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Field-based aeolian sediment transport threshold measurement : sensors, calculation methods, and standards as a strategy for improving inter-study comparison

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FIELD-BASED AEOLIAN SEDIMENT TRANSPORT THRESHOLD MEASUREMENT: SENSORS, CALCULATION METHODS, AND STANDARDS AS A STRATEGY FOR IMPROVING INTER-STUDY COMPARISON

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ABSTRACT

Aeolian sediment transport threshold is commonly defined as the minimum wind speed (or shear stress) necessary for wind-driven sediment transport. Threshold is a core parameter in most models of aeolian transport. Recent advances in methodology for field-based measurement of threshold show promise for improving parameterizations; however, investigators have varied in choice of method and sensor. The impacts of modifying measurement system configuration are unknown. To address this, two field tests were performed: (i) comparison of four piezoelectric sediment transport sensors, and (ii) comparison of four calculation methods. Data from both comparisons suggest that threshold measurements are non-negligibly modified by measurement system configuration and are incomparable. A poor understanding of natural sediment transport dynamics suggests that development of calibration methods could be difficult. Development of technical standards was explored to improve commensurability of measurements. Standards could assist future researchers with data syntheses and integration.

PREFACE

Over the past two years, this project has changed substantially. Initially my thesis project was composed exclusively of two field studies examining seasonal variability in aeolian sediment transport threshold. However, after spending time attempting to qualify these results, I realized that the methods used for measuring aeolian sediment transport threshold were insufficiently evolved. Although the field results were interesting, my persistent concerns with the methods undermined their potential applicability. Following suggestions from Dr. Chris Hugenholtz, my thesis project evolved from a series of regionally relevant field studies to the internationally relevant issue of inter-study threshold comparability. Although this was not the original goal, I believe that the shift in focus was necessary and has resulted in a more applicable, cohesive, and rigorous thesis.

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Thank you all friends here in Lethbridge for your encouragement, understanding, and opportunities to do more than work during my time in Alberta. Special thanks are due to those who visited us in Lethbridge: Rosie, Justin, Bruce, Chris, Sarah, and my parents. Finally, thank you to Emily Barnewall for her love, help, support, and companionship during the course of this project.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
FCRN	Fluxnet Canada Research Network
GTFEM	Gaussian Time Fraction Equivalence Method
IMOP	Instruments and Methods of Observation Programme
PSTS	Piezoelectric Sediment Transport Sensor
TFEM	Time Fraction Equivalence Method
WMO	World Meteorological Organization

CHAPTER 1: INTRODUCTION AND BACKGROUND

> "The precise measurement of threshold is of fundamental importance in aeolian research."
>
> - John E. Stout, in A method for establishing the critical threshold for aeolian transport in the field, Earth Surface Processes and Landforms 29, p. 1195.

1.1 Rationale

Aeolian sediment transport threshold is commonly defined as the minimum wind speed for wind driven sediment transport (Bagnold, 1941). Threshold is a core parameter in models predicting sediment transport (e.g., Lettau & Lettau, 1978), dune activity (e.g., Lancaster & Helm, 2000), agricultural soil erosion (e.g., Fryrear et al., 2000), and dust emissions (e.g., Zender, Newman, & Torres, 2003). Threshold is also useful as a practical measurement of the relation between a given wind speed and the presence of transport. For example, Stout and Arimoto (2010) used threshold to monitor the temporal patterns of aeolian transport of contaminated soils. It is widely acknowledged that threshold varies both spatially and temporally (e.g., Stout, 2007). However, a comprehensive understanding of the controls and dynamics of threshold variability has remained elusive.

Parameterizing threshold has challenged investigators in aeolian geomorphology since the seminal works of Bagnold (1941). Initial attempts relied upon simple analytical models based on the geometry of grain to grain contact and cohesion. These analytical models were validated with wind tunnel studies (both in field and laboratory). The analytical/wind tunnel approach to threshold parameterization remains a common method up to present (e.g., Cornelis & Gabriels, 2003).

Although wind tunnels offer a controlled environment for systematic study of threshold, there are important limitations. Due to the limited size and fetch of wind tunnels, it is difficult to reproduce natural characteristics of turbulence and sediment transport (Spies, McEwan, & Butterfield, 1995; Farrell & Sherman, 2006; Sherman & Farrell, 2008). To obtain a true picture of natural threshold variability, investigators have recently realized that measurement must occur in the field.

The determination of threshold in the field is much more challenging. Rapid and chaotic shifts in wind speed result in intermittent transport that requires high resolution sampling. These challenges have prompted investigators to develop new techniques and new sensors for estimating threshold as a dynamic variable (reviewed in Chap. 2, 3). Many of these new systems can be deployed for long periods of time (months) and produce high resolution (minutes) records of threshold variability. The advances possible with the quantity and quality of these data are just beginning to be realized (e.g., Sankey, Germino, & Glenn, 2009a, 2009b). However, there are several aspects of these methods that require consideration.

Many of the methods and sensors available for investigating threshold remain un-standardized. Consequently, investigators have considerable latitude in their choice of methods and sensors. If the choices in methods modify the measured threshold values, the comparability of these field measured thresholds could be limited. Such a situation may constrain progress and limit the ability of aeolian geomorphologists to develop a comprehensive understanding of natural threshold variability.

In this thesis I examine the impact of modifying sediment transport sensor (Chap. 2) and threshold calculation method (Chap. 3). Overall, results suggest that the adoption of technical standards would help ensure commensurate threshold data. I examine technical standards in more detail in Chapter 4. However, prior to examining the details of the studies in this thesis, I will provide background information necessary to place these chapters within the present framework of aeolian study.

1.2 Background

In this background section I will first examine contemporary modeling of aeolian sediment transport, and how threshold is incorporated into these models. I will then review the approaches used to develop threshold parameterizations, and how field-based methods represent a new and exciting opportunity to improve understanding of threshold variability, and as a result, improve sediment transport prediction.

Although threshold is a core parameter in many models, in this background section I only discuss models used to predict aeolian *sand* transport (on dunes and beaches). Threshold is equally as important for models predicting agricultural wind erosion and dune activity. As the field studies in this thesis are dune-based, I maintain prediction of sand transport as my type example.

1.3 Contemporary modeling of aeolian sediment transport

The seminal contributions of R.A. Bagnold (1941) outlined a framework for description of aeolian sediment transport that is still followed to date. Aeolian transport is conceptualized to be a spatio-temporally homogenous blanket of sediment that is driven by an unchanging shear stress, described with surface shear velocity (u_*). A threshold wind speed (or threshold shear velocity, u_{*t}) exists where the shear stress from wind is sufficient enough to entrain particles. When wind speed is above threshold, transport can occur; when wind speed is below threshold, no transport occurs. A series of models have been developed from the work of Bagnold (1941) (e.g., Kawamura, 1951; Lettau & Lettau, 1978; reviewed in Sherman, Jackson, Namikas, & Wang, 1998). Nearly all follow the basic form:

$$\begin{aligned} q \;&\alpha\; u_*^3 \quad && if \quad u_* > u_{*t} \\ q \;&=\; 0 \quad && if \quad u_* < u_{*t} \end{aligned} \tag{1.1}$$

where q is sediment mass flux (in kg s^{-1} per crosswind meter). Although shear velocity (u_*) is used extensively in these models, in reality the parameter is impossible to measure directly. Investigators typically measure wind speed (u) at some height above the surface and extrapolate measurements to the surface with the Law of the Wall (Lancaster & Nickling, 1994).

Overall, it is widely acknowledged that these models perform poorly (Arens, 1996; Sherman et al., 1998; Delgado-Fernandez, 2009), and can over-predict transport by orders of magnitude (Davidson-Arnott & Law, 1996). Many traditional explanations for these discrepancies have been investigated extensively, including: (i) differences among measurements made in the field and wind tunnels (Farrell & Sherman, 2006; Sherman & Farrell, 2008), (ii) spatio-temporal heterogeneity in sediment transport (Baas & Sherman, 2005, 2006), (iii) fetch effects (Bauer & Davidson-Arnott, 2003; see review by Delgado-Fernandez, 2010), and (iv) threshold variability due to variable surface conditions. Although it is likely that issues with aeolian sediment transport predictions are caused by all of the effects listed above, threshold variability has received the most study. Transport predictions made with these formulae can be exceedingly sensitive to the threshold value(s) used (Arens, 1996).

1.4 Threshold variability

In most environments, surface conditions vary substantially from the bare dry sand that transport models assume (Arens, 1996; Sherman et al., 1998). Non-ideal surface conditions typically increase threshold (Lancaster & Nickling, 1994). The most common examples of non-ideal surface conditions are the presence of adjacent vegetation (e.g., Raupach, Gillette, & Leys, 1993; Okin, 2008) and surface sediment moisture (e.g., McKenna Neuman & Nickling, 1989; Ravi & D'Odirico, 2005). Many investigators have shown that threshold can vary dramatically on a variety of scales, presumably due to these and similar effects (e.g., Stout, 2004, 2007; De Oro & Buschaizzo, 2009). Despite this acknowledgement, in many investigations, threshold is assumed to be static (e.g., Wolfe, 1997). However, it is important to note that this is primarily due to a lack of modeling tools for natural threshold variability, rather than a lack of recognition that threshold is dynamic. Natural variability in threshold is very poorly understood and quantified (Sankey et al., 2009a, 2009b; Stout, 2007).

The challenge of parameterizing threshold variability and relating this variability to controls has spurred the development of a series of measurement and modeling techniques (e.g., Marticorena, Bergametti, Gillette, & Belnap, 1997; Zender, Newman, & Torres, 2003; Wiggs, Atherton, & Baird, 2004). I examine these approaches in Section 1.5; however, prior to this, it is useful to briefly discuss the current phenomenological definition of threshold.

1.4.1 Remarks on the definition of threshold

Threshold is commonly conceptualized as a property of the surface. Every surface subject to aeolian erosion has a threshold, which is defined as the minimum wind speed necessary for sediment transport (Bagnold, 1941).

It has long been realized that threshold cannot be easily represented as only one number. Bagnold's (1941) work showed the presence of two quantifiable thresholds: (i) the minimum wind speed for initiation of sediment transport without antecedent transport, or *fluid threshold*, and (ii) the minimum wind speed for sustaining sediment transport with the presence of transport, or *impact threshold* (Bagnold, 1941). From wind tunnel data, Bagnold (1941) demonstrated that the impact threshold is approximately 80% of the fluid threshold. This difference is attributed to a positive feedback effect caused by the presence of impacting grains, which eject sediment into the airstream, thereby sustaining the process at a lower wind speed than required to initiate transport.

Commonly the fluid and impact thresholds are each defined as a single wind speed (or shear stress). In reality, most sediment is composed of a range of grain sizes and shapes. Thus, for a given surface, variability in positioning is expected due to the positioning of sediment grains. Because the positioning of grains affects their susceptibility to entrainment, the fluid or impact threshold for a given surface is not easily described by one number (Lancaster & Nickling, 1994). This has been demonstrated in wind tunnel studies by Nickling (1988) where the measured fluid and impact thresholds could not be reproduced, presumably because it is impossible to replicate grain positioning between each test. As a solution, it is likely that threshold is best defined as an indeterminate phenomenon (Chepil, 1945; Nickling, 1988; Sørensen, 1993; Zhen-Shan, Xiao-hu, & Wen, 2008), perhaps as two empirical frequency distributions (for fluid and impact thresholds) (Williams, Butterfield, & Clark, 1994).

Despite the reality that a probabilistic characterization of threshold may be a more accurate representation, most threshold parameterizations only describe one wind speed for the fluid or impact threshold, or are approximations of both thresholds as one value. Although this is phenomenologically erroneous, the approach matches the present modeling framework (which can only account for one threshold) and functions appreciably (Wiggs et al., 2004). Throughout this thesis, the methods used to determine threshold all produce discrete, single-valued thresholds. The error associated with this simplification has yet to be fully evaluated, but in this thesis it is assumed to be negligible.

Throughout this thesis, I discuss threshold as threshold wind speed (u_t) (measured at some elevation above the surface) rather than threshold shear velocity (u_{*t}) (extrapolated to the surface). This simplifies comparison, as all threshold wind speeds reported in this thesis were measured at an identical elevation (1.35 m). These values could be extrapolated to the surface if required for sediment transport prediction (see example in Chap. 3, Section 3.5). Several results from the body of this thesis could refine the semantics of threshold determination. I revisit aspects of the semantics in Chapter 5, Section 5.3.

1.5 Approaches to quantifying threshold

Methods for parameterizing threshold are dominated by three approaches: (i) analytical models (e.g., Shao & Lu, 2000), (ii) controlled setting measurement (wind tunnel) (e.g., Nickling, 1988), and (iii) uncontrolled setting (field) measurement (e.g., Stout, 2007). Analytical models use mathematical analyses of the forces on sediment grains to determine a threshold shear stress. Controlled setting measurement is an approach where threshold is measured in a wind tunnel with precise control on wind, bed surface, and allied environmental controls (temperature, humidity, and air pressure). Uncontrolled setting measurement of threshold is performed in the field, with natural wind and sediment conditions, and is the focus of this thesis.

1.5.1 Analytical models

Analytical models have been developed to describe the entrainment of particles by reducing the problem to a mathematical analysis of the forces acting on individual sediment grains. Commonly the bed is simplified as a population of spherical grains of constant size, and the wind is represented as a constant velocity (see Fig. 1.1) (Pye & Tsoar, 1990). The main forces acting on grains include: (i) gravity (acting vertically, holding the grain to the bed), (ii) cohesion between particles (holding grains in place), and (iii) wind, which imparts a drag force on the surface of the grain and also lifts the grain due to the curvature of the upper hemisphere of the grain (Einstein & El-Samni, 1949).

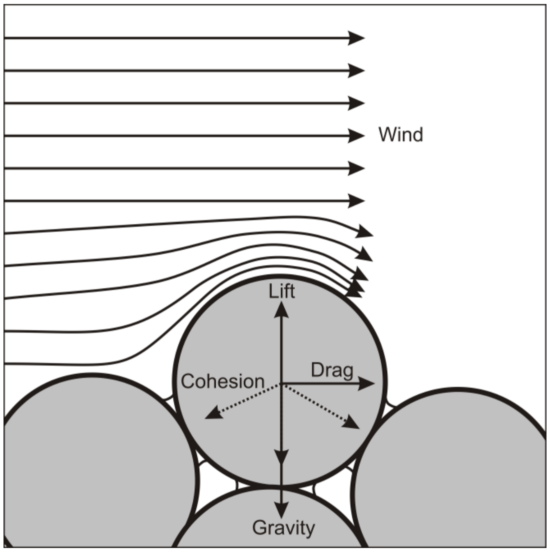

Figure 1.1. Common forces used to derive analytical models of threshold.

