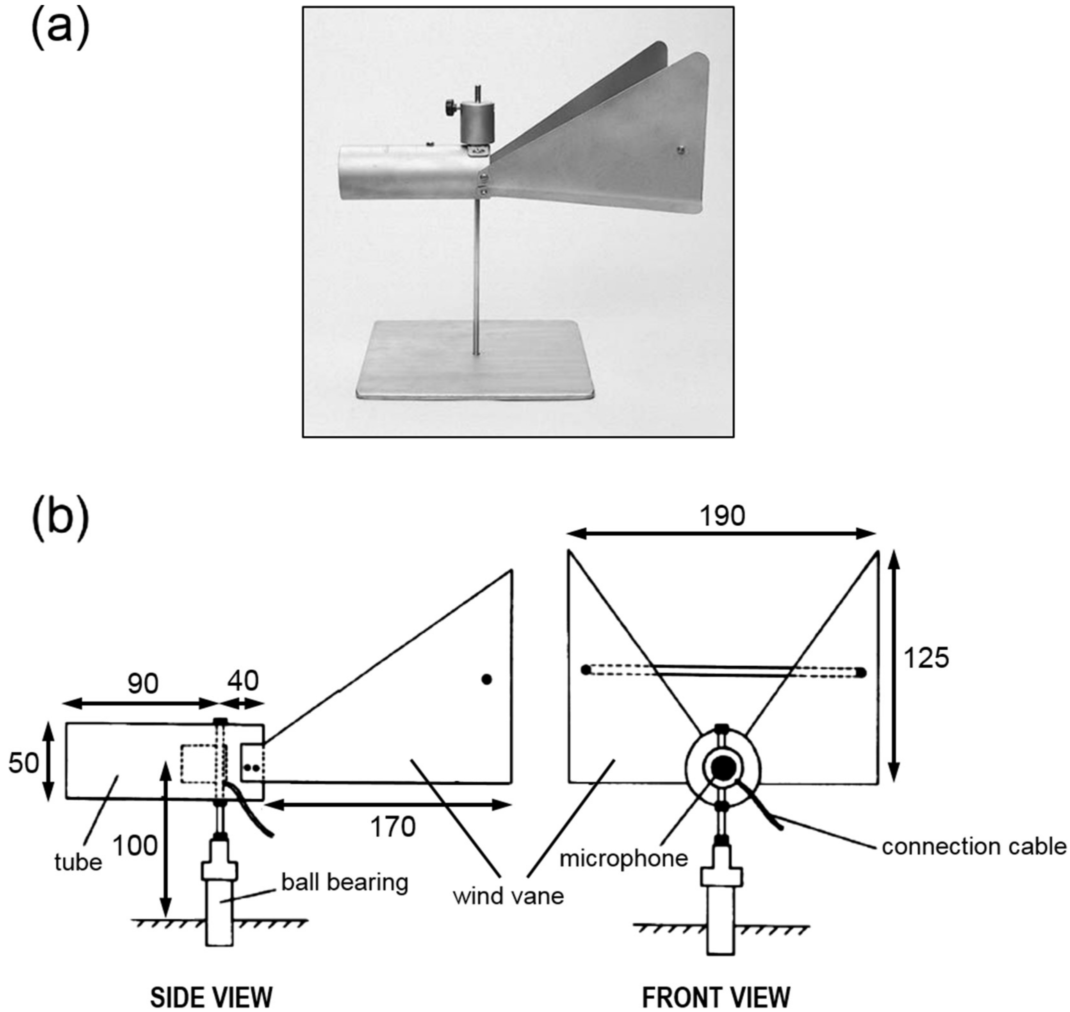

Fig. 3. Photograph and schematic of the Saltiphone (all units in mm).

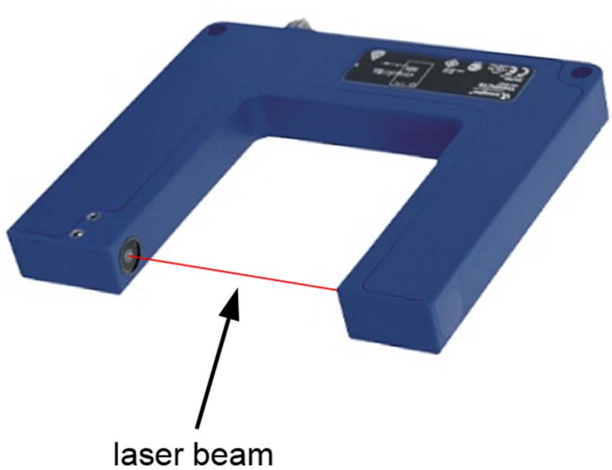

Fig. 4. Wenglor sampler.

The SANTRI devices used for this study were each equipped with four optical gate devices (OGD), with a pair at each of two heights. The OGD (Optek, Model OPB800W55Z, Carrollton, Texas, USA) consists of an infrared light source (emitter) and a light-sensitive phototransistor (sensor) that are separated by 9.5 mm. Both the sensor and emitter are enclosed in an opaque shell with only a square opening (side of 1.27 mm) that light can travel through. The openings for the emitter and sensor are aligned with one another across the gap of the OGD. When saltating sand passes through the active area of the OGD, the light from the emitter that reaches the sensor (and subsequent, the signal from the sensor) is reduced by an amount that is essentially proportional to the cross-sectional area of the sand particle (Etyemezian et al., 2017). The sensor on each OGD device translates the light it receives into an analogue voltage. A specific data point is considered to be associated with the particle blockage of the OGD if its voltage level is some threshold below the baseline (nominally, a difference of about 6.5 mV). For each data point that meets the threshold criteria, the counter in the appropriate bin was incremented. Seven bins were used in the current study. The output ("counts") of the bins was recorded every second.

3.5. Modified Leatherman sampler

The Leatherman sampler is a passive, cylindrical and non-rotating vertical sand trap originally developed by Leatherman (1978) and improved later by Rosen (1978). In the modified version used in the Sand Motor experiment, the part of the sampler that traps the sand closely follows the original design. The modification relates to the added capacity of the sampler to automatically measure and store the weight of the trapped sand. This allows measuring aeolian sand transport at user-defined temporal resolutions, which was not possible in previous designs.

Fig. 6 shows a schematic of the modified Leatherman sampler and its employment in the field. The part that traps the sand consists of a