There is disagreement over the relative magnitude of lift and drag forces (Sheilds & van Uchelen, 1936; White, 1940; Chepil, 1945, 1959). This is important because it defines the initial movement of grains. Empirical observations of sediment transport at the grain scale do not provide clear evidence to support either theory. Observations from Chepil (1959) and Bagnold (1941) indicate that grains slide or roll along the bed prior to sediment transport. Contrarily, results from Bisal and Nielson (1962) and Lyles and Krauss (1971) suggest grains lift off vertically under the influence of lift forces. While the exact mechanism remains unresolved, it is likely that both processes occur in tandem (Lancaster & Nickling, 1994). Despite disagreement on the effects of forces on grains, grain-scale derivation is reproducible. For example, Bagnold (1941) derived the relationship between threshold shear velocity (u_{*t}) and grain size as

$$u_{*_t} = A\sqrt{\frac{(\rho_p - \rho_a)gd}{\rho_p}} \tag{1.2}$$

where A is a constant (typically 0.1 for fluid threshold and 0.08 for impact threshold), ρ_p is the density of sand grains, ρ_a is the density of air, g is gravitational acceleration, and d is the grain diameter (Bagnold, 1941; following Jeffreys, 1929; Sheilds & van Uchelen, 1936). Empirical measurements have validated this model (Chepil, 1945, 1959; Greeley, Iverson, Pollack, Udovich, & White, 1974); and as a result, the formula is frequently applied (e.g., Craig, 2000; Arens, Slings, & de Vries, 2004; Hugenholtz, Wolfe, Walker, & Moorman, 2009). Other analytical models have been developed by Chepil (1959) and Shao and Lu (2000). This model is for sand; for grains smaller than 0.1 mm diameter, cohesion increases threshold beyond the results of this model (Sagan & Bagnold, 1975).

Analytical models are also frequently modified to explain many of the external controls on threshold, including: bed slope (e.g., Howard, 1977; Hardisty & Whitehouse, 1988; Iverson & Rasmussen, 1994), cohesion from pore water (e.g., McKenna Neuman & Nickling, 1989; Gregory & Darwish, 1990; Fécan, Marticorena, & Bergametti, 1999), and air density changes with temperature (McKenna Neuman, 2003). Despite the quantity and quality of these analyses, the models fail to provide precise results for a population of grains due to the unique positioning, sorting, and grainsize of natural sediment (as discussed in Section 1.4.1). Consequently, the main usefulness of grain-scale threshold derivation is to provide a rough, but sometimes useful, approximation of the actual threshold.

1.5.2 Controlled setting measurement

The primary method of validating analytical threshold models is with controlled setting measurement. This is typically performed in a wind tunnel. Wind tunnels can either be installed permanently in laboratories, or be portable and deployed in the field over a specific surface (see Fig. 1.2).

In wind tunnels, the wind speed and sediment transport are measured simultaneously. Commonly, both the fluid and impact thresholds are measured. The fluid threshold is denoted by the wind speed corresponding to the first measured instance of sediment transport, while the impact threshold is denoted by the wind speed corresponding to the last measured instance of sediment transport as wind speed decreases (Nickling, 1988). Wind speed is commonly measured with pitot tubes or thermal anemometers (e.g., Butterfield, 1993). These instruments are situated close to the bed (centimeters). The presence or absence of sediment transport is recorded by visual observation (e.g., Bagnold, 1941), camera monitoring equipment (e.g., Williams et al., 2004), impact sensors (e.g., Ravi, D'Odirico, Over, & Zobeck, 2004), or laser based detection systems (e.g., Nickling, 1988). Results from these methods are not directly comparable because each method has a different sampling area for detecting the presence of transport (Fécan et al., 1999).

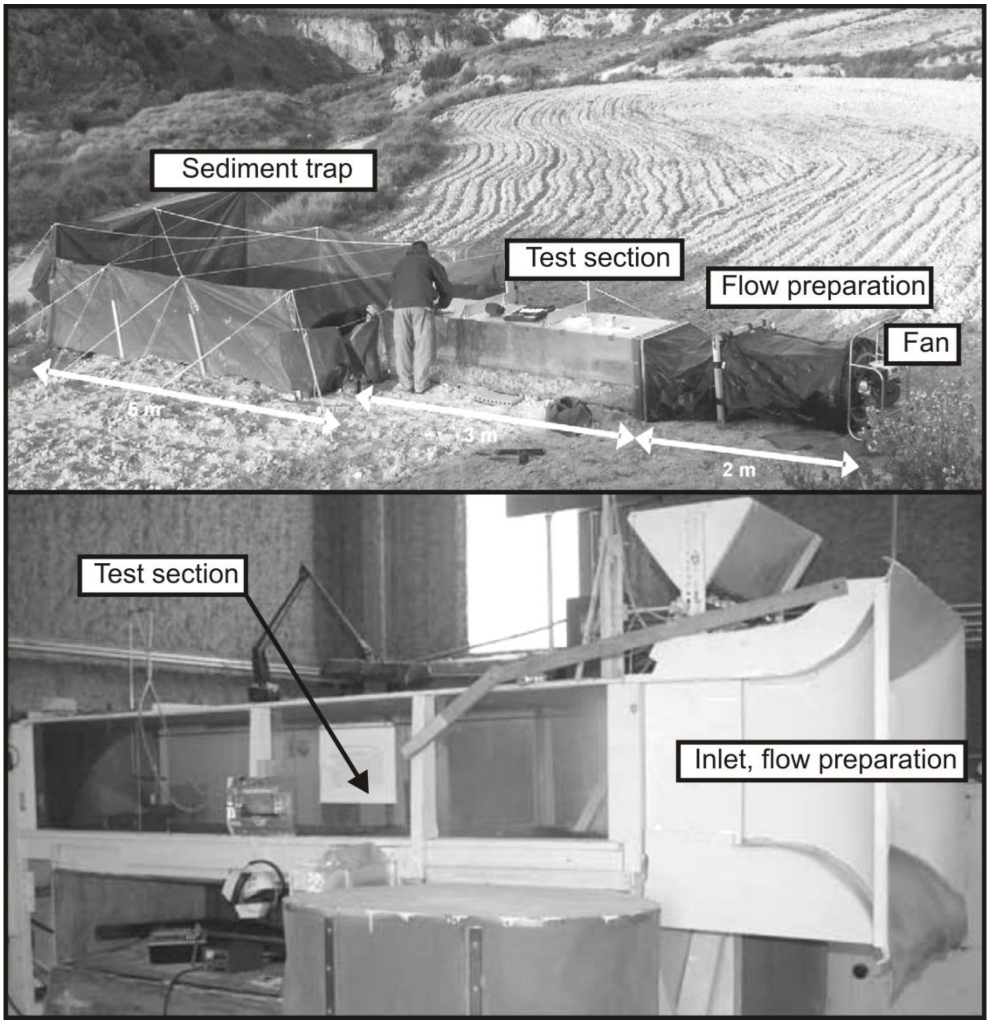

Figure 1.2. Wind tunnel measurement of threshold. A) a portable wind tunnel used for study of agricultural wind erosion (from Fister & Ries, 2009; image reproduced with permission from Elsevier), B) laboratory wind tunnel used for analysis of sensor performance (from Van Pelt, Peters, & Visser, 2009; image reproduced with permission from Elsevier).

Wind tunnels are also commonly used for assessing the impact of surface conditions on threshold. Some important examples include: cohesion from pore water (e.g., Chepil, 1956; Hotta, Kubota, Katori, & Horikawa, 1984; McKenna Neuman & Nickling, 1989; Saleh & Fryrear, 1995; Shao, Raupach, & Leys, 1996; Cornelis & Gabriels, 2003; Ravi et al., 2004; Ravi, Zobeck, Over, Okin, & D'Odirico, 2006), cohesion from pore ice (e.g., McKenna

Neuman, 1989; 1990; Van Dijk & Law, 1995), changes in atmospheric properties (e.g., McKenna Neuman, 2003, 2004), salt content (e.g., Nickling & Ecclestone, 1981; Nickling, 1984), and cohesion from biogenic crusts (e.g., McKenna Neuman, Maxwell, & Boulton, 1996; McKenna Neuman & Maxwell, 1999; Leys & Eldridge, 1998).

The reductionism inherent in wind tunnels has both advantages and disadvantages. Precise results are possible when the controls of threshold variability can be examined in isolation. However, wind tunnels do not reproduce the turbulent fluctuations of wind speed present in natural settings (Stout, 2004; Farrell & Sherman, 2006; Sherman & Farrell, 2008). Furthermore, reproducing natural surfaces in wind tunnels is difficult (Lancaster & Nickling, 1994). Finally, the applicability of these synthetic parameterizations is perhaps most constrained by challenges in measuring surface properties in the field, which can be very dynamic and difficult to measure (e.g., Davidson-Arnott, MacQuarrie, & Aagaard, 2005; Davidson-Arnott, Yang, Ollerhead, Hesp, & Walker, 2009; Baas, 2008). Despite these drawbacks, the use of wind tunnels in tandem with analytical models has resulted in significant progress in understanding the controls of threshold variability.

1.5.3 Uncontrolled setting (field) measurement

Field measurement techniques for aeolian sediment transport threshold have been developed only recently. These methods were developed as a number of investigators began to note the ubiquitous presence of turbulence induced variability in aeolian transport (Stout & Zobeck, 1997; Baas & Sherman, 2005; Baas, 2006; Baas, 2008). With regard to threshold, one of the key implications of turbulence at the instantaneous spatio-temporal scale is transport intermittency (on 1-60 second scales; Stout & Zobeck, 1997).

Parallel to an acknowledgement of the turbulent nature of aeolian sediment transport, investigators developed new high resolution sediment transport sensors (e.g., Stockton & Gillette, 1990; Baas, 2004). These instruments are small sensors placed directly in the airstream a few centimeters above the surface. Each sediment grain that impacts the sensor can be recorded. These sensors are only capable of measuring relative flux magnitude, as precise relations have yet to be determined exhaustively between instrument response and true sediment flux (e.g., Baas, 2004). Despite this, the sensors have been proven to be most useful as an indicator of the presence or absence of transport (e.g., Stout, 2004; Davidson-Arnott et al., 2008). Electronic sediment transport sensors can be sampled digitally at a very high resolution (sub-second), which is a substantial improvement over manual or electronic sediment traps (e.g., Bauer & Namikas, 1998; Davidson-Arnott et al., 2005).

With the technical capability to measure the presence and absence of sediment transport at a high frequency (1 Hz) and acknowledgement of intermittency, several workers began to develop simple methods to measure threshold in the field (e.g., Larney, Bullock, McGinn, & Fryrear, 1995; Gillette, Hardebeck, & Parker, 1997; Lancaster & Baas, 1998). However, field-based threshold measurement did not become popular until Stout and Zobeck (1996, 1997) introduced the Time Fraction Equivalence Method (TFEM). The details of this method (and others) are described in Chapter 3. The primary impact of Stout and Zobeck's (1997) work was the description and demonstration of a reliable technique to measure threshold variability in the field over long time periods with relatively simple instrumentation (see Fig. 1.3 for photo of threshold measurement station).

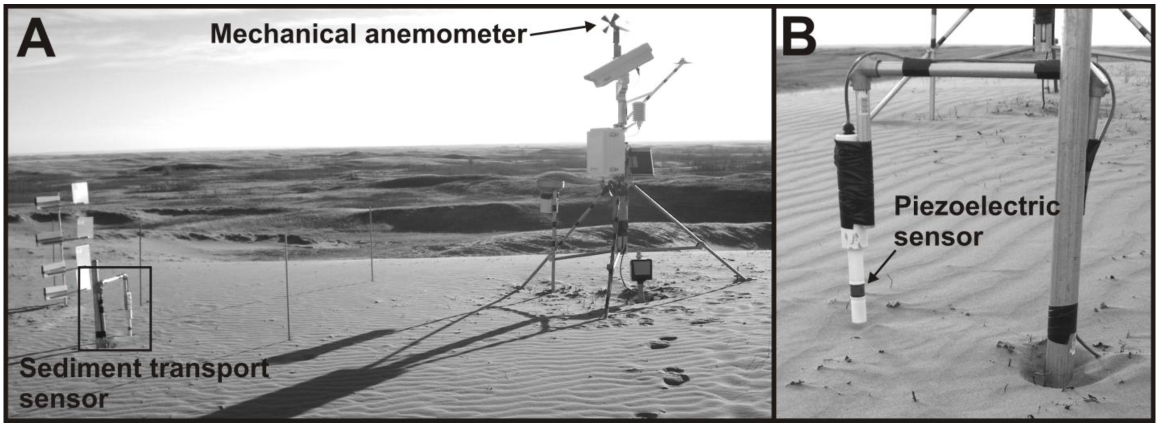

Figure 1.3. Photographs of field-based threshold measurement system. A) computerized erosion monitoring system with B) piezoelectric sediment transport sensor.

Field-based threshold measurement has several important advantages for parameterizing threshold compared to wind tunnels:

(1) Threshold is parameterized under the influence of natural wind. Wind tunnels have come under criticism for misrepresenting the character of wind and sediment transport (Farrell & Sherman, 2006; Sherman & Farrell, 2008). As such, field threshold values are more applicable.

(2) Threshold can be measured over long timescales. The apparatus for field-based threshold measurement consists of, at minimum, an electronic sediment transport sensor, anemometer, and datalogger. Seasonal changes in surface erodibility can be examined on a near-continuous basis (e.g., Sankey et al., 2009a, 2009b; Stout & Arimoto, 2010). This is an unprecedented increase in the possible temporal resolution and extent for studies, when compared to previous methods.

(3) Enough data can be collected to parameterize threshold empirically. This could be a realistic approach for future investigators. At present, there are large challenges with parameterizing surface conditions with enough detail to apply a controlled setting or analytical threshold model (e.g., Davidson-Arnott et al., 2005, 2009). It could be more practical and accurate to measure threshold directly (although see Delgado-Fernandez, 2009).

Field-based threshold measurement holds promise to revolutionize understanding of threshold variability by facilitating the collection of large quantities of empirical data. A growing body of work highlights success with long-term measurement campaigns (e.g., Stout, 2007; De Oro & Buschiazzo, 2009; Sankey et al., 2009a, 2009b; see Chap. 3, Table 3.1 for more). However, there are issues with these methods that require consideration, some of which are addressed in this thesis.

1.6 Thesis outline

In this thesis I present results and discussion intended to guide the future trajectory of field-based measurement of aeolian sediment transport threshold. At present, many aspects of field threshold measurement systems can be modified. These modifications could result in different threshold values. This is concerning for inter-study comparison of threshold results. My objective is to demonstrate some of these issues and introduce technical standards as a potential solution.

First, following work by Baas (2004) and Van Pelt et al. (2009), I perform a comparison of electronic sediment transport sensors (Chap 2). There are many types of sediment transport sensors available, but it is unknown how they differ in their ability to detect transport. Results indicate differences in response, which in turn, result in different threshold values. Although this issue could be considered a “sensor problem”, there is no theoretical reason to pick one sensor over another. In this case, a technical standard would provide a reliable definition of the presence of sediment transport, improving the applicability of threshold measurements by allowing inter-study comparison.