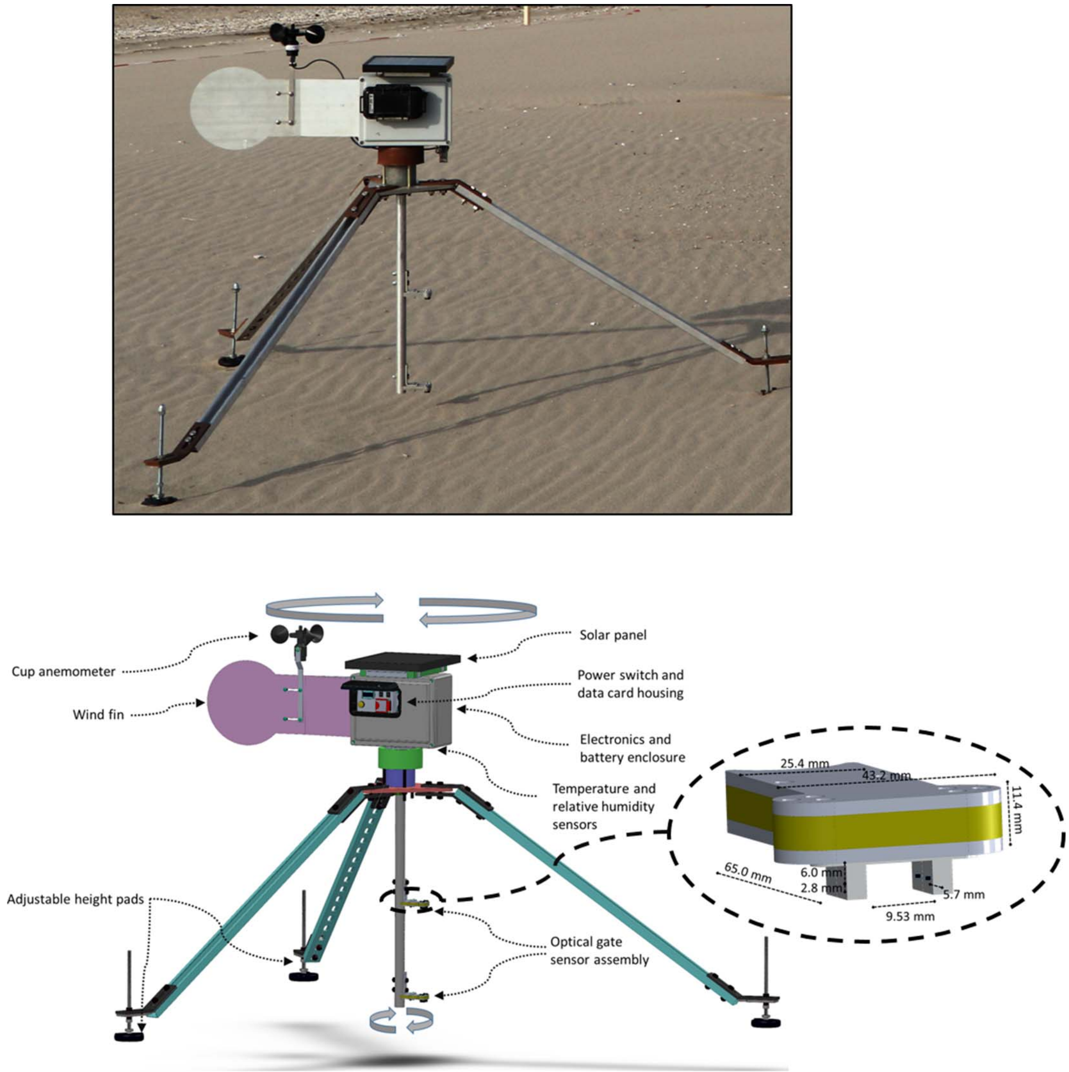

Fig. 5. Photograph and schematic of the SANTRI platform used in this study.

100 cm long aluminum pipe 4 cm in diameter that has two 50 cm long vertical slits at opposite sides that extend above the beach surface. The 2 cm wide front slit acts as a collection inlet for sand particles, while the 4 cm wide back slit allows for air to flow through the pipe. The back slit is covered by a 0.5 mm stainless steel mesh to block sand particles from being blown through the pipe.

The aluminum pipe extends downward into a 20 cm diameter and 150 cm long PVC tube buried beneath the beach surface. The PVC tube houses a 75 cm long 50-µm nylon mesh bag for sand collection, which is suspending from a tension load cell with a rated capacity of 25 kg. The cumulative weight of the trapped sand is measured at 10-min intervals at a 0.24 g resolution. To help prevent clogging up, for example by wet sand, the sampler is fitted with a vibration motor that is activated for a few seconds every 30 min.

4. Methodology and procedure

A total of 23 samplers were deployed during the Sand Motor experiment: 5 MWAC samplers (with 7 sampling bottles each), 3 Saltiphones, 6 Wenglors, 6 SANTRI's (3 instrument platforms containing 2 OGD measurement units each), and 3 modified Leatherman samplers. The configuration of the setup is shown in Fig. 7. For the Wenglors and the SANTRI's, two copies (optical gate devices) were installed on top of each other (back-to-back in the case of the SANTRI) at each measuring spot, the lowest between 5 and 10 cm above the beach surface and the upper between 30 and 35 cm above the beach surface. One pair of Saltiphones was installed the same way; the third Saltiphone was installed individually, at 10 cm above the surface. The modified Leatherman samplers were oriented to the east so that their inlets were perpendicular to the direction of sand transport. The exact height of each sampler was measured prior to the start of the measurements and a second time after completion of the experiment. A wind tower containing 6 anemometers at 35, 76, 114, 165, 217 and 268 cm above the surface and a wind vane at 285 cm above the surface was installed close to the sampling array (Fig. 7).

The type of output differs between the samplers tested. The MWAC and modified Leatherman directly collect the sediment in transport, and the result can be expressed in terms of a horizontal flux. Both instruments sample a vertical column of air, the modified Leatherman in an uninterrupted column but the MWAC in up to 7 individual points within the sampling column. The other three samplers do not collect sediment but register individual grains during their airborne transport. The Saltiphone counts the number of grain impacts against the microphone. The Wenglor and the SANTRI count the number of signal interruptions caused by particles travelling through the detection beam. Therefore, to be able to objectively compare all samplers, a common metric should be chosen.

In this study we opted for using the MWAC as the reference to which all other samplers can be compared. The reason is that the MWAC is the only sampler in the test that can be used for this purpose. By integrating

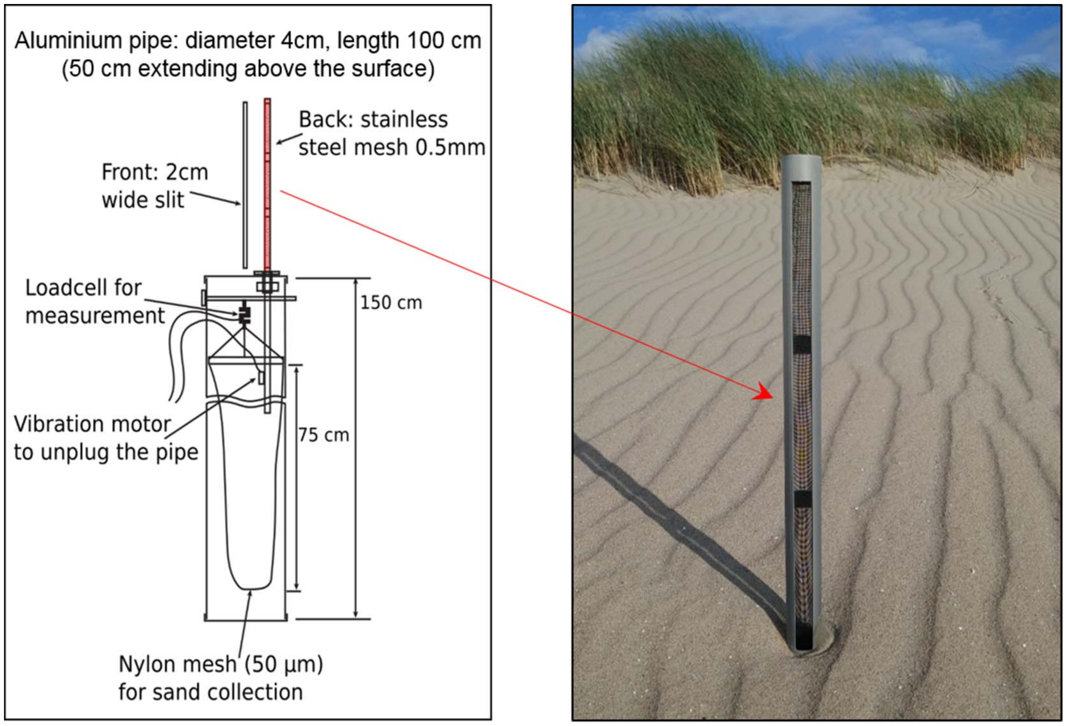

Fig. 6. Photograph and schematic of the modified Leatherman sampler.