Second, there are a variety of methods available for calculating threshold, all based on different generalizations of the relation between wind and sediment transport. In Chapter 3 I perform a comparison of four methods to calculate threshold from field data. Results suggest the methods produce similar (but not identical) estimates of threshold. From a practical standpoint, the present situation with a number of threshold estimates that are similar (but incommensurate) could be improved by picking one method as a standard. I discuss which method could be used as an appropriate standard.

In Chapter 4 I describe several approaches for standardizing threshold and outline the issue in the format of a commentary. Results from Chapters 2 and 3 serve as examples to support the idea. I believe the issue of inter-study comparability extends beyond threshold, and consequently have focused the chapter on aeolian process measurement in general. Although developing standards is clearly a daunting challenge, I believe the aeolian geomorphology community would benefit from such an approach.

Finally, in Chapter 5 I summarize my findings and recommendations. I also highlight several possible areas for future research. This thesis does not examine all aspects of threshold measurement methodology. Consequently, there are many similar analyses that could be completed in the future.

Overall, this thesis provides a series of important contributions. Threshold remains a central parameter in modeling of sediment transport; however, at present, I believe the aeolian geomorphology community is ill-equipped to handle a future influx of empirical data from field-based measurement methods without a framework for data integration. These contributions cohesively support the idea of using a standard method for threshold measurement. This work could help solidify the foundation of field-based threshold measurement, allowing data integration, comparison, and synthesis.

1.7 Remarks on external contributions and thesis format

This project has benefited from guidance and assistance from numerous individuals. Previous versions of all three major chapters have been submitted for publication (all with co-authors) and some have been reviewed. These reviews have improved the versions present in this thesis.

A previous version of Chapter 2 was submitted 18 February 2010, and subsequently published in *Geomorphology* on 08 April 2010 (Volume 120, pp. 368-371). Dr. Chris Hugenholtz was second author and contributed editorially and through discussions improving the focus of the paper. The manuscript was reviewed as part of the formal review process by Drs. Bernard Bauer and Robin Davidson-Arnott. Permission to reproduce portions of the chapter was obtained from Elsevier. A previous version of Chapter 3 was submitted to *Geomorphology* on 24 June 2010, returned 12 August 2010, and will be resubmitted following the completion of this thesis document. The submission was second-authored by Dr. Chris Hugenholtz. Formal reviews by Dr. Robin Davidson-Arnott and one anonymous reviewer have improved the version in this thesis. A previous version of Chapter

4 was submitted for publication 02 September 2010 in *Earth Surface Processes and Landforms*, and has presently been accepted with minor revisions. Formal reviews were performed by two anonymous reviewers. This submission was co-authored by Drs. Chris Hugenholtz and Jean Ellis. Dr. Chris Hugenholtz contributed editorially and through discussion. Dr. Jean Ellis contributed editorially.

This thesis is "manuscript style"; however, the chapters have been modified to improve flow and cohesiveness. Given this format, there are repeated sections in all chapters. I have rephrased portions of the repeated sections to improve flow.

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CHAPTER 2: FIELD COMPARISON OF FOUR PIEZOELECTRIC SENSORS FOR DETECTING AEOLIAN SEDIMENT TRANSPORT

> "Some of the most important aspects of sediment transport dynamics cannot be reproduced in laboratory settings"
>
> - Andreas Baas, in Challenges in aeolian geomorphology: Investigating aeolian streamers, Geomorphology 93, p. 14.

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2.1 Chapter abstract

Piezoelectric sediment transport sensors (PSTSs) are commonly used to detect aeolian sediment transport. Detection of particles in the near-surface airstream can be used to derive measures of sediment transport threshold, which is an important parameter in sediment transport modeling. However, despite common usage, little comparative field data regarding the detection capabilities of PSTSs are available. This study compares the sediment transport detection of four PSTSs: Sensit H11-B, Sensit H11-LIN (10X configuration), Safire, and Sensit H11-LIN (1X configuration). These sensors were co-located on an active sand dune for 11 days with data measured and recorded at 1 Hz. During this period the time that measured sediment transport occurred was as follows: Sensit H11-B: 20.07 hr., Sensit H11-LIN 10X: 9.07 hr, Safire: 5.10 hr. and, Sensit H11-LIN 1X: 0.25 hr. The large relative differences suggest that the transport detection capabilities of the sensors are inconsistent. The cylindrical design and variable sensitivities restrict straightforward prediction of field detection according to sensor specifications. From these data I demonstrate that the

response of each sensor influences estimates of sediment transport threshold. Regardless of the source of variability, the very presence of detection inconsistency is problematic. Overall, results from this investigation indicate that comparison of metrics derived from measures of sediment transport presence/absence (such as threshold) with different PSTSs is, at present, tenuous.

2.2 Introduction

Aeolian sediment transport varies on sub-second, minute, and hour time scales (Stout & Zobeck, 1997). This has spurred the development of electronic sensors that can measure temporal variability in sediment transport at a high resolution (≥1 Hz). Many designs have been developed: (i) piezoelectric impact sensors (e.g., Safire: Baas, 2004; Sensit: Stockton & Gillette, 1990; Stockton, 2009; UD-101: Udo, 2009); (ii) acoustic impact sensors (e.g., Saltiphone: Spaan & Van Den Abeele, 1991; Miniphone: Ellis, Morrison, & Priest, 2009), (iii) photo-electronic instruments (e.g., SPC laser sensor: Mikami et al., 2005), or (iv) electronic sediment traps (e.g., TBASS tipping bucket: Bauer & Namikas, 1998). Most of these sensors are custom built, not commercially available, or prohibitively expensive. Due to limited availability and/or high cost, few sensors have been compared side-by-side. Several recent investigations have demonstrated inconsistencies in sensor response within different manufacturers, models, and sensors (Heidenreich, Leys, McTainsh, & Larney, 2002; Baas, 2004; Davidson-Arnott et al., 2009; Van Pelt, Peters, & Visser, 2009). These studies largely focused on comparing sensor response to varying sediment flux rather than the capabilities of sensors to detect the presence or absence of sediment transport, which is the focus of the research described in this chapter. Differences in detection are relevant for comparison of field measured aeolian sediment transport threshold. Examples of studies that have used these sensors are summarized in Chapter 3, Table 3.1.

Two types of inconsistencies in sensor response are problematic. First, sensors could identically detect the presence and absence of sediment transport but differ in the relation between measured and true flux. This problem requires sensor-specific calibration functions to be developed, as described in detail by Baas (2004) and Van Pelt et al. (2009). Second, sensors could differ in detecting the presence and absence of sediment transport. This implies that one sensor would record transport while at the same instance and location another sensor would not. Differences in detection are more concerning because there is no calibration that can be used to modify a measured absence of transport without relying on potentially erroneous assumptions regarding a direct relation between wind speed and sediment flux.

The objective of this investigation is to determine whether differences exist in the ability for different sensors to detect transport. I compared the proportion of time sediment transport was detected among four commonly used piezoelectric sediment transport sensors (PSTSs) in an 11-day field deployment, measured at 1 Hz. This differs from the approaches of Van Pelt et al. (2009) and Baas (2004), who both used one or more synthetic environments (such as a wind tunnel or laboratory flume) to assess their sensors. The use of a field test in this study is deliberate for two reasons: (i) I am primarily interested in differences in field response (these sensors are primarily designed for field use), and (ii) relating a synthetically-determined sensitivity to field response is difficult and involves many assumptions (e.g., Baas, 2004). A drawback of our field measurement approach is lower precision and deployment specific results. Thus, I limit the scope of this study to demonstrating the *presence* of detection inconsistency. I discuss possible sources of discrepancies measured, but do not conclusively provide an estimate of the magnitude or determine the cause of sensor inconsistency.

Overall, results showed substantial differences in the sediment transport detection capabilities of the four sensors. I discuss theoretical considerations regarding sensor response, including relations between sensor specifications and field detection. I demonstrate implications of these results: variability in transport detection produces different estimations of aeolian sediment transport threshold. Although limited to four sensors, these results illustrate a significant challenge in comparing threshold measurements performed with PSTSs.

2.3 Field test

The four PSTSs were deployed from 9 July 2009 to 21 July 2009 on an active sand dune in the Bigstick Sand Hills of Saskatchewan, Canada (50° 12’ 31.55” N, 109° 12’ 23.85” W). The purpose of the deployment was to collect raw data under representative conditions in a style that is typical for threshold monitoring campaigns (examples of typical deployments are listed in Chap. 3, Table 3.1).

2.3.1 Study area

The Bigstick Sand Hills are approximately 360 km^2 in area and form the southern portion of the Great Sand Hills of Saskatchewan. The sand is derived from glaciofluvial and glaciolacustrine outwash deposited during the retreat of the Laurentide Ice Sheet (Klassen, 1994; Dyke & Prest, 1987; Wolfe, Huntley, & Ollerhead, 2004). Following initial formation, dunes in this area have undergone several periods of activity and stabilization over the past 10 000 years (Wolfe et al., 2001; Wolfe, Ollerhead, Huntley, & Lian, 2006).

Within the past 200 years, there is evidence suggesting that dune activity has dramatically declined. Wolfe and Hugenholtz (2009) demonstrate how the shape of dunes recorded in relict dune ridges has shifted from barchanoid (200 years before present) to parabolic (present). Widespread dune activity in the mid-1850's (A.D.) in adjacent dunefields is also documented by early Euro-Canadian explorers Hind and Palliser (reviewed in Hugenholtz, Bender, & Wolfe, 2010). Within the air-photo record, dune activity has declined over the past 65 years (Hugenholtz and Wolfe, 2005). More recently, a decade long sequence of repeat topographic surveys of the specific dune used in this study (Hugenholtz, Wolfe, Walker, & Moorman, 2009; Hugenholtz, 2010) also documents a shift towards stabilization. Figure 2.1 shows the location of the study area.

Despite the decadal trend towards stabilization, the Bigstick Sand Hills provide an excellent environment for the study of aeolian processes. The climate is continental with low precipitation, cold winters, and short, warm summers. The climate is classified as sub-humid to semi-arid (Middleton & Thomas, 1997). Average monthly temperatures range from -11°C in January to 19°C in July. Annual precipitation is on average 380 mm (110 mm falling as snow) (climate data recorded in Maple Creek, 45 km to southwest, as reported by Hugenholtz et al., 2009). Wind speed varies seasonally; the highest average wind speeds occur during winter and spring months, and there is a well-defined drop in mean wind speed during summer months. However, transport can occur at any time of the year. The strongest winds are typically from the west (Wolfe, 1997; Hugenholtz and Wolfe, 2005).

Further information on the characteristics of this specific dune can be found in Hugenholtz, Wolfe, and Moorman (2008) (as Dune A), Hugenholtz et al. (2009), or Hugenholtz (2010). The study site and instrument array is pictured in Figure 2.2.

2.3.2 Field measurements

Data were recorded continuously during the deployment at 1 Hz. The lengthy 11-day detection campaign ensured measured transport was representative of a range of transport intensities. Instruments included two dataloggers (Campbell Scientific CR1000), two propeller anemometers and wind direction sensors (RM Young 5103; mounted at 1.35 m elevation), and four piezoelectric sensors (Sensit H11-B, Sensit H11-LIN 10X, Safire, Sensit H11-LIN 1X). The four piezoelectric sensors were situated in a row on an angle of 270°, 5-10 cm apart (pictured in Fig. 2.2 and 2.3). The middle of each sensor ring was set 0.05 m above the sand surface and adjusted mid-deployment on 14 July 2009. A time-lapse camera, co-located with the sensors, acquired images of the array every 0.5 hours between 6:00 - 21:00 daily (local time). This ensured that sensors were situated correctly (40 – 60 mm above bed) and allowed rain-splashed sediment to be distinguished from wind-blown sediment. The dataloggers were programmed to record data when a minimum of one count was recorded by one of the piezoelectric sensors in the last 300 seconds *and* when wind was blowing perpendicular to the line of sensors (225 – 330 degrees). This ensured recorded sediment transport was incident to the sensor array (avoiding shadowing effects from adjacent sensors), while also conserving datalogger memory.

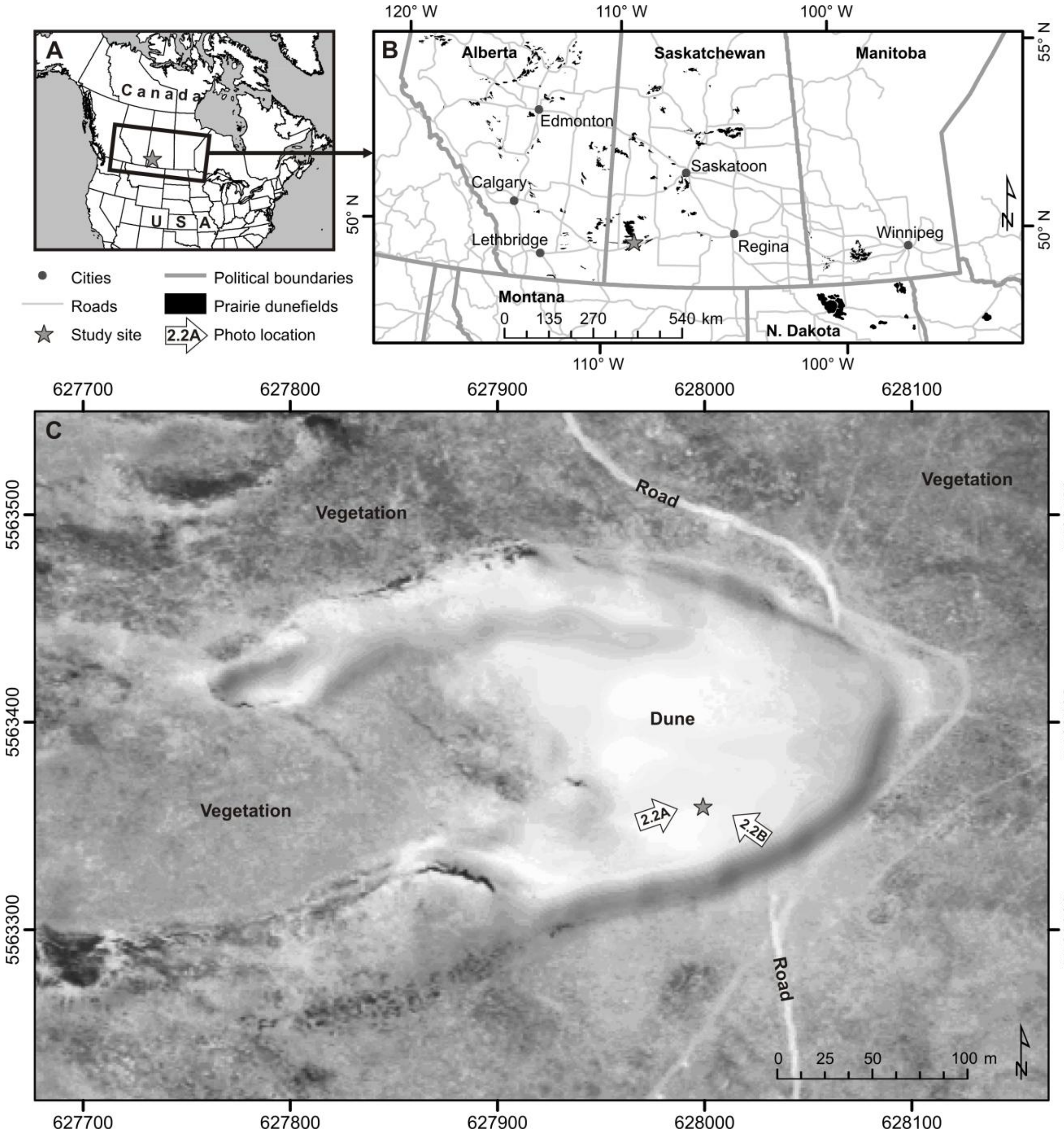

Figure 2.1. Location of study area: A) within North America, B) within the northern Great Plains, C) on dune. The photos in Figure 2.2 are shown with an arrow. Coordinates in C) are UTM Zone 12N. Prairie dune data in B) are courtesy S. A. Wolfe.