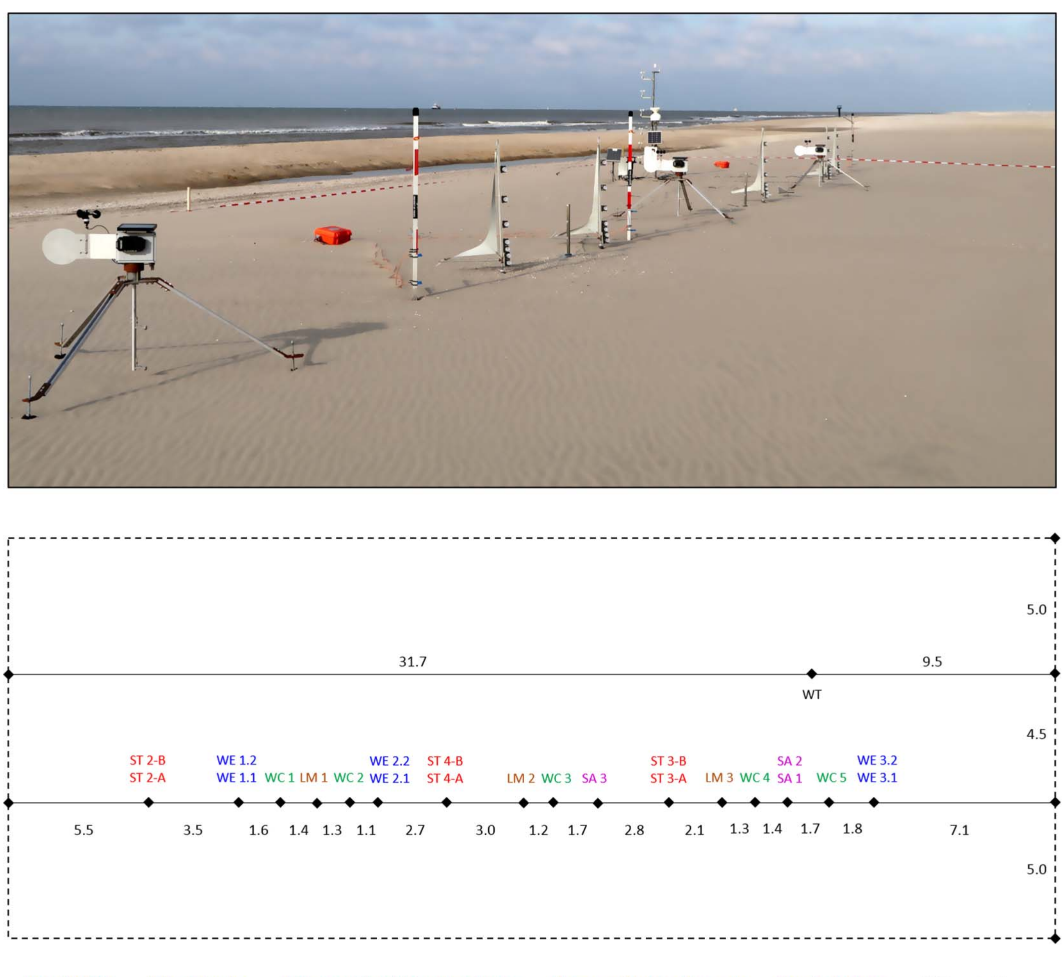

Fig. 7. Experimental setup on the Sand Motor.

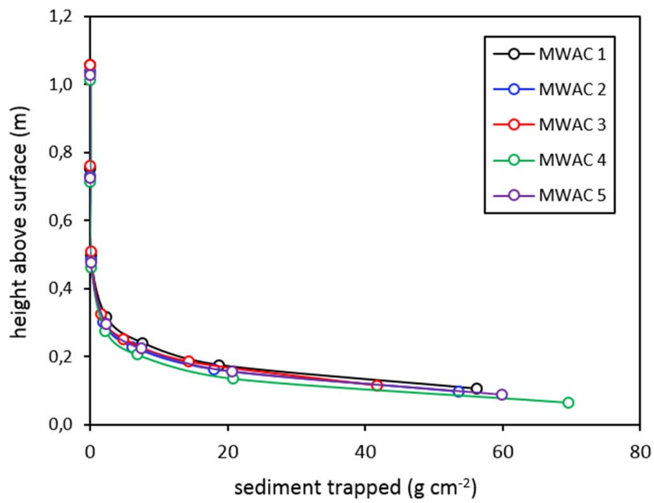

Fig. 8. Vertical sediment profiles measured by the MWACs.

the sediment mass measured at its 7 individual measuring points over the same vertical column as the inlet of the modified Leatherman, a direct comparison between these two samplers can be achieved. The number of counts by the Saltiphone, Wenglor and SANTRI, on the other hand, can be transformed into a sediment mass provided the mass density and grain size distribution of the sediment registered by these instruments is accurately known.

The procedure adopted in this study is as follows. First, we calculated the horizontal particle mass (per vertical unit area of 1 cm^2) for the MWAC, at all seven heights, for all five MWAC masts. By fitting a curve through the data points (see Fig. 8), the horizontal particle mass can then be calculated for any desired vertical interval by integration. Using the same vertical interval as the inlet of the modified Leatherman (and expressing the modified Leatherman data in $g\,cm^{-2}$), a direct comparison between the MWAC and modified Leatherman can then be made. For the Saltiphone, we transferred the number of counts into a sediment mass using the following formula (Goossens et al., 2000):

$$M_T = \frac{(\frac{\pi}{6})\rho_k S}{\sum_{i=1}^{m} \frac{Q_i}{(D_i)^3}} \quad (1)$$

where M_T = total mass of the grains recorded by the Saltiphone (g), ρ_k = mass density of the grains ($g\,cm^{-3}$), S = total number of grains recorded by the Saltiphone (number of counts), Q_i = relative proportion of grain size class i in the sediment, $D_i = (D_1 + D_2)/2$, with D_1 (cm) the lower limit and D_2 (cm) the upper limit of grain size class $[D_1,D_2]$, and m = total number of grain size classes. The data for Q_i were obtained by determining a detailed grain size distribution for the sediment collected by the MWAC bottles. Grain size distribution was determined by laser diffraction using a Malvern Mastersizer S laser particle size analyzer (Malvern Ltd., Malvern, UK). Some dispersion was applied, but it was not necessary since all samples consisted of coarse sand (Fig. 9) and none of the samples had particles < 80 µm. To be able to span the whole sediment in a large number of grain size classes (necessary for a better calculation of M_T), we calculated D_i for 100 grain size classes: 0–10 µm, 10–20 µm, 20–30 µm, and so on until 990–1000 µm. M_T was then calculated per vertical unit area of 1 cm^2. To optimally compare with the MWAC, the data and sediment from the nearest MWAC sample bottle (closest MWAC mast, closest height) were used for each Saltiphone. The MWAC result was then recalculated to the same height as the center of the Saltiphone's microphone using the vertical sediment profile measured by the MWAC mast. This ensures that the distance between the location of the MWAC measuring point and the Saltiphone measuring point is minimal, and that the data are calculated for the same height above the surface.

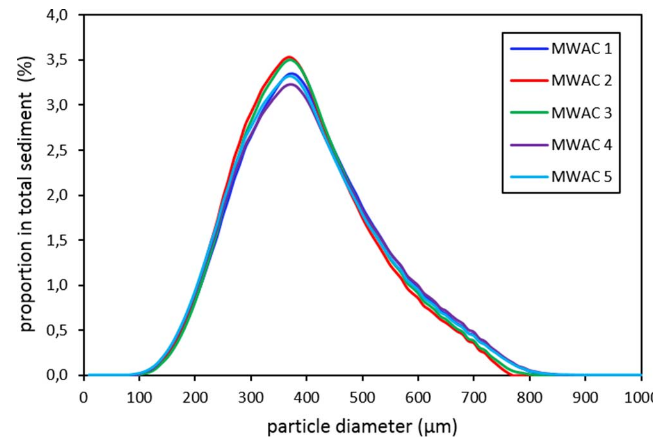

Fig. 9. Grain size distribution of the airborne sediment in the experiment.

For the Wenglor, which counts the number of interruptions of the laser beam due to passing particles, we can use the same formula as in Eq. (1) if we assume that all particles travelling through the beam are effectively recorded. By calculating M_T per cm^2 (the length and width of the beam determine the sampling area), comparing to the nearest MWAC bottle, and recalculating the MWAC data to the same height as the center of the beam of the Wenglor, an optimal comparison between the two samplers is possible. By taking the MWAC as the reference to which all samplers are compared, a comparison between the Wenglor and the Saltiphone also becomes possible.

The assumption that all particles travelling through the laser beam of the Wenglor are effectively registered, and that the registrations by the Wenglor effectively represent all the particles that have travelled through the beam, is prone to criticism because multiple particles can travel simultaneously through the beam (resulting in only a single interruption of the signal), and particles may also partly hit the beam and partly remain outside the beam, causing either signal interruption or not, depending on what portion of the particle travelled through the beam. An additional problem is that the intensity of the laser beam is not constant but decreases outwards, which implies that the effective detection width of the beam is smaller for fine grains than it is for coarse grains (Duarte-Campos et al., 2017). When calculating the efficiency of the Wenglor, we used the effective detection widths shown in Fig. 14a in Duarte-Campos et al.'s paper. We will come back to these problems in the discussion section of this article.

For the SANTRI, which counts the number of interruptions of the infrared beam due to the passing particles, we used the same approach as for the Wenglor. But in contrast to the Wenglor, which provides a global result (one single channel), the SANTRI measures the signal changes in up to 7 channels, each channel corresponding to a different grain size spectrum. Since the other samplers tested in this study measure only the global result we have to sum the number of signal changes for all 7 channels. However, the signal noise (background noise) differs strongly between the 7 SANTRI channels. To remove all signal noise from the data, we carefully checked all 7 channels, for all SANTRI counters. Channel 7, representing the smallest grain sizes, was heavily affected by signal noise and removed from the calculations. For some of the units, also channel 6 had to be removed. Fortunately, the effect of these removals on the final result is rather small since channels 6 and 7 represent the smallest particles in the sample, which do not contribute much to the total mass of the entire sample (recall that the volume of a particle is proportional to the third power of the particle radius).

Similar to the Wenglor, the SANTRI analysis assumes that all particles travelling through the infrared beam are effectively registered, and that the registrations effectively represent all the particles that have travelled through the beam.

The Saltiphone registered the sediment transport in number of particle counts per 10 s. The Wenglor, on the other hand, provided the number of particle counts per 30 s, and the SANTRI, the number of particle counts every second. For subsequent analysis, the Saltiphone and SANTRI output were rearranged into number of counts per 30 s so that the intensity of the particle transport could be objectively compared for these 3 particle counters. Note that this rearrangement is not necessary to determine the efficiency of the samplers relative to the MWAC, since for that procedure the total number of counts has to be considered irrespective of the data output interval.

Using the approach elaborated above, the Sand Motor experiment allowed us to compare the five instruments in an objective way despite the differences in type of data collection, height, and location during the experiment.

The instruments were installed on 6 October 2016 and the MWACs, modified Leathermans and Saltiphones started recording immediately after installation. For the Wenglors, registration started on 8 October 2016, and due to battery issues, the SANTRI's started only on 13 October 2016. Fortunately, the later start dates of the Wenglors and SANTRI's do not affect the results of this study because almost no wind erosion and resulting sand transport occurred before 13 October 2016. This was confirmed by the Saltiphone data, which showed that 98.8% of the sediment transport between 6 and 14 October occurred between 13 October 6:00 h (when the SANTRI's were turned on) and the end of the measurements on 14 October. Accepting that the same percentage also applies to the SANTRI, the SANTRI results were divided by 0.988. For the Wenglor, no correction was necessary since not even a single count was registered by the Saltiphones before 8 October 18:20, when the Wenglors were turned on.

5. Results

5.1. Meteorology and sediment transport

Fig. 10 shows the wind speed (measured at 165 cm height from the meteorological mast), wind direction, friction velocity, and aeolian activity (average of all particle counters) from 13 October 7:00 h until 14 October 7:00 h. During these 24 h, 98.8% of all sediment transport during the test occurred. Wind speed varied between approximately 4.5 m s^{-1} and 8.0 m s^{-1}. Wind erosion predominantly occurred between 11:00 h and 18:00 h on 13 October, when wind speed exceeded 6 m s^{-1}, a normal threshold value for blowing sand (Mezösi et al., 2015). Friction velocity during this period was 0.5 m s^{-1} or higher, well enough to create wind erosion over a dry sandy surface. Wind direction was fairly constant: 93 degrees on average, almost exactly from the east, and more or less perpendicular to the line along which the samplers were installed (Fig. 7). No rain occurred during the measurements. This means that all particle transport during the experiment was aeolian.

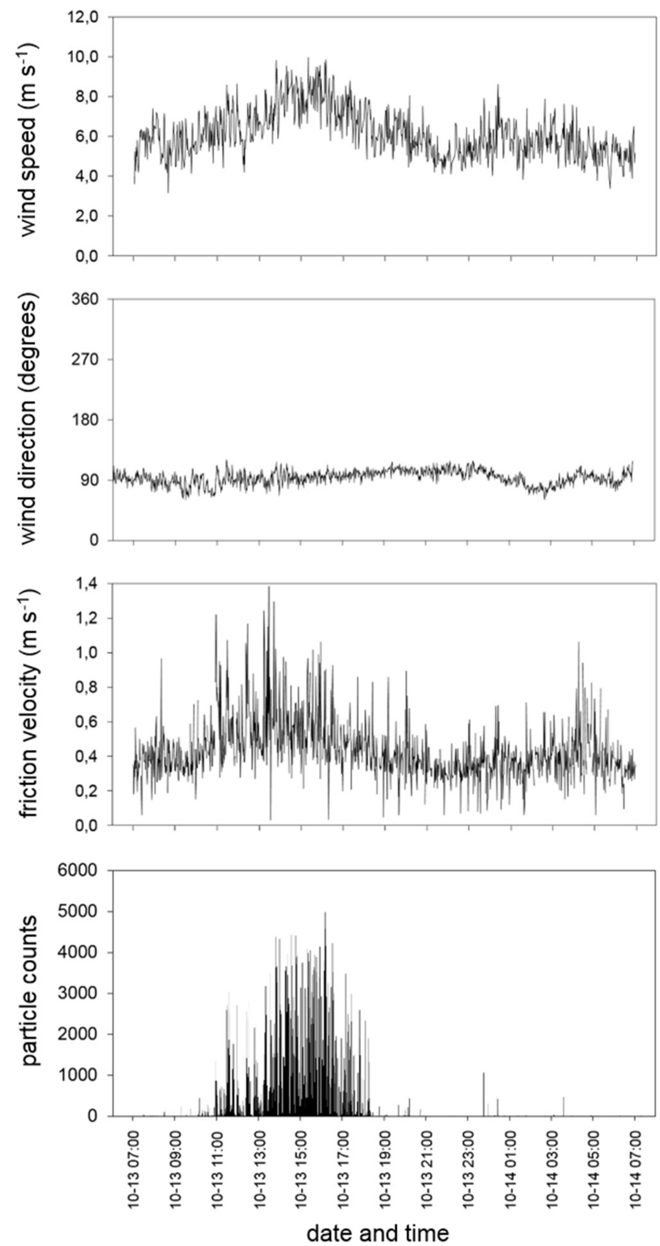

Fig. 10. Wind speed, wind direction, friction velocity and aeolian activity during the wind erosion event of 13 Oct 2016 (7:00) to 14 Oct 2016 (7:00).