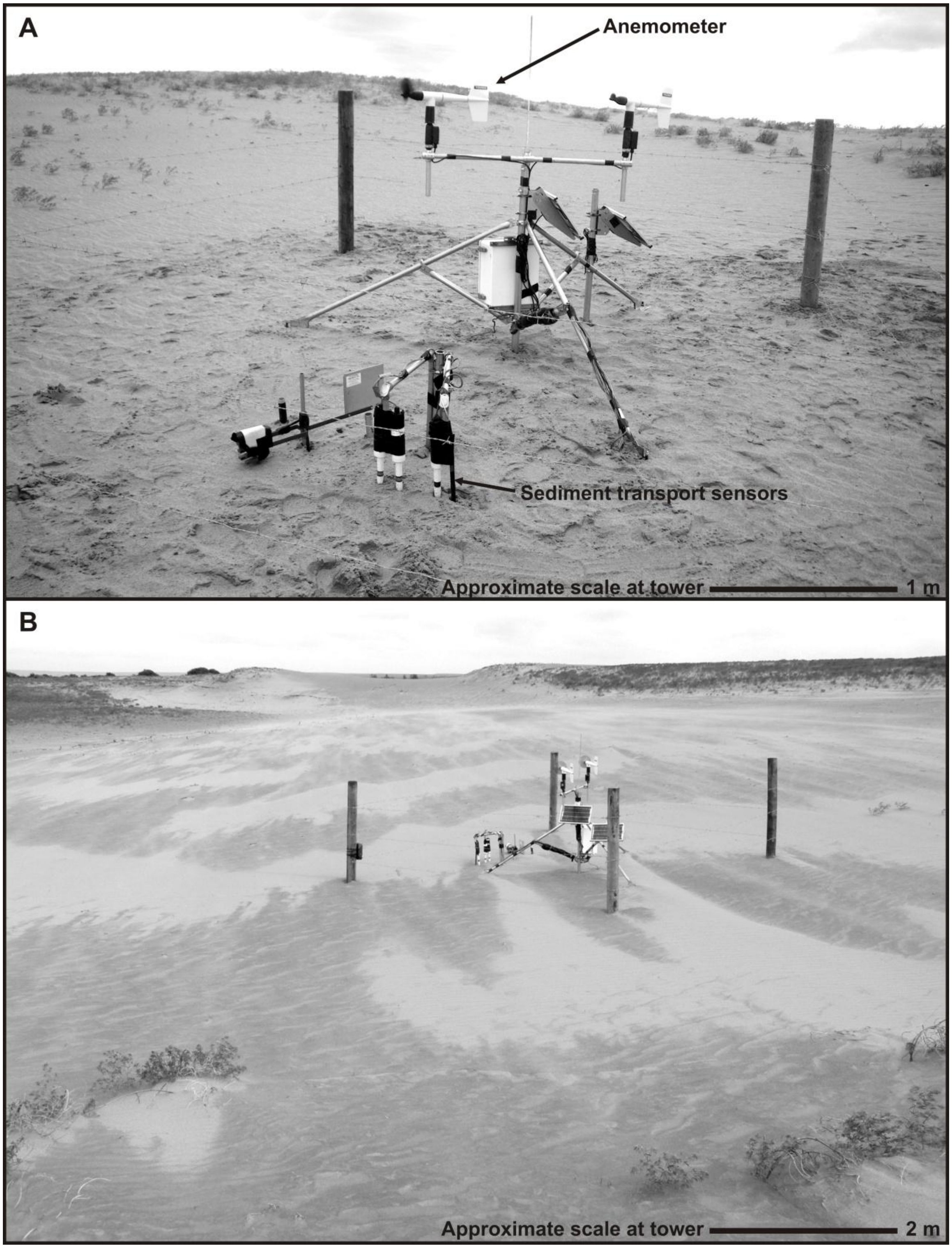

Figure 2.2. Photographs of study site. A) Instrument array at deployment. B) Instrument array looking upwind mid-deployment (photo courtesy C. H. Hugenholtz). Photo locations are marked on Figure 2.1.

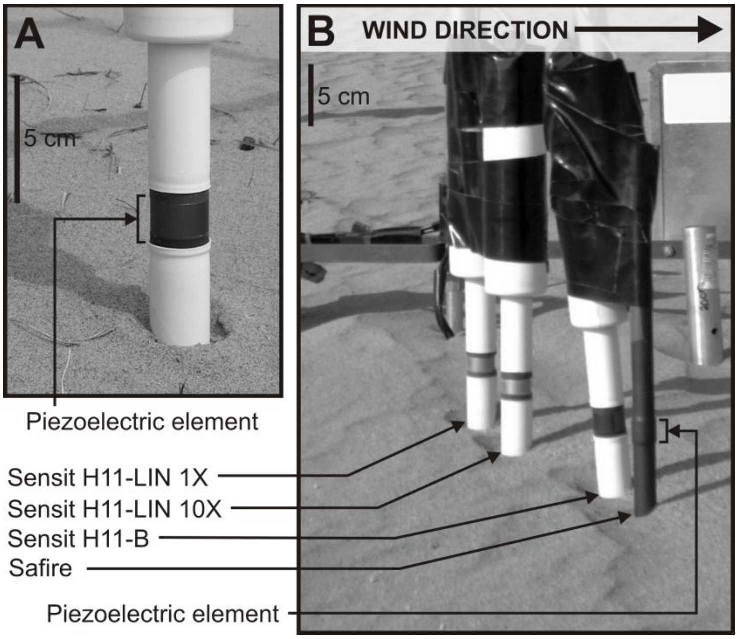

Figure 2.3. Piezoelectric sediment transport sensors deployed in field test. The piezoelectric element (where impacts are recorded) corresponds to the indicated band on each sensor located 0.05 m above the sand surface. Scales are approximate.

Following collection, data were removed when rain was present in images or recorded at a weather station located 2.65 km to the southeast. Due to the observed presence of streamers (Baas & Sherman, 2005) occurring along the sensor array, data among sensors were not compared on a per second basis. I assumed that over the full deployment approximately equivalent conditions of sediment transport were experienced by each sensor.

The time sediment transport was detected was calculated for each sensor at 1 Hz following a method modified from Stout and Zobeck (1996). The following conditional statements defined the duration of transport recorded for each data record:

$$\begin{array}{lllllllll} d_i & = & 1 & \mathit{if} & q_i > 0 & \mathit{and} & q_{i-1} > 0 & \mathit{and} & q_{i+1} > 0 \\ d_i & = & 0.5 & \mathit{if} & q_i > 0 & \mathit{and} & q_{i-1} = 0 & \mathit{and} & q_{i+1} > 0 \\ d_i & = & 0.5 & \mathit{if} & q_i > 0 & \mathit{and} & q_{i-1} > 0 & \mathit{and} & q_{i+1} = 0 \\ d_i & = & 0.5 & \mathit{if} & q_i > 0 & \mathit{and} & q_{i-1} = 0 & \mathit{and} & q_{i+1} = 0 \\ d_i & = & 0 & \multicolumn{6}{l}{\mathit{all\ other\ cases}} \end{array} \qquad (2.1)$$

where d_i is the duration of sediment transport recorded at time i (in seconds), q_i is sediment transport at time i, q_{i-1} is sediment transport at time $i-1$, and q_{i+1} is sediment transport at time $i+1$ (in seconds). The total duration of transport for the deployment was recorded as the sum of all d_i. This approach was adapted because it cannot be known precisely when transport begins or ends within a one-second interval; it is unlikely that a full second of sediment transport occurred in records when transport begins or ends. Thus, this method increases the accuracy of transport duration estimates. All analyses were programmed in R, version 2.10.1 (R Core Development Team, 2009).

Two surface samples were collected on 14 July 2009 and 21 July 2009 to determine sediment grainsize (0-3 cm depth, adjacent to sensor array). The purpose of the sediment samples was to ascertain if sediment at this site was anomalously fine or coarse. If the sediment was atypical, the results of the study could be less applicable. Samples were air dried and sieved. The graphic mean was 1.55 Φ, and graphic standard deviation was 1.31 Φ.

Ahlbrandt (1979) compiled grain size data for 191 dune samples worldwide and derived an average graphic mean of 1.83 Φ, and average graphic standard deviation of 0.73 Φ. The sand at this study site is slightly coarser and poorer sorted than typical dune sand, but is not anomalous for aeolian environments.

2.3.3 Sensors

Four types of sensors were tested (Fig. 1): (i) Sensit model H11-B (serial no. 653), (ii) Sensit model H11-LIN, 1X configuration (serial no. 817), (iii) Safire (unknown serial no., purchased 2005), (iv) Sensit model H11-LIN, 1X configuration (serial no. 815). The three Sensit type sensors were manufactured by Sensit Company in Portland, North Dakota, USA (http://www.sensit.com; accessed: 05 October 2010). The Sensit H11-LIN is the most recent model and is configurable to two sensitivity settings: '1X' (less sensitive) and '10X' (more sensitive). The Sensit H11-B model is an older model and is no longer available. The Safire was manufactured by Sabatech in Amsterdam, Netherlands (Baas, 2004).

All of the PSTSs in this study have a similar design. The piezoelectric element is mounted as a ring in a vertically positioned, plastic coated metal cylinder. The surface of the piezoelectric element is covered with metal for all Sensits, and plastic for the Safire. The cylindrical design allows the sensor to remain stationary with changing wind directions and does not require a wind vane to orient the sensor into the wind direction (shown in Fig. 2.3). Impacts from sand grains create an electrical pulse that is filtered by internal electronics into a digital pulse that is recorded by a separate datalogger (Stockton & Gillette, 1990; Baas, 2004). Dimensions of the sensing area (parallel to sediment transport direction) vary among sensors (listed in Table 2.1).

Published sensitivities are available for all sensors (listed in Table 2.1). Sensitivity is given as the minimum particle momentum required for the sensor to record a particle impact. Other investigators have noted variability in the sensitivity among different sensors, even with the same specifications. This may be related to characteristics of the piezoelectric crystal, which can be (anecdotally) difficult to reproduce in manufacturing (John Stout, personal communication: 08 July 2010).

Variability in the ability of sensors to record flux magnitude has been noted around the circumference of individual sensors (Baas, 2004). An approach used to minimize this error is adjusting the sensor manually so that only one side of the sensor records sediment transport; typically the most sensitive side (the “sweet spot” of Baas, 2004). This is possible for short experiments; however, in long unattended deployments with variable wind directions, impacts occur on all sides of the sensors. I did not attempt to pre-determine the most (or least) sensitive side of my sensors and mounted all sensors randomly. I believe this configuration is more representative of long-term field conditions where variations in the direction of transport negate any effects of preferential alignment.

2.4 Results

The sensors were deployed for: 278 hr., 18 min., 19 sec. Recorded wind speeds had a mean of 6.13 m s^{-1}, median of 5.97 m s^{-1} and maximum of 16.95 m s^{-1} (from 53 hr., 48 min., 25 sec. of recorded data; wind measured at 1.35 m elevation). The total time that transport was detected by each sensor is listed in Table 2.1. The differences in transport detection time were large; the relative difference between the most sensitive sensor (Sensit H11-B) and least sensitive sensor (Sensit H11-LIN 1X) was 81.03 times. It must be noted that the difference between the Sensit H11-LIN 1X and Sensit H11-LIN 10X is a published difference in minimum detectable momentum of approximately 10 times. Consequently, it is expected that the H11-LIN 1X detected less transport than the Sensit H11-LIN 10X.

Two observations support my assumption that sensors were subject to approximately equivalent sediment transport conditions over the full deployment. Camera images show that ripples moved past the sensor array in a straight and parallel manner during all daylight transport events. No cross-wind spatial differences in micro-topography were noted (e.g., deposition or erosion) that could be related to the magnitude of spatial differences in sediment transport duration seen in Table 2.1.

Table 2.1. **Sensor dimensions, specifications, and results**

Sensor	Reference (s)	Width (mm)	Height (mm)	Area (mm^2)	Published minimum momentum (N s)	Transport duration (hr)
Sensit H11-B	Stockton & Gillette, 1990; Stout & Zobeck, 1997	25.0	13.5	337.5	5.0×10^{-8}	20.07
Sensit H11-LIN 10X	Stockton, 2009	23.5	12.0	282.0	1.16×10^{-6} [a]	9.07
Safire	Baas, 2004	19.0	17.0	323.0	6.0×10^{-8} - 1.2×10^{-7}	5.10
Sensit H11-LIN 1X	Stockton, 2009	23.5	12.0	282.0	2.38×10^{-6} [a]	0.25

Footnote:

[a] minimum particle momentums were published in dyne-cm (a unit of energy) and required conversion to N s (momentum). The values were estimated by Stockton (2009) with a particle drop test. I derived the following calibration for conversion: $p = m(E * 10^{-7} / (0.5m))^{0.5}$ where p is momentum in N s, m is particle mass (estimated at 7.36×10^{-7} kg with a 0.001 m diameter glass sphere and a glass density of 2500 kg m^{-3}), E is potential energy in dyne-cm. Air resistance was assumed to be negligible.

2.5 Discussion

2.5.1 Sensor design limitations

There are difficulties with relating sensor specifications (listed in Table 2.1) to transport detection. Detection of sediment transport depends on at least one particle impacting the sensing element with sufficient momentum to surpass the momentum threshold. All else being equivalent, detection is primarily a function of the momentum threshold and cross-sectional area.

The published minimum detectable particle momentums differ (listed in Table 2.1). The Sensit H11-B has the lowest minimum particle momentum (most sensitive); this corresponds to the high detection observed. Likewise, the Sensit H11-LIN 1X is the least sensitive and recorded the least sediment transport. However, the Sensit H11-LIN 10X and Safire do not match this trend. Minimum detectable momentum is, alone, not a suitable determinate of detection capabilities in the field. Furthermore, there have been numerous generations of all sensors and (anecdotally) poor control of sensitivity (see Section 2.3.3). Overall, both the poor correspondence and limited confidence with published sensitivities confirm the importance of field testing.

The cross-sectional area of the piezoelectric element also differs among sensors (listed in Table 2.1). With a uniform particle concentration in the airstream, the probability of a particle impacting a given cross-sectional area is related to the size of the cross-sectional area. However, with a cylindrical sensor the cross-sectional area does not remain constant with particle momentum (also discussed by Baas, 2004). If the minimum recordable particle momentum is similar to that of the particles measured, particles with a low momentum that impact the sides of the sensor may not be recorded. Particles that impact the center of the cylinder are much more likely to be recorded because a more direct collision applies more force to the sensor. This effect has two implications: (i) the true cross-sectional area of a sensor is not equivalent to the measured cross-sectional area as listed in Table 2.1, and (ii) the cross-sectional area differs with particle momentum. This implies that the particle momentum modifies the probability that a given particle will be detected. Consequently, a reliable determination of the true cross-sectional area is not currently feasible without detailed knowledge of particle masses and velocities. Particle masses and velocities in natural sediment transport systems (with streamers as described by Baas & Sherman, 2005) have not been parameterized to a sufficient level of detail to enable derivation of transport response for a given sensor. Also, dominant particle momentum likely changes with ripple and streamer positioning. Hence, consistent and comparable detection is not possible without using sensors that have identical dimensions and momentum thresholds. These limitations are not as pronounced with flat plate or photo-electronic sensors.

I believe that the majority of the magnitude of sensor discrepancies observed can be attributed to cross-sectional area and momentum threshold effects; but I must caution that these effects may not be responsible for all of the inconsistency measured. First, as this investigation is field-based, I do not have precise control over all aspects of the study and there could be spatial differentiation in characteristic particle momentums. The magnitude of differences is large and the length of the deployment is relatively long; this suggests that these effects are less important. Second, issues such as temperature sensitivity (e.g., Heidenrich et al., 2002) and variability in response around the circumference of the element remain unexplored. However, regardless of the source of variability, inconsistency among sensors in detecting sediment transport presence and absence is a concern, particularly for threshold determination.

2.5.2 Implications of discrepancies in sensor detection for threshold measurement

One of the primary uses of measurements of the temporal patterns in transport presence/absence is for estimating sediment transport threshold (e.g., Stout & Zobeck, 1996, see Chap. 3). To illustrate how threshold estimates could vary if measured with different sensors, I present kernel density estimations of threshold wind speeds measured with each of the sensors in this study (Fig. 2.4). Estimates of threshold were approximated by extracting wind speeds measured during seconds when sediment transport is present (one or greater count s^{-1}), but absent the second prior and/or second following, according to the following conditional statements:

$$
\begin{aligned}
u_{t\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} > 0 \quad \text{and} \quad q_{i+1} = 0 \\
u_{t\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} = 0 \quad \text{and} \quad q_{i+1} > 0 \\
u_{t\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} = 0 \quad \text{and} \quad q_{i+1} = 0 \\
u_{t\,(i)} &= N/A \quad \text{all other cases}
\end{aligned}
\qquad (2.2)
$$

where $u_{t\,(i)}$ is the threshold wind speed at time i, u_i is the wind speed at time i, q_{i} is sediment transport at time i, q_{i+1} is the sediment transport at time $i+1$ (in seconds), and q_{i+1} is the sediment transport at time $i+1$ (in seconds). This method is described further in Chapter 3 as the instantaneous method.

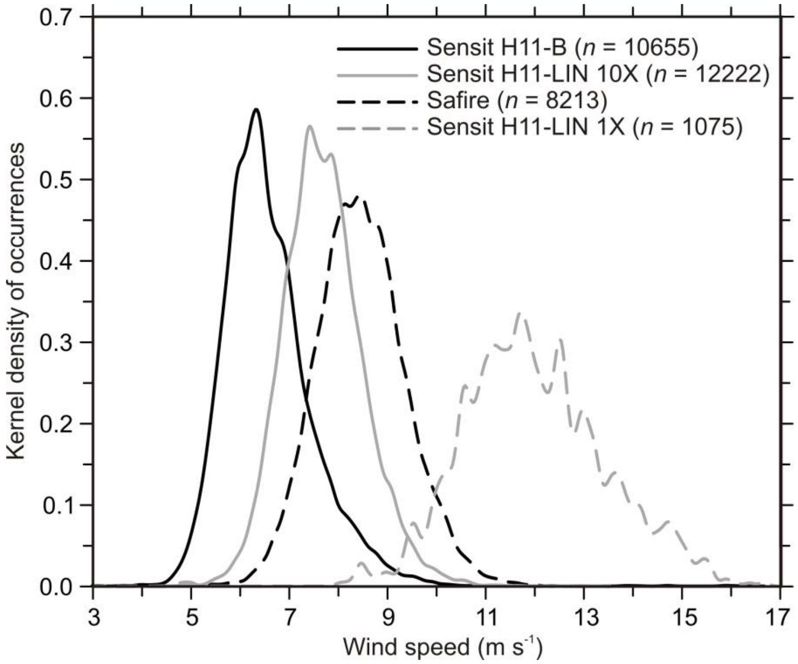

Figure 2.4. Kernel density estimates of thresholds by sensor. Results mirror the measured durations of transport, with the Sensit H11-B showing lowest thresholds and the Sensit H11-LIN 1X showing highest thresholds. These data suggest threshold values determined with one sensor are not comparable to threshold values determined with other sensors and highlight the importance of qualifying threshold results with sensor response. *n* = number of threshold measurements. Kernel: Gaussian, standard deviation: 0.1 m s^{-1}.

Variability in threshold was expected with changes in surface conditions (e.g., distributions were expected, rather than single points). The cause of threshold variability is unknown, but is likely related to changes in surface moisture (e.g., observe spatial differences in surface moisture in Fig. 2.2B). However, as illustrated in Figure 2.4, threshold estimates measured with different sensors are inconsistent. These data suggest field measured thresholds are susceptible to sensor detection capabilities.

Although inconsistency in threshold estimates could be construed as a "sensor problem", it hints at a larger issue underlying the present mode of threshold measurement: the definition of sediment transport remains poorly defined. As threshold is commonly defined as the minimum wind speed to begin sediment transport, the "presence of sediment transport" requires definition. Is "sediment transport" one grain, or multiple grains? Or the whole bed? This definition is not clear (Lyles & Krauss, 1971). Each of the sensors used in this test could be described as an individual definition of sediment transport. Presently, there is no unified or standard definition of transport within the context of threshold measurement (field or wind tunnel). Consequently, none of the sensors used in this test can be identified as more correct than any other.

Previous investigators have also varied in their individual definitions of sediment transport. For example, Nickling (1988) used an elaborate laser based detection system with lasers crossing numerous times millimeters above the bed in a wind tunnel. The sampling area of this system is large in spatial extent and cross-sectional area when compared to the sensors tested in this study. Consequently, Nickling (1988) has a different definition of sediment transport than the sensors used in this study, one with a much larger sampling area. One may expect Nickling (1988) to record thresholds at a lower wind speed than any of the sensors used here. This inconsistency in the definition of threshold constrains the applicability of threshold parameterizations as thresholds measured with different instruments are fundamentally incommensurate.

A viable solution to the issue of sediment transport definition is the development a standard instrument. A standard instrument would allow the collection of commensurate data, as all investigators would be using a consistent definition of the presence of sediment transport. However, at present, none of the sensors in this test are suitable as the piezoelectric elements are (anecdotally) difficult to reproduce with consistent sensitivity (John Stout, personal communication, 08 July 2010). However, there are new sensors being developed that could provide a more consistent definition of transport, such as the Wenglor YH03PCT08 (Hugenholtz & Barchyn, unpublished data). Also, discussion of a standard sensor would increase the importance of assessing sensor consistency, a sensor characteristic that has received little attention in the aeolian geomorphology literature.

2.6 Conclusions and recommendations

This chapter described a comparison of the detection capabilities of four piezoelectric sediment transport sensors in an 11-day field test. Data suggest that the sensor detection response was inconsistent. I explored if sensor detection capability could be predicted by sensor specifications; however, complications with the determination of the true cross-sectional area of the sensing element, variability in sensor sensitivities, and limited knowledge regarding field particle momentums preclude a straightforward derivation of transport detection from specifications alone. I also examined the implications of using different sensors to determine sediment transport threshold and found that threshold estimations differ substantially when measured with different sensors. These results call to question any attempt at comparing threshold values measured with different piezoelectric sensors and provide an example of inconsistency in the definition of sediment transport used for threshold measurement.

Several tentative recommendations could help with the issues raised in this chapter. With respect to sensor design, the cylindrical element of PSTSs poses great problems for determining the true cross-sectional area that can record impacts. This issue could be avoided if future sensors were not cylindrical. Aeolian sediment transport investigators should consider the use of photo-electronic sensors such as the SPC laser sensor (Mikami et al., 2005) or Wenglor YH03PCT08 (Hugenholtz & Barchyn, unpublished data). Photo-electronic sensors have no minimum impact momentum, consistent cross-sectional area, and the presence of sediment transport can be more reliably and statistically related to the density of particles in the airstream. However, further testing is required with such sensors prior to widespread adoption.

If a standard sensor and measurement protocol were chosen, I believe none of the sensors tested in this study should be candidates. The issues with momentum dependent cross-sectional areas and potential inconsistencies with response around the circumference of the piezoelectric element are concerning (Baas, 2004). A sensor chosen as a standard would need to have consistent and reproducible response.

In conclusion, these results highlight the relative nature of many aeolian process studies. In effect, although measurements are made, the numbers are only applicable qualitatively. More on the issue of inter-study comparison of measurements can be found in Chapter 4. In the next chapter, I examine the common methods of using measurements of sediment transport presence and absence (such as those from this study) in conjunction with wind speed to calculate estimates of threshold.

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CHAPTER 3: COMPARISON OF FOUR METHODS TO CALCULATE AEOLIAN SEDIMENT TRANSPORT THRESHOLD FROM FIELD DATA AND IMPLICATIONS FOR MASS TRANSPORT PREDICTION

3.1 Chapter abstract

Aeolian sediment transport threshold defines the minimum wind speed (or shear stress) required for wind-driven sediment transport. Because threshold is an input variable in models used to predict wind erosion, dune activity, and dust emissions, accurate and consistent quantification is essential. Although several methods of calculating threshold from field data have been developed, their comparability is unknown. To address this issue I collected high resolution sediment transport and wind measurements (1 Hz) on an active sand dune for 11 days and compared four different methods of deriving threshold: (i) time fraction equivalence method (TFEM); (ii) Gaussian time fraction equivalence method (GTFEM); (iii) instantaneous method; and (iv) regression method. The two most widely used methods (TFEM and GTFEM) were similar in distribution and strongly correlated (r = 0.977); however, values and correlations among other methods varied (from r = 0.861 to r = 0.261). To demonstrate the implications of using different threshold calculation methods, I predicted mass transport, which ranged from 63.6 (instantaneous method) to 126.6 kg per span-wise meter (regression method). This inconsistency is concerning because it suggests that the method used to calculate threshold can have an appreciable impact on transport predictions. Each method represents a generalization of the relation between wind speed and sediment transport. Due to complexities in natural sediment transport, it is unlikely that reliable calibrations can be developed. To enable progress in practical applications of

threshold measurement, a viable solution for investigators to consider is the development of a technical standard.

3.2 Introduction

Aeolian sediment transport threshold is commonly defined as the minimum wind speed (or shear stress) required for wind-driven sediment transport. A variety of surface controls modify threshold such as moisture (e.g., Ravi & D'Odorico, 2005), vegetation (e.g., Raupach, Gillette, & Leys, 1993), biogenic crusts (e.g., Argaman, Singer, & Tsoar, 2006), slope (Howard, 1977), and pore ice (e.g., McKenna Neuman, 1990).

Threshold measurements have several important applications. Threshold is a central parameter in models predicting sediment transport (e.g., Lettau & Lettau, 1978), wind erosion (e.g., Fryrear et al., 2000), dune activity (e.g., Lancaster & Helm, 2000), and dust emissions (e.g., Marticorena & Bergametti, 1995). When wind speed varies near threshold, model predictions are highly sensitive to the value(s) used. Threshold also has practical applications as a standalone parameter. For example, Stout and Arimoto (2010) used threshold to track the temporal patterns in aeolian transport of radionuclide contaminated soil. De Oro and Buschiazzo (2008) used threshold to track seasonal changes in the susceptibility of an agricultural field to wind erosion. In areas where the surface is managed to minimize occurrences of wind erosion, threshold measurement provides a practical and useful assessment of these management strategies.

Threshold has been measured in wind tunnels (e.g., Marticorena, Bergametti, Gillette, & Belnap, 1997), air gun disturbance experiments (e.g., Li et al., 2010), and modeled through mathematical derivation of forces acting on sediment grains (e.g., Bagnold, 1941).

Although these parameterizations are invaluable from experimental and theoretical standpoints, threshold is rarely static in space and time (e.g., Davidson-Arnott, MacQuarrie, & Aagaard, 2005; Davidson-Arnott & Bauer, 2009). Furthermore, conditions of sediment transport in synthetic environments (e.g., wind tunnels) are not fully representative of the rapid and chaotic shifts in wind speed that occur in the field (Farrell & Sherman, 2006; Sherman & Farrell, 2008). Consequently, a need exists for field measurement of threshold in conditions of natural wind and sediment transport.

To address this need, several methods have been developed recently to measure threshold in field deployments (e.g., Stout & Zobeck, 1996; Stout, 2004; Schönfeldt, 2004). All are based on high resolution (~1 Hz) time series of wind speed and sediment transport. These data are collected with computerized data logging systems, fast responding anemometers, and electronic sediment transport sensors (e.g., Stockton & Gillette, 1990; Spaan & van den Abeele, 1991; Baas, 2004). From these high resolution records of transport, threshold can be estimated in discrete temporal intervals. To clarify semantics in threshold measurement, there are two time intervals that require specification: (i) sampling interval: the rate that raw data are collected (typically one second or less); and (ii) measurement interval: the rate that generalized threshold measurements are calculated (typically minutes).

Despite recent progress and the growing adoption of field measurement, there has been little scrutiny of the protocols used. Table 3.1 summarizes the methods, sensors and protocols used in recent field campaigns. These investigations all produce values denoted as "threshold", even though the methods and sensors vary. Recently, important issues surrounding sensor performance and temporal intervals have been revealed (Stout, 1998; Baas, 2004; Wiggs, Atherton, & Baird, 2004; Van Pelt, Peters, & Visser, 2009; see Chap. 2);

however, there is a growing gap in the literature concerning the performance and comparability of different methods. In particular, it is not known whether different methods produce similar threshold values with the same input data. The possibility of inconsistencies amongst threshold calculation methods poses a major challenge for reliable parameterization, synthesis, and integration of threshold results from field-based methods.