5.2. Grain size distribution

The grain size distribution of the sand surface where the samplers were installed is shown in Fig. 11. The sand was rather coarse, with a median diameter of 417 μm. This is in line with the measurements by Huisman et al. (2016), who measured median grain diameters between 300 and 450 μm close to where the experiment was carried out.

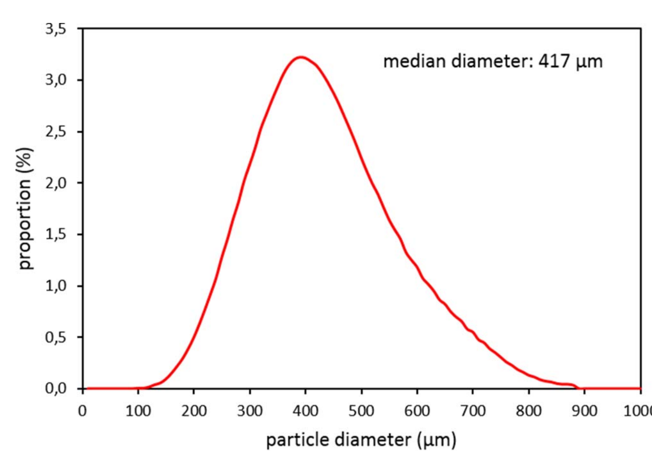

Fig. 11. Grain size distribution of the sand surface where the samplers were installed.

The grain size distribution of the airborne sediment collected by the MWAC masts is displayed in Fig. 9 for each mast. The lowermost 4 bottles could be analyzed; for the uppermost 3 bottles (installed at a height of 50 cm or higher) there was insufficient sediment to allow for a grain size analysis. Somewhat surprisingly, grain size distribution was almost constant as a function of height; there was no tendency for the airborne sediment to become finer with increasing height above the ground. Therefore it suffices to show the average grain size distribution for each MWAC mast in Fig. 9. No significant differences were

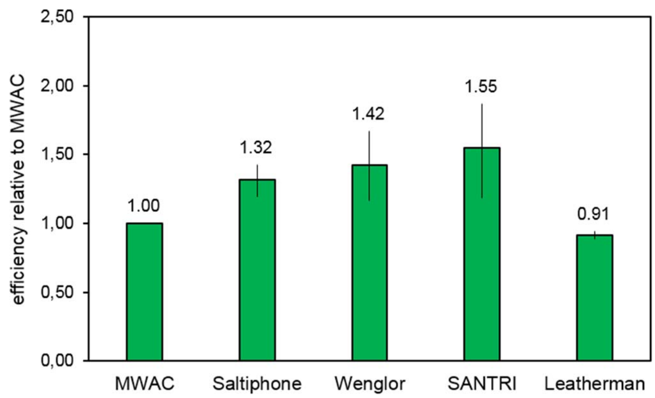

Fig. 12. Efficiency (relative to the MWAC) of the samplers tested in this study.

measured between the masts. The median diameter D_{50} varied between 364 μm (bottle 1 at MWAC mast 2) and 396 μm (bottle 4 at MWAC mast 1). Average median diameter for all samples was 384 μm.

5.3. Comparison of the samplers

In Fig. 12 the efficiency (relative to the MWAC) of the 5 samplers tested in this study is compared. In this study, "efficiency" refers to the ratio of the total particle mass passing through the air (per unit of surface, for example in g cm^{-2}) that is estimated from an instrument to that measured by the MWAC, which we assume is very close to the actual value (see, for example, Goossens and Offer, 2000; Goossens et al., 2000). Note that this does not necessarily imply that the measured and actual masses are equal for every particle size fraction within the sample. For example, an under-estimation of fine particles can be compensated by an over-estimation of coarser particles. Except for the SANTRI, where each bin represents a particular size class, no information is available for the other samplers to test for this criterion; therefore the efficiency in Fig. 12 refers to the total sediment mass. The bars and numbers in the figure represent the average result for each sampler: 5 copies for the MWAC, 3 copies for the Saltiphone, 6 copies for the Wenglor, 5 copies for the SANTRI, and 2 copies for the modified Leatherman. For SANTRI ST2 one of the measuring units failed, which explains why only 5 copies could be tested. For modified Leatherman LM3 the sampler tube above the balance became clogged with sediment early in the test and no further data could be collected; therefore only 2 copies of the sampler could be tested. The vertical line on top of the bars in Fig. 12 represents the standard deviation as an indicator for the spread within each sampler.

Compared to the MWAC, which serves as the reference to which all other samplers have been calibrated, the 3 particle counters (Saltiphone, Wenglor and SANTRI) recorded a higher particle transport whereas the modified Leatherman recorded a lower particle transport. But the differences are not that large: they remain less than a factor two for all samplers. It should be noted that the actual efficiency of the modified Leatherman (relative to the MWAC) is almost certainly larger than 0.91 because during some of the measuring intervals the balance of the sampler recorded a negative sediment weight. This could be caused by under-pressure in the buried part of the tube when strong winds blew through the aluminum pipe of the sampler, or it could result

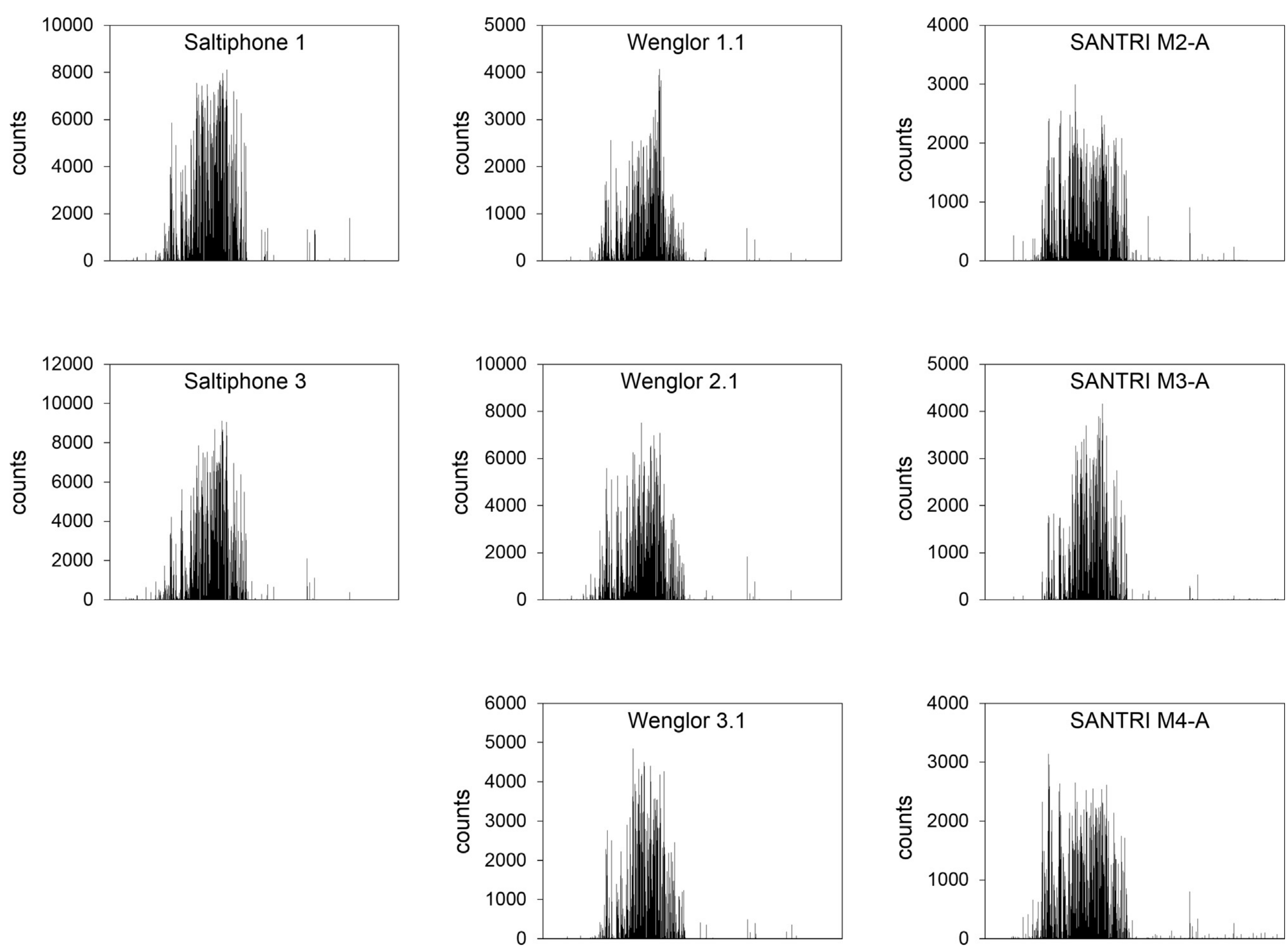

Fig. 13. Registration of sediment transport by the lower samplers (installed between 5 and 10 cm height) during the wind erosion event of 13 Oct 2016 (7:00) to 14 Oct 2016 (7:00). The ordinate shows the number of hits ("counts") registered by each instrument.

from the drying of sediment already collected in the sand bag, or both. Since we don't know how much the balance has been affected by these phenomena, the actual efficiency of the modified Leatherman cannot be accurately determined although we know that it should be larger than 0.91.

In conclusion, all 5 samplers tested in this study measured the sediment transport quite comparatively, within a factor of two, which is encouraging given the differences in methodology of registration, the recalculations necessary to compare the results, and the assumptions and uncertainties associated with the measurements and the data processing. In Section 6 these assumptions and uncertainties will be discussed in more detail.

5.4. Registration by the particle counters

The three particle counters (Saltiphone, Wenglor and SANTRI) and the modified Leatherman registered the sediment transport for short time intervals, which allows one to follow the intensity of the transport process during the wind erosion event of 13–14 October 2016. The registrations of the lower samplers (all located close to the ground, between 5 and 10 cm) are shown in Fig. 13; those of the upper samplers (located between 30 and 35 cm) are shown in Fig. 14, and those of the modified Leathermans are shown in Fig. 15. To allow for a correct comparison between the Saltiphone, Wenglor and SANTRI, all data (bars) in Figs. 13 and 14 refer to identical sampling intervals of 30 s.

In general, the data are very comparable between the samplers although minor differences can be detected when the graphs are investigated in detail. For example, for the lower samplers (Fig. 13) the Wenglors registered the last part of the erosion event less intense than the Saltiphone. This is further illustrated in Fig. 16, where the normalized cumulative particle counts are shown for the data in Fig. 13. The Wenglor curve is located well left from the Saltiphone curve. The SANTRI's, on the other hand, registered the first part of the erosion event more intense than the Saltiphone; hence the SANTRI curve is also located left from the Saltiphone curve in Fig. 16. It is unclear whether these small differences are caused by the operation of the instruments or result from spatial differences in sediment concentration in the saltation cloud; also recall that minor differences were present in the height of the measuring units above the ground.

Looking at the data of the modified Leatherman samplers (Fig. 15), the general pattern is comparable to the one for the Saltiphone, Wenglor and SANTRI although the Leatherman samplers continued to register substantial sediment transport after 18:00 h on 13 October whereas the other samplers did not. Whether this extra transport was real or the difference is a result of less accuracy in the modified Leatherman technique remains to be investigated, although the results from the Saltiphone, Wenglor and SANTRI are very consistent. We will come back to this in Section 6.

6. Discussion

The five samplers tested in this study measured the amount of sediment transport quite comparatively. The three particle counters (Saltiphone, Wenglor and SANTRI) measured more sediment transport than the MWAC and the modified Leatherman sampler measured less sediment transport than the MWAC, but the differences were rather

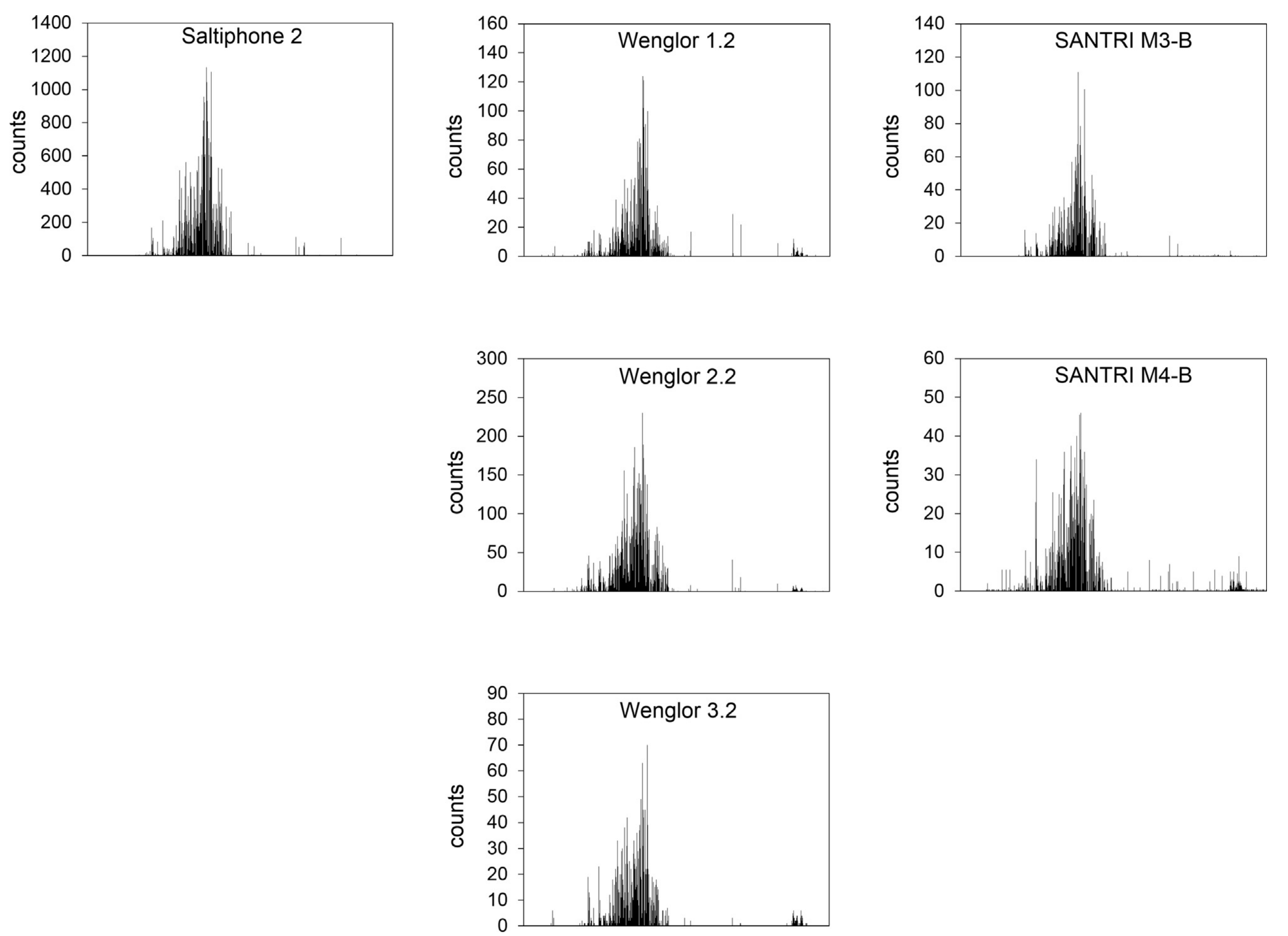

Fig. 14. Registration of sediment transport by the upper samplers (installed between 30 and 35 cm height) during the wind erosion event of 13 Oct 2016 (7:00) to 14 Oct 2016 (7:00). The ordinate shows the number of hits ("counts") registered by each instrument.