To address this issue I collected high resolution wind and sediment transport data (1 Hz) on an active sand dune for 11 days. These field data were used as input in four different threshold calculation methods: (i) time fraction equivalence method (TFEM; Stout & Zobeck, 1996, 1997), (ii) Gaussian time fraction equivalence method (GTFEM; Stout, 2004), (iii) instantaneous threshold (used in Chap. 2; also discussed by Schönfeldt, 2004), and (iv) regression threshold (Gillette, Hardebeck, & Parker, 1997b; Schönfeldt, 2004). I also investigated how the use of different threshold calculation methods can affect prediction of mass flux. Overall, results reveal inconsistency among the four methods. As all methods are based on different generalizations of the relation between wind and sediment transport, it is difficult to ascertain the "correct" threshold estimate. However, the assumptions underlying methods can be discussed in terms of reliability. To enable inter-study comparison and integration, investigators may wish to develop a standard threshold measurement protocol. I discuss the advantages and disadvantages of all methods, and recommend the use of the TFEM.

Table 3.1 **Summary of methods used in recent field studies of threshold**

Study	Calculation method	Sampling interval	Measurement interval	Sediment transport sensor			Anemometer	
				Type [a]	Height (mm)	Area (mm^2)	Type (distance constant)	Ht. (m)
This study	various	1 Hz	5 min.	Sensit H11-B	50	337.5	RM Young 5103 (2.7 m)	1.35
Arens, 1996	regression	0.2 Hz	1-42 hr.	Saltiphone	100	201.0 [b]	N/A	5.0
Davidson-Arnott et al., 2005	TFEM, u_{tmin}, u_{tmax} [c]	1 Hz (0.2 Hz) [d]	18-25 min.	Balance trap	0-500	5000	RM Young cup, DC (2.3 m)	0.3
Davidson-Arnott et al., 2008	TFEM, u_{tmin}, u_{tmax} [c]	1 Hz	10 min.	Safire	20	323.0 [e]	RM Young cup, DC (2.3 m)	0.3
Davidson-Arnott & Bauer, 2009	TFEM, u_{tmin}, u_{tmax} [c]	1 Hz	10 min.	Safire	20	323.0 [e]	RM Young cup, DC (N/A)	0.6
De Oro & Buschiazzo, 2009	GTFEM	1 Hz (sed); 1 min. (wind)	5 min.	Sensit	20	337.5 [e]	N/A	2.0
Gillete et al., 1997	regression	20 min.	N/A	Sensit	100	337.5 [e]	MetOne 014	2.0
Larney et al., 1995	u_{tmin} [c]	2 min.	2 min.	Sensit	50	337.5 [e]	N/A	2.0
McKenna Neuman et al., 2000	TFEM	10 sec.	16-120 min.	Balance trap	N/A	N/A	RM Young cup (2.8 m)	0.3
Ravi & D'Odorico, 2005	N/A	1 Hz [e]	5 min. [f]	Sensit H7	N/A	337.5 [e]	RM Young 5103 [f] (2.7 m)[g]	3.0
Sankey et al., 2009a, 2009b	GTFEM	1 Hz	5 min.	Sensit	50	337.5 [e]	MetOne 014A (4.5 m)[h]	2.0

Table 3.1 (continued)

				Sediment transport sensor			**Anemometer**	
Study	**Calculation method**	**Sampling interval**	**Measurement interval**	**Type** [a]	**Height (mm)**	**Area (mm^2)**	**Type (distance constant)**	**Ht. (m)**
Schönfeldt, 2004	TFEM, regression	1 Hz	5 min.	Saltiphone	35	201.0 [b]	Gill cup (N/A)	0.35
Speirs et al., 2008	GTFEM	8 Hz	1 min.	Sensit	N/A	337.5 [e]	Cup (N/A)	2.1
Stout, 2004	GTFEM	1 Hz	5 min.	Sensit	50	337.5 [e]	RM Young 5103 [i] (2.7 m)[g]	2.0
Stout, 2007	GTFEM	1 Hz	5 min.	Sensit	50	337.5 [e]	RM Young 5103 [j] (2.7 m)[g]	2.0
Stout & Arimoto, 2010	GTFEM	1 Hz	5 min.	Sensit	N/A	337.5 [e]	N/A	2.0
Stout & Zobeck, 1997	TFEM	1 Hz	5 min.	Sensit	0	337.5 [e]	cup (2.3m)	2.0
Stout & Zobeck, 1998	TFEM	1 Hz	5 min.	Sensit	0	337.5 [e]	cup (N/A)	2.0
Udo, 2008	TFEM	1 Hz	5 min.	UD-101; Sensit	40	113 (UD-101)	Delta Ohm HD2003 (sonic) (0)[k]	0.9
Wiggs et al., 2004	TFEM	1-60 sec.	20 min.	Sensit H7	0	337.5 [e]	Flow master (thermal) (0)[k]	0.25, 0.1
Zobeck & Van Pelt, 2006	GTFEM	1 Hz	1 min.	Sensit	0	337.5 [e]	cup (N/A)	2.0

Table 3.1 (continued)

Footnotes:

[a] References for further information on each sediment transport sensor are as follows: Sensit (Stockton & Gillette, 1990; Stout & Zobeck, 1997; Van Pelt et al., 2009); Safire (Baas, 2004; Van Pelt et al., 2009); Balance trap (Davidson-Arnott et al., 2005; Nickling & McKenna Neuman, 1997); UD-101 (Udo, 2009); Saltiphone (Spaan & Van den Abeele, 1991; Van Pelt et al., 2009).

[b] I assume that the Saltiphone used is identical dimensions to that of the sensor described in Spaan and Van den Abeele (1991).

[c] u_{tmin} is a threshold measurement method that extracts the minimum wind speed with saltation (approximating the impact threshold); u_{tmax} is a threshold measurement method that extracts the maximum wind speed without saltation (approximating the fluid threshold); both methods are described by Davidson-Arnott et al. (2005).

[d] Sediment transport and wind speed data were smoothed with a 5 second mean filter.

[e] Sediment transport sensor dimensions are assumed to be identical to those measured in Chapter 2 (Table 2.1)

[f] I assumed these data are from United States Geological Survey CLIM-MET internet site; instrument parameters are described here: http://esp.cr.usgs.gov/info/sw/clim-met/anatomy/index.html (accessed: 03 October 2010).

[g] RM Young 5103 anemometer distance constants are assumed to be identical to current specifications as published at: http://www.campbellsci.com/documents/manuals/05103.pdf (accessed: 03 October 2010).

[h] MetOne 014A anemometer distance constant is assumed to be identical to current specifications as published at: http://www.campbellsci.com/documents/manuals/014a.pdf (accessed: 03 October 2010).

[i] Anemometer model was determined from a photo (Fig. 5) in Stout (2004).

[j] Anemometer model was determined from a photo (Fig. 3) in Stout (2007).

[k] Sonic and thermal anemometers are assumed to have negligible inertia, and consequently have been assigned a distance constant of zero.

3.3 Field study and data collection methods

The purpose of the field study was to collect raw data, from which the four different methods of calculating threshold could be compared. This contrasts with typical threshold monitoring campaigns where the chosen method is predetermined and programmed into the data logging system. The instrument array was designed to mimic instrument arrays used by other investigators (see Table 3.1), thus providing a more realistic assessment of the impact of modifying threshold calculation method.

3.3.1 Data collection methods

The instrument array was deployed from 09 July 2009 to 21 July 2009 on an active sand dune in the Bigstick Sand Hills of Saskatchewan, Canada (50° 12' 31.55" N, 109° 12' 23.85" W). This deployment is identical to that used in Chapter 2; more detail on the study area and sediment at this site can be found in Chapter 2, Section 2.3. Data were measured at 1 Hz continuously. The lengthy 11-day deployment ensured a variety of conditions were encountered. Instruments included a datalogger (Campbell Scientific CR1000), propeller anemometer and wind direction sensor (RM Young 5103, 2.7 m distance constant, mounted at 1.35 m height), and a piezoelectric impact sensor (Sensit H11-B, mounted with the center of the piezoelectric element at 50 mm height and adjusted mid-deployment on 14 July 2009). Details on the performance of the Sensit H11-B in this specific deployment are available in Chapter 2. A time-lapse camera, co-located with the sensors, acquired images of the array every 0.5 hours from 0600 to 2100h daily. The images were used to ensure the sensor was situated within 40 - 60 mm of the bed and to discern occurrences of rain-splashed sediment from wind-blown sediment. The datalogger was programmed to record data when a minimum of one count was recorded by the sensor in the previous 300 seconds, and when wind was blowing from 225 – 330 degrees during the past 300 seconds. This conserved datalogger memory and ensured recorded sediment transport was not influenced by adjacent sensors. To avoid calculating threshold with erroneous data from rain drop impacts, data were removed when rain was present in images and/or recorded at a weather station located 2.65 km to the southeast.

The raw 1 Hz data were used to calculate threshold at 5 min intervals from an origin of 17:15:00 on 09 July 2009. A measurement interval of 5 minutes was chosen as it is the most common interval used in other investigations (Table 3.1). Threshold was only calculated for measurement intervals with a complete record (300 sec.) of data. Comparisons were only performed for records when threshold could be calculated with all methods. All analyses were programmed in R, version 2.10.1 (R Core Development Team, 2009).

3.4 Threshold calculation methods

From a review of the literature four different methods of calculating aeolian sediment transport threshold were selected for comparison. Figure 3.1 and 3.2 illustrate the principles behind each of the methods.

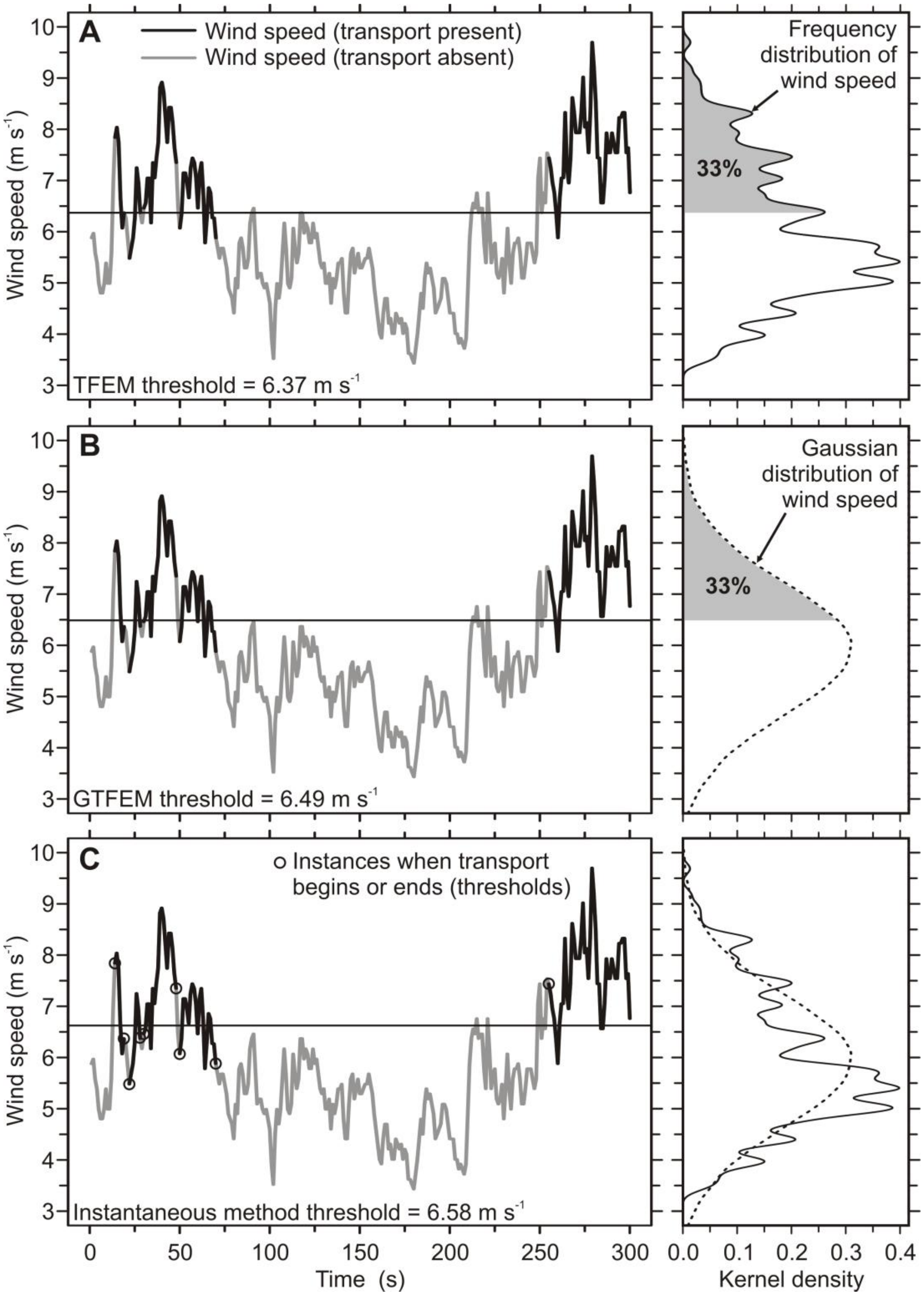

Figure 3.1. Illustration of principles behind threshold calculation methods for a sample measurement interval (wind speed mean = 5.92 m s^{-1}, standard deviation = 1.28 m s^{-1}, transport duration = 99 s. or 33 % of 300 s.). Horizontal lines represent threshold values for each method. A) Time fraction equivalence method (frequency distribution of wind speeds represented by kernel density estimate, Kernel: Gaussian with standard deviation 0.1 m s^{-1}). The time fraction of highest wind speeds is set to be equivalent to the time fraction of sediment transport. B) Gaussian time fraction equivalence method. The time fraction of highest wind speeds in a Gaussian distribution is set to be equivalent to the time fraction of

sediment transport. C) Instantaneous method: instances of transport beginning or ending are extracted (denoted by circles). The mean of instantaneous thresholds for the measurement interval is reported. Wind speeds measured at 1.35 m height.

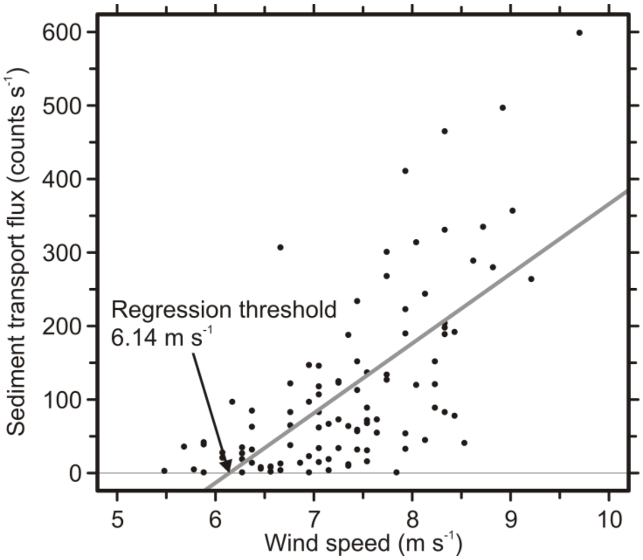

Figure 3.2. Regression method for calculating threshold. A linear regression of non-zero measurements of sediment transport is performed, the intercept where sediment transport equals zero is the regression threshold. Wind speeds measured at 1.35 m height.