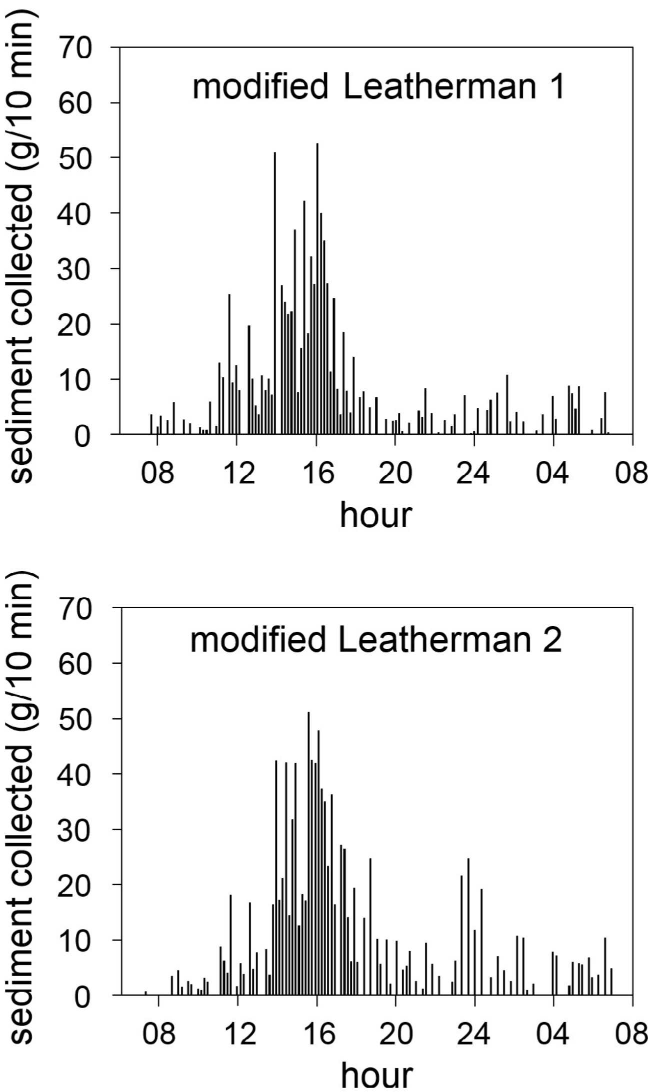

Fig. 15. Registration of sediment transport by the modified Leatherman samplers during the wind erosion event of 13 Oct 2016 (7:00) to 14 Oct 2016 (7:00).

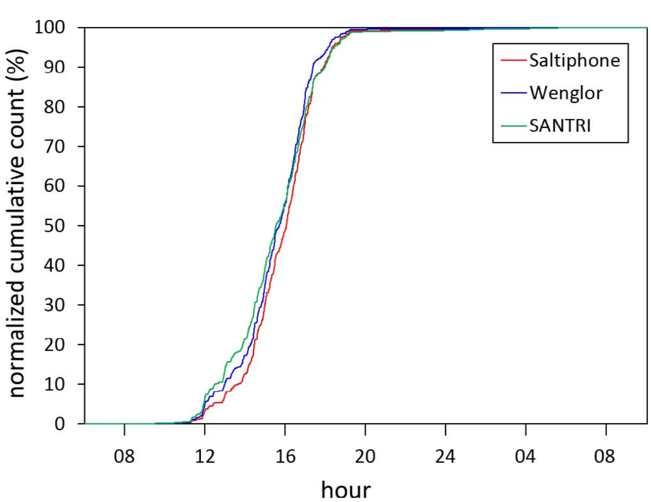

Fig. 16. Normalized cumulative particle counts for the lower samplers during the wind erosion event of 13 Oct 2016 (7:00) to 14 Oct 2016 (7:00).

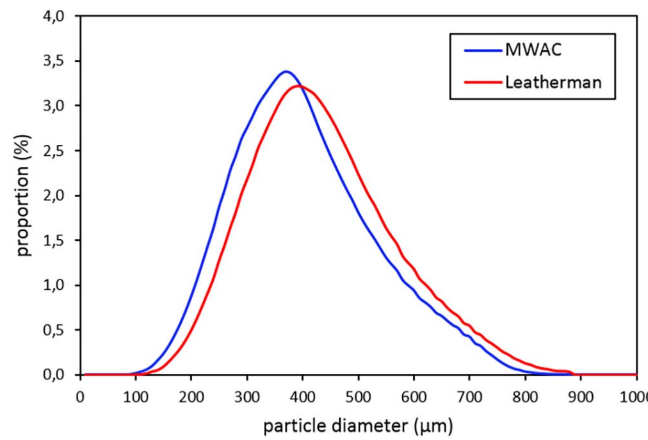

Fig. 17. Grain size distribution of sediment collected by the modified Leatherman samplers compared to grain size distribution of sediment collected by the MWAC samplers.

small, less than a factor two for all samplers. The internal variation within a sampler type, represented by the standard deviation in Fig. 12, was highest for the SANTRI and the Wenglor (the two optical samplers) followed by the Saltiphone and the modified Leatherman sampler.

Looking at the temporal registration of the wind erosion event (Figs. 13–15), all samplers operated satisfactorily. The differences in registration are small although minor differences do exist, as illustrated by Fig. 16. The only sampler with a different pattern in registration is the modified Leatherman, which continued to detect substantial particle transport after 18:30 on October 13 whereas the other samplers did not. Taking into account that the modified Leatherman underestimates the actual transport (see Section 5.3), this extra registration after 18:30 on October 13 must be real and should not be a result of malfunctioning of the balance inside the instrument since the balances of the modified Leathermans were carefully calibrated before the experiment. We hypothesize that some wind erosion happened after 18:30 on October 13, but because it was not severe the particles remained close to the ground, in the lowermost few cm, out of the detection range of the other samplers. An observation that might support this assumption is that the sediment collected by the modified Leathermans was a little coarser compared to that collected by the MWAC bottles (Fig. 17) and might possibly also have contained some particles displaced by surface creep, which tend to be coarser than those transported in saltation (Lancaster, 2009).

A problem inherent to the three particle counters (Wenglor, SANTRI and Saltiphone) is that multiple particles can travel simultaneously through the detection beam (or hit the microphone in the case of the Saltiphone), resulting in only a single particle registration. Correcting for this shortcoming is almost impossible since there is no way to detect its occurrence from the signal, but one can expect that the risk should be higher for the Saltiphone than for the Wenglor, and be lowest for the SANTRI because of the difference in size of the particle detection area (0.785 cm^2 for the Saltiphone, 0.300 cm^2 for the Wenglor (the version YH05PCT8, which was used in this study) and 0.121 cm^2 for the SANTRI). Short registration intervals and low sediment concentrations will also produce a lower risk for simultaneous particle registration. The problem is discussed in more detail in a paper by Barchyn et al. (2014), who call it saturation although in reality the phenomenon can already occur if only 2 particles are transported by the wind.

The two optical sensors (Wenglor and SANTRI) suffer from an additional problem. Particles moving largely outside the detection beam can still be counted if the portion that hits the beam is large enough to attenuate the signal below the threshold installed by the software. This leads to an over-estimation of the particle transport. The magnitude of the error varies throughout an event as it depends, apart from the length and thickness of the beam, also on the size and shape of the particles and the sediment concentration near the beam. On the other hand, the intensity of the Wenglor's laser beam is not constant but decreases outwards, which implies that the effective detection width of the beam is smaller for fine grains than it is for coarse grains. This will result in an under-estimation of the particle transport. Duarte-Campos et al. (2017) measured the effective detection width of the Wenglor for a large number of particle diameters. In our Sand Motor study we used their values when calculating the efficiency of the Wenglor samplers. For comparison, if the intensity of the laser beam is assumed uniform the efficiency of the Wenglor becomes 1.30, which is somewhat lower than the "true" value of 1.42. For the SANTRI, Etyemezian et al. (2017) report that there is relatively little variation of intensity inside the infrared beam of the OGD sensor; therefore no corrections were made and the efficiency of 1.55 assumes a uniform infrared beam.

Another problem with the Wenglor and the SANTRI is that very fine particles may cause insufficient attenuation of the beam signal to become registered. Experiments by Duarte-Campos et al. (2017) showed that particles smaller than 210 μm are not detected by the Wenglor. In the Sand Motor experiment reported in this article this did not lead to problems because the sediment was rather coarse (only 3% of the particle mass consisted of particles < 210 μm), but for finer sediment the error may become considerable. For the SANTRI the smallest particles are recorded in bins 6 and 7, which are characterized by substantial electronic noise that causes false positive particle counts. For optical sensors, the reliability for measuring sand transport thus seems to diminish as the particles become finer.

As already indicated before, a problem with the modified Leatherman sampler is the under-estimation of the sediment weight that may sometimes occur and that, apart from drying of the collected sediment, could also be caused by the negative pressure inside the collector tube underneath the surface during strong winds. This results in an under-estimation of the sediment transport. To check whether under-pressure in the tube affects the measurements, experiments could be performed in a wind tunnel. No such experiments have been conducted so far; therefore we don't know how much the efficiency of the modified Leatherman sampler in Fig. 12 has been under-estimated. A minimum estimate of the error can be calculated by excluding all periods with negative weight registrations (and excluding the same periods for the MWAC, which is the reference in our study) and comparing with the efficiency for the total duration of the experiment. Excluding the periods of negative weight registrations resulted in an efficiency of 0.97 compared to 0.91 for the entire experiment. If under-pressure plays a role, then the real error will be higher since under-pressure occurs anytime there is wind, but without an appropriate wind tunnel calibration it cannot be accurately determined.

It is important to mention that, besides the efficiency, also other factors play a role in the choice of a sampler, such as the type of research (should the measured sediment be collected for subsequent physical or chemical analysis or not, is a detailed temporal registration of the event necessary or is the final erosion result sufficient), the duration of the measurement (MWAC bottles may become filled with sediment, electronic sensors may run out of memory when registering at very short time intervals), the durability of the equipment (wear of the Saltiphone's microphone, contamination of the lens of the Wenglor), the cost of the sampler, the power supply (solar panels, battery or direct connection to the grid; no power necessary for passive samplers), local environmental factors, etc.

Finally, one should realize that the results of this study are also affected by unavoidable instrumental and environmental error sources. These errors are at least partly responsible for the internal spread in the data for each sampler. A list of potential errors and uncertainties is given below:

1. The MWAC was used as the reference sampler to which all other samplers were compared, but the MWAC itself is also prone to measuring errors, just like any other sampler. An estimation of possible uncertainties in MWAC measurements has been made in a study by Tidjani et al. (2011).
2. Uncertainties exist in the grain size distribution near the measuring units of the Saltiphone, Wenglor and SANTRI. Although we used the sediment collected by the nearest MWAC bottle, slight differences in the grain size distribution are possible.
3. Uncertainties also exist in the elevation of the instruments above the beach floor. We measured the exact vertical positions before and after the wind erosion event and used the average elevation to calculate the sediment transport, but we don't know how the elevation changed during the wind erosion event.
4. Sand transport is almost always affected by sand streamers (Baas, 2008), which generate spatial variations in the sediment flux. We don't know how much the results of this study have been affected by the sand streamer effect. On the other hand the wind erosion event lasted for more than 8 h without interruption (Fig. 10), which is quite long and may have been enough to smooth the effect.
5. Unlike the other samplers, the modified Leathermans and Wenglors had a fixed orientation and could not adapt their position to changes in wind direction. However, wind direction was very constant during the periods of sand transport (Fig. 10) and the inlets of the modified Leathermans and Wenglors were perfectly directed to the wind; therefore the results of this study should not have been affected. Making these samplers rotatable in the wind will increase their suitability for aeolian sand transport measurements over longer time periods.
6. Under-pressure in the sampling tube and/or drying of sediment collected in the bag of the modified Leatherman sampler has affected the measurements by this sampler but we don't know how large the error is.
7. The results of the particle counters (Saltiphone, Wenglor and SANTRI) may have been affected by under-registration when several particles hit the microphone (Saltiphone) or travel through the beam (Wenglor, SANTRI) at the same time, leading to an under-estimation of the particle transport.
8. For the optical counters (Wenglor and SANTRI), particles travelling largely outside the beam may still have been recorded if the signal has been sufficiently attenuated. We don't know how much the measurements have been affected by this error although calculations suggest that the error was probably rather small.
9. Variations of intensity inside the detection beam affect the effective detection width of the beam. For the Wenglor this resulted in an under-estimation of the particle transport by 9% if a uniform intensity was assumed.
10. The SANTRI channels that correspond to the smallest size bins were subject to false positive particle counts, probably due to signal noise being interpreted as the presence of particles in the sampling volume.

7. Conclusions

Five types of samplers designed to measure aeolian sand transport (MWAC, Saltiphone, modified Leatherman, Wenglor and SANTRI) were tested in this study. All samplers produced comparable results despite their differences in operating principle. The three particles counters (Saltiphone, Wenglor and SANTRI) measured more, and the modified Leatherman sampler measured less particle transport compared to the MWAC but the differences were restricted to within a factor of two. It was also found that the temporal evolution of aeolian sand transport was adequately, and also very comparably registered by all the samplers. Problems were observed with the modified Leatherman sampler, which may suffer from under-pressure in the collection tube and from drying of collected sediment, resulting in an under-estimation of the sediment transport. Problems also happened with the SANTRI, where the SANTRI channels that correspond to the smallest size bins were subject to false positive particle counts, probably due to signal noise being interpreted as the presence of particles in the sampling volume.

An additional problem inherent to optical particle counters such as the Wenglor and the SANTRI is that a particle that is only partially travelling within the detection beam may still be registered even if most of the particle is outside the beam. This is more likely to be prominent for the coarsest sand grains. Particle counters may also suffer from saturation when several particles are simultaneously hitting the microphone (Saltiphone) or passing through the detection beam (Wenglor and SANTRI). In addition, variations in intensity inside the detection beam affect the effective detection width of the beam, resulting in an under-estimation of the particle transport. Future work in the development of these samplers could focus on these topics. Registering the occurrence and intensity of sand transport works very well with the samplers tested, but determining the exact amounts remains a challenge although the results of this study show that the differences between the samplers tested were not that large, within a factor of two or even less.

Conflicts of interest

None.

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