3.4.1 Time fraction equivalence method

The time fraction equivalence method (TFEM, $u_{t\,TFEM}$) was introduced by Stout and Zobeck (1996, 1997) and subsequently reviewed by Wiggs et al. (2004). The TFEM assumes that threshold can be represented by one wind speed (within a measurement interval), where sediment transport *only* occurs when wind is above threshold. Within the measurement interval, the time fraction of wind speeds above threshold is set to be equivalent to the time fraction of sediment transport (see Fig. 3.1A).

I calculated TFEM threshold with the following procedure. First, the total number of seconds of sediment transport was tabulated for each measurement interval. One second of sediment transport was recorded for each second when counts were not equal to zero, up to a maximum of 300. Next, wind speed measurements within the measurement interval were re-organized in descending order. The number of wind speed measurements above threshold was determined by the number of seconds of sediment transport. Likewise, the number of wind speed measurements below threshold was determined by the number of seconds with no sediment transport. Threshold was calculated to be between the lowest wind speed measurement above threshold and the highest wind speed measurement below threshold. These two measurements were averaged. For measurement intervals when sediment transport occurred for more than 1 sec. and less than 300 sec. $u_{t\ TFEM}$ was defined as:

$$u_{t\ TFEM} = (u_j + u_{j+1}) / 2 \qquad (3.1)$$

where $u_{t\ TFEM}$ is the TFEM threshold, j is the number of seconds sediment transport occurred, u_j is the j^{th} wind speed measurement (ordered descending), likewise, u_{j+1} is the $(j + 1)^{th}$ wind speed measurement (ordered descending) (Stout & Zobeck, 1996; 1997; Wiggs et al., 2004).

3.4.2 Gaussian time fraction equivalence method

The Gaussian time fraction equivalence method (GTFEM; $u_{t\ GTFEM}$) was developed by Stout (2004). The GTFEM method is similar to the TFEM method with an important modification. Instead of using measured wind speed values directly, the mean and standard deviation of wind speeds are calculated to synthetically reproduce the wind speed distribution as Gaussian (found to be the best synthetic distribution by Stout & Zobeck, 1997). Consequently, this method relies upon the assumption that wind speeds in the measurement interval closely follow a Gaussian distribution. The calculation of threshold remains similar; the fraction of time that sediment transport occurred is used to determine the fraction of wind speeds above threshold (see Fig. 3.1B). The GTFEM threshold is calculated as:

$$u_{t\ GTFEM} = \bar{u} - \sigma\, \Phi^{-1}\, (j / 300) \tag{3.2}$$

where $u_{t\ GTFEM}$ is the GTFEM threshold, $\bar{u}$ is the mean wind speed in the measurement interval, σ is the standard deviation of wind speed, $\Phi^{-1}\ (j\ /\ 300)$ is the inverse normal distribution function of j (number of seconds sediment transport occurred) divided by 300 (the total number of seconds in the 5 min. measurement interval). As in Stout (2004), I removed measurements where $j\ /\ 300$ was less than 0.02 or higher than 0.98 because these calculations lie in the tails of the Gaussian distribution and are systematically unreliable. The advantage of this method is simple programming and efficient usage of datalogger memory; only the wind speed mean, standard deviation, and the number of seconds sediment transport occurred are required to be recorded for each measurement interval. The GTFEM threshold can be calculated easily post-deployment in a spreadsheet with a series of data manipulations.

3.4.3 Instantaneous method

The instantaneous method is a field interpretation of the traditional definition of threshold proposed by Bagnold (1941) (the minimum wind speed to initiate transport). I used this method in Chapter 2. The method identifies the wind speed when sediment transport begins or ends; these wind speeds correspond to the instances that threshold is passed (see Fig. 3.1C). I used the following rules to define wind speeds extracted as threshold measurements for each second in the timeseries:

$$\begin{aligned}
u_{t\,inst\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} > 0 \quad \text{and} \quad q_{i+1} = 0 \\
u_{t\,inst\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} = 0 \quad \text{and} \quad q_{i+1} > 0 \\
u_{t\,inst\,(i)} &= u_i \quad \text{if} \quad q_i > 0 \quad \text{and} \quad q_{i-1} = 0 \quad \text{and} \quad q_{i+1} = 0 \\
u_{t\,inst\,(i)} &= N/A \quad \text{all other cases}
\end{aligned} \tag{3.3}$$

where $u_{t\,inst\,(i)}$ is the instantaneous threshold at time i, u_i is the wind speed at time i, q_i is the sediment transport at time i, q_{i+1} is the sediment transport at time $i+1$ (in seconds), and q_{i-1} is the sediment transport at time $i-1$ (in seconds). For each 5 min. measurement interval, a variety of metrics can be reported to describe the distribution of $u_{t\,inst.}$ values. Row 1 in Eqn. 3.3 approximates the impact threshold and Row 2 in Eqn. 3.3 approximates the fluid threshold as traditionally defined by Bagnold (1941); these measurements could be extracted separately and examined in further detail. However, to simplify threshold determination in this study, I only report the mean of all $u_{t\,inst.}$ values for each measurement interval.

3.4.4 Regression method

Many investigators have used different regression equations to develop an estimate of threshold. A model is fitted to wind speed and sediment flux data and the intercept where sediment flux equals zero is defined as threshold. A variety of models have been used, for example Arens (1996) and Clifton, Ruedi, & Lehning (2006, snowdrift study) used a cubic regression; Gillette et al. (1997b) used an empirical equation, and Schönfeldt (2004) used a variant of a linear model.

With these data higher order exponents were investigated (cubic, square); however, higher order exponents systematically produced thresholds that were unreasonable (e.g., negative, less than 3 m s^{-1}). Consequently, I have used linear models throughout.

The regression threshold method ($u_{t\ regression}$) requires an assumption that sediment transport flux varies linearly with increasing wind speed. I performed a linear regression of sediment transport flux and wind speed for each 5 min. interval. Threshold is taken as the predicted value where sediment transport equals zero (see Fig. 3.2). I used counts s^{-1} from the piezoelectric sensor as a measure of sediment transport flux and assume linear proportionality between flux and count rate (found to be a reasonable assumption for similar sensors by Baas, 2004 and Gillette et al., 1997a; however, see discussion of sensor response in Chap. 2, Section 2.5.1). The dependability of linear regression thresholds relies on the validity of these assumptions. Both count rate and wind speed were treated as continuous measurements in the regression

$$q = a\ (u - u_{t\ regression}) \tag{3.4}$$

where q is non-zero sediment transport flux, a is a regression coefficient, u is wind speed, and $u_{t\,regression}$ is the regression threshold, determined as a coefficient in the regression.

3.5 Mass transport predictions

I calculated predicted mass transport to explore the potential implications of using different threshold calculation methods. Mass flux estimates were performed for every 5 minute measurement interval and totaled to calculate a prediction of total mass transport. As the purpose of these estimates is simply comparative, I follow common protocols for predicting mass flux. I do not know how these estimates compare to true mass flux; the focus of this study was strictly on comparing the implications of modifying threshold calculation method.

Mass flux was predicted with the Lettau and Lettau (1978) equation. A version of this equation is used in the widely acknowledged "Fryberger method" (Fryberger, 1979). Any similar equation would produce similar results. For all records where wind speed (u) exceeded threshold wind speed (u_t) with

$$q = C\sqrt{\frac{d}{D}}\frac{\rho_a}{g}(u_* - u_{*_t})u_*^2 \tag{3.5}$$

where q is mass flux in kg s^{-1} per crosswind meter, C is a constant (4.2; from Sherman, Jackson, Namikas, & Wang, 1996), d is the mean grainsize of the study site (≈ 0.34 mm), D is a reference grainsize (0.25 mm), ρ_a is the air density (1.22 kg m^{-3}), g is the acceleration of gravity (9.81 m s^{-2}), u_* and u_{*t} are the surface friction velocity and threshold friction velocity, which can be determined by re-arranging the "Law of the Wall" to

$$u_* = \frac{\kappa u_z}{\ln\left(\frac{z}{z_0}\right)} \tag{3.6}$$

where κ is von Karman's constant (0.41), u_z is the wind speed at elevation z (1.35 m), and z_0 is the aerodynamic roughness length, which assumed to be 1/30th of the mean grainsize, calculated as 1.13 x 10^{-5} m (see for example Sherman et al., 1996). The total transport prediction (Q) was calculated with

$$Q = \sum (300q) \tag{3.7}$$

where q is the mass flux prediction for each 5 min. (300 sec.) measurement interval. Calculations were repeated for thresholds measured with each method.

3.6 Results

During the 278.31 hour deployment, measured sediment transport occurred 20.07 hours under a variety of surface conditions and wind speeds. With a measurement interval of 5 min., threshold estimates were possible with all methods in 468 records. Within these 468 records mean wind speed varied from 3.82 m s^{-1} to 10.15 m s^{-1}, with a mean of 6.38 m s^{-1}.

Measured threshold values varied throughout the deployment (Fig. 3.3). The focus of this study is a comparison of methods to calculate threshold, so the precise causes of threshold variability are not clear and remain unexplored.

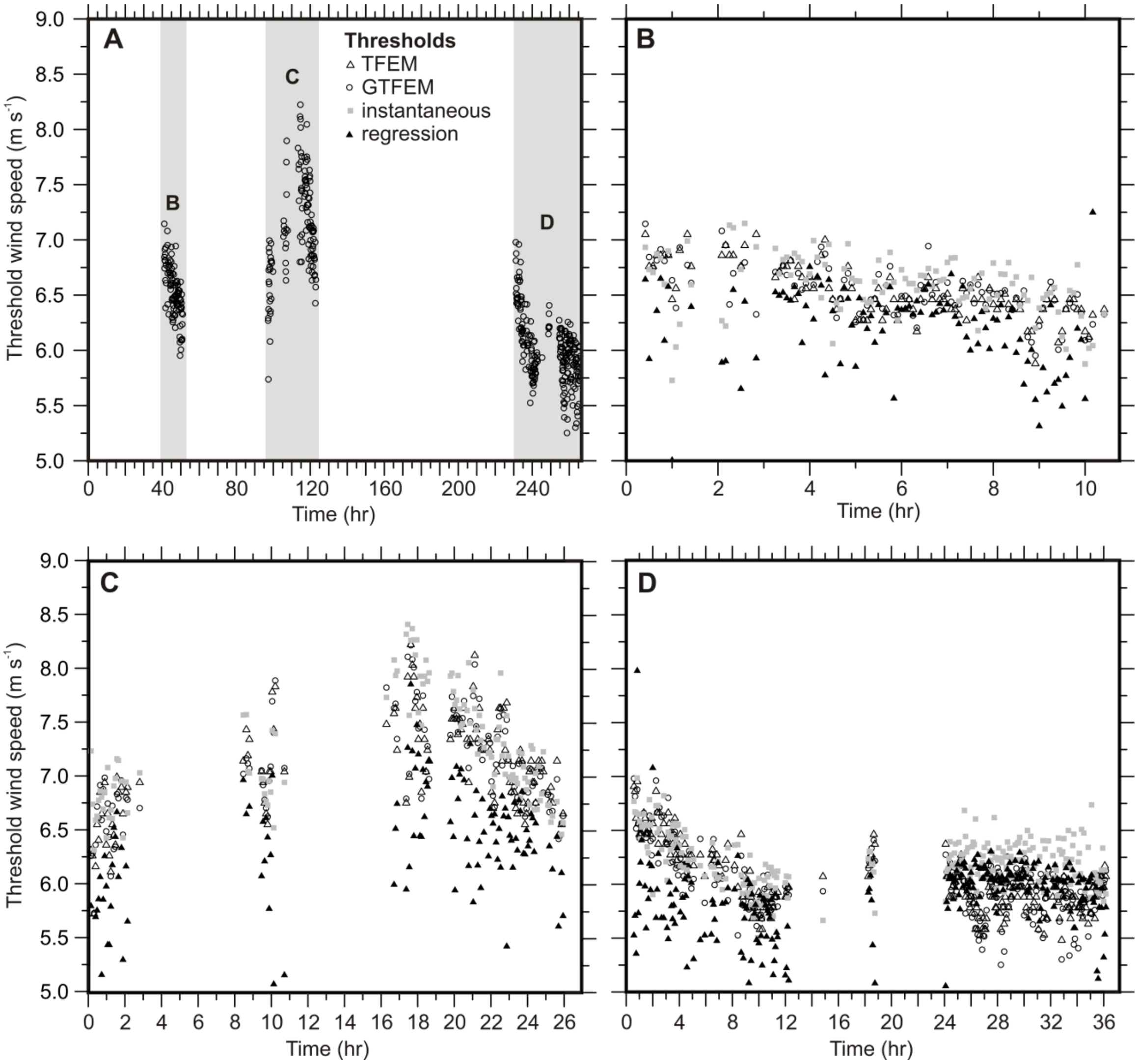

Figure 3.3. Threshold wind speeds throughout the deployment. GTFEM threshold is shown for the full deployment (A). Most threshold estimates occurred in one of three distinct time periods. Each time period is shown in more temporal detail in B, C, and D. Threshold wind speed is measured at 1.35 m height.

In general, large scale variability (5 hr. scale) in threshold is consistently measured by all threshold methods; however, high frequency variability (5 min.) in threshold differs among methods (Fig. 3.3). Kernel density estimates of all threshold estimates for the full deployment are shown in Figure 3.4.

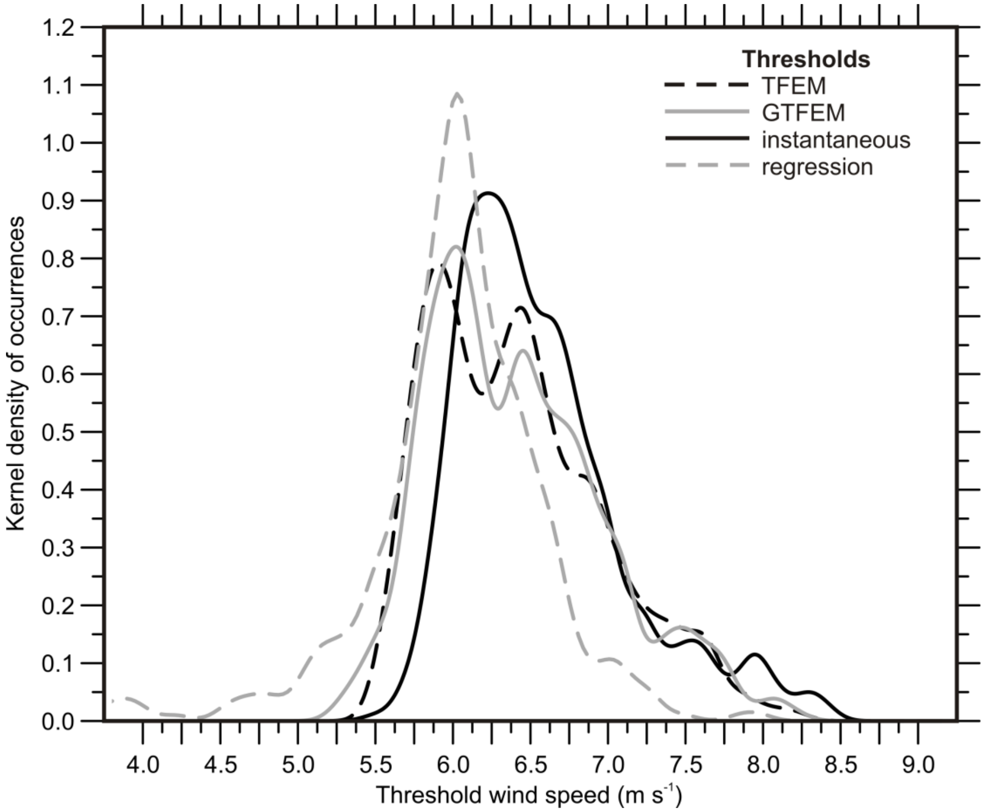

Figure 3.4. Kernel density estimates of all thresholds for the full deployment (between 4 and 9 m s^{-1}). There are systematic differences in the magnitude of threshold estimates. Regression thresholds were rarely measured above 6.5 m s^{-1}, where other methods have significant quantities of measurements above 6.5 m s^{-1}. Overall, it is not clear why the methods differ. Kernel density estimates were performed with Gaussian kernel, standard deviation = 0.09 m s^{-1}, $n = 468$.

To investigate if threshold measurements co-varied, I plotted scatterplots of all combinations of threshold measurements (Fig. 3.5). As the GTFEM and TFEM are very similar methods, the correlation was strong ($r = 0.977$). The instantaneous method correlated well with the TFEM and GTFEM thresholds; however, the regression method did not correlate well with any of the other methods throughout the range of threshold measurement.

3.6.1 Mass transport predictions

Mass transport predictions are shown in Table 3.2. Large differences in predicted transport occurred. The differences match systematic trends in threshold. The largest transport predictions occurred with the lowest thresholds (regression method), and the smallest transport predictions occurred with the highest threshold measurements (instantaneous method). Estimates from the TFEM and GTFEM are similar, but not identical.

Table 3.2. Predicted mass transport with different threshold methods

Threshold calculation method	Predicted mass transport (kg per crosswind meter)
TFEM	95.92
GTFEM	93.60
Instantaneous	63.57
Regression	126.62

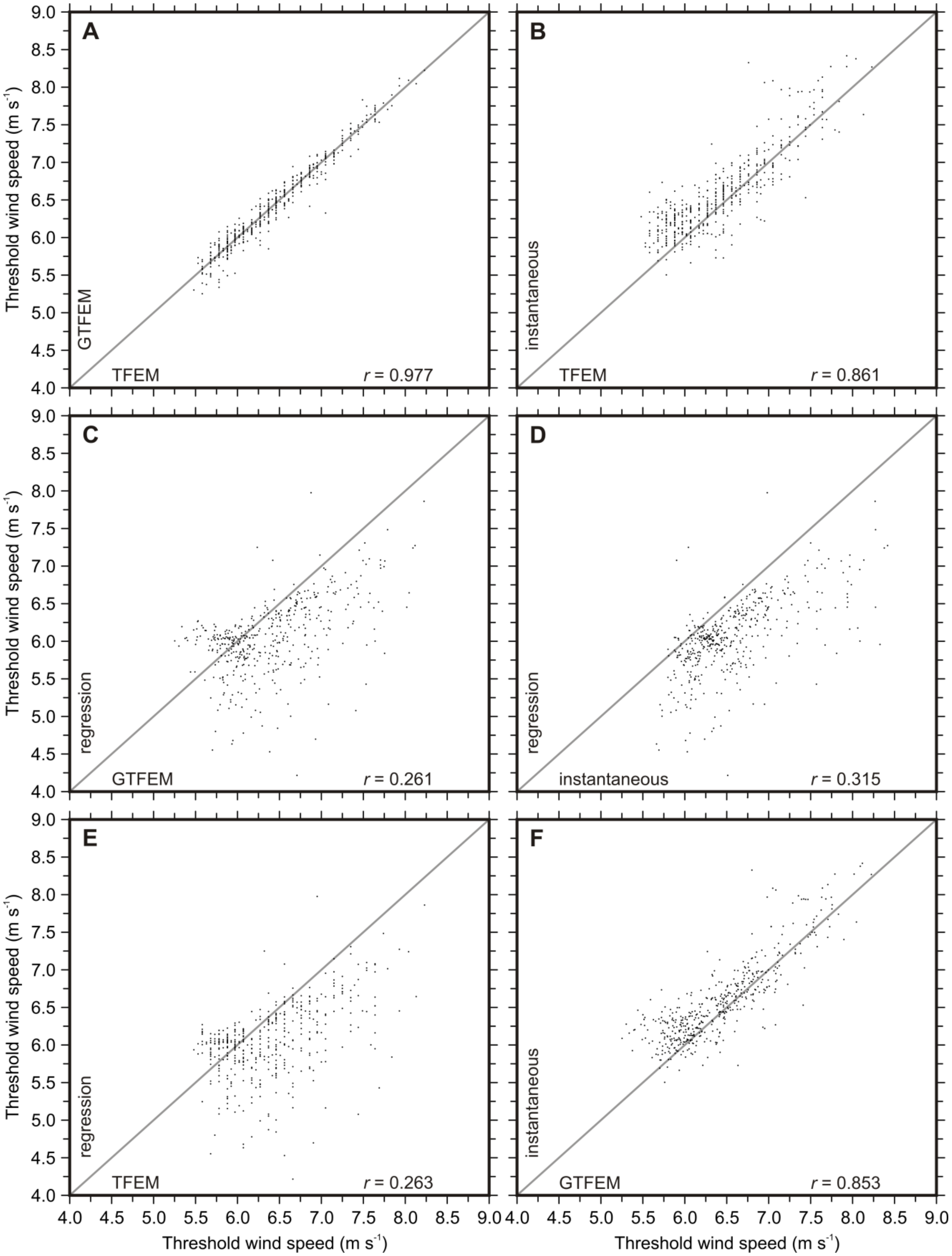

Figure 3.5. Method to method comparisons of threshold wind speeds. Grey lines are 1:1. Only shown are thresholds between 4 - 9 m s^{-1}, *r* = Pearson's correlation coefficient from all data, *n* = 468.

3.7 Discussion

Threshold was variable over the 11 day deployment (Figs. 3.3, 3.4). As a consequence, threshold estimates were not constant; distributions were expected, rather than single values. The source of threshold variability is unclear. However, it is likely that threshold variability is controlled by complex spatio-temporal interactions among surface moisture (e.g., see photo in Fig. 2.1A), air temperature, relative humidity, and wind characteristics (similar to findings from studies listed in Table 3.1). Although unexplained, the variability in threshold present in Figure 3.2 also supports the underlying impetus of this thesis. If threshold variability is pervasive (e.g., Fig. 3.3), future investigators will require reliable methods to accurately and consistently measure this variability.

The threshold methods did not produce identical measurements of threshold (Fig. 3.3). Intuitively, this can be expected as each method is based on a different set of assumptions and generalizations regarding the relation between wind and sediment transport. However, it is important to stress that these results are deployment and sensor specific; these values can only be used to illustrate the *presence* of differences among methods. These results do not represent a reliable estimate of the magnitude of differences and cannot be used as a correction factor. Regardless of these limitations, the very existence of differences in this relatively routine deployment provides evidence that suggests that values from different threshold calculation methods are incommensurate. Although the differences may appear minor (ranging 0.5 - 2.0 m s^{-1}; Figs. 3.3, 3.4), threshold is an important nonlinearity in sediment transport prediction (see Chap. 1, Section 1.3) and the discrepancy results in non-negligible differences in estimated mass transport (Table 3.2).

The source of differences among threshold estimates is very difficult to determine conclusively. Underlying each of the threshold measurement methods is a series of assumptions and generalizations. It is difficult to determine which generalizations are more accurate than others. This is a challenge for determining the "best" threshold method.

One may ask, if all threshold estimates are different, what is the true threshold? Unfortunately, at present, the definition of true threshold in the context of field measurement is insufficiently developed. For example the sediment transport conditions (particle concentration in the airstream, momentum) that are required to result in a measurement of a presence of "sediment transport" are not defined in a standard manner (e.g., see Chap. 2). Consequently, it is not possible to determine the value for a true threshold. Without knowing the true value, accuracy assessments are difficult.

Despite these challenges, the present situation is especially concerning because there are a variety of methods under present use (Table 3.1) and all produce values that are similar, but incommensurate. The simplest comparative questions remain unanswerable. For example, how does threshold vary between coastal and inland sites? Without some method of comparing threshold values a synthesized view of empirical threshold remains elusive. Unfortunately, there are limited possibilities for the development of calibrations among threshold calculation methods because it is widely acknowledged that the relation between wind and sediment transport is very poorly understood. Only recently have investigators been able to quantify high resolution sediment transport and examine natural spatio-temporal variability in transport; and no investigator has been able to predict it (e.g., Baas & Sherman, 2005).

A possible solution is the development of a standard method. This would, at minimum, enable synthesis of threshold measurements from different investigators. However, it is important to note that method is not the only aspect of the threshold measurement system that would require standardization to ensure commensurate data. Although none of the methods presented here can be theoretically argued to be a "correct" method, it is useful to examine some of the assumptions underlying the methods in more detail. The reliability of some assumptions can be questioned, and it would be preferable to use a method with reliable assumptions. This discussion could aid future investigators in picking a standard method, if such an approach is adopted.

3.7.1 Comparison of TFEM and GTFEM

Both the TFEM and GTFEM methods present generalizations of threshold variability at the 5 minute scale. Both assume threshold is static within the measurement interval and all wind speeds above threshold correspond to instances of sediment transport. Wiggs et al. (2004) examined this assumption in detail and found that sediment transport could occur at wind speeds below the TFEM threshold and instances of no sediment transport occurred when wind speeds were above the TFEM threshold. This implies that sub-measurement interval variability in threshold could be pervasive. However, the source of this variability remains unclear, and Wiggs et al. (2004) suggested that the TFEM provides a useful and practical assessment of the approximate threshold condition for the measurement interval.

The GTFEM differs from the TFEM by the assumption of a synthetic wind speed distribution. The close correlation (Fig 3.5) suggests that the wind speed distributions during the field deployment were commonly close to Gaussian. To assess this in more detail, I calculated skew and kurtosis for each measurement interval to examine the systematic trends in the shape of wind speed distributions throughout the deployment (Fig. 3.6).

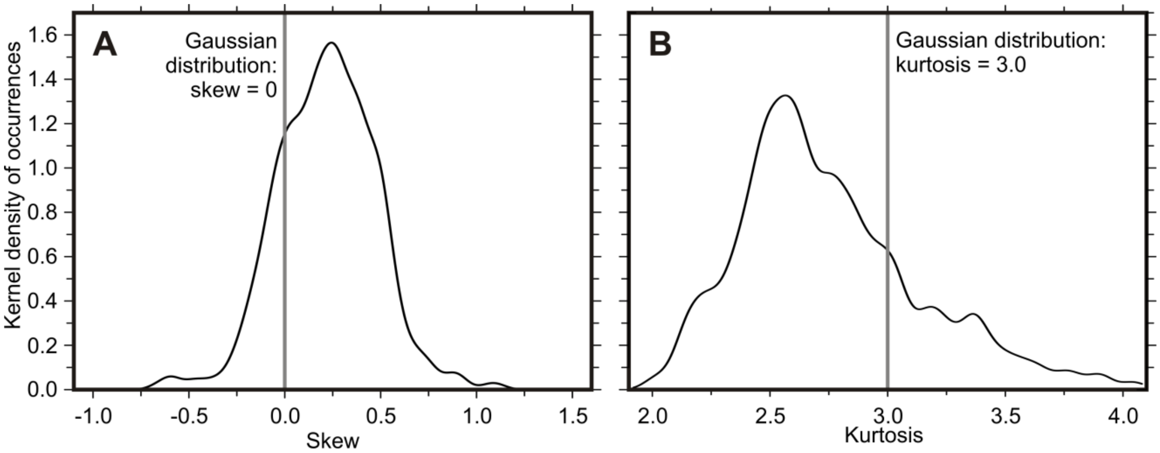

Figure 3.6. A) Kernel density estimate of skew values for each 5 min. measurement interval (*n* = 468, Kernel: Gaussian, standard deviation = 0.05 m s^{-1}). B) Kernel density estimate of kurtosis values for each 5 min. measurement interval (*n* = 468; Kernel: Gaussian, standard deviation = 0.05 m s^{-1}).

Results indicate that distributions during the deployment were systematically positively skewed and platykurtic, in comparison to a Gaussian distribution. Because the results are deployment specific, I hesitate to draw extensive conclusions regarding the applicability of assuming a Gaussian wind speed distribution. However, the comparability of TFEM and GTFEM results explicitly relies upon the assumption that wind speed distributions are Gaussian. This assumption may be valid in certain deployments; however in other deployments error could be much larger than seen here. As noted in Stout (2004), skew and kurtosis could be calculated and used to assess the quality of threshold estimates; however, this practice would likely restrict the number of threshold estimates and require a subjective determination of an acceptable skew and kurtosis cutoff.

Consequently, I believe that it would be preferable to avoid assumptions regarding the distribution of wind speed values, and question the use of the GTFEM method. However, it does appear that the errors associated with this assumption are minor in comparison to other inconsistencies (see Fig. 3.5). The GTFEM and TFEM are the most widely used methods (Table 3.1) and have a history of successful application. As such, both are likely good choices for a standard method; however, investigators should be prepared, if using the GTFEM, to measure skew and kurtosis of wind speed distributions, to ensure distributions closely matched Gaussian. As such, if a recommendation for one method were required, I would recommend the TFEM.

3.7.2 Instantaneous threshold

The instantaneous threshold assumes that the passing of a threshold can be described by the instantaneous wind speed that is measured as transport begins or ends. This follows the classic definition of threshold from Bagnold (1941). As wind speed is measured at 1.35 m, there are differences between the wind at anemometer height and the wind at bed surface. The variability associated with this assumption requires further assessment. Lowering the anemometer closer to the bed could reduce some of this variability.

This method could provide threshold estimates at finer temporal scale than other methods and the distributions could be analyzed and presented as frequency distributions. Several workers have discussed the possibility of describing threshold as a probabilistic parameter (e.g., Davidson-Arnott et al., 2008; Zhen-Shan, Xiao-hu, & Wen, 2008, see Chap. 1, Section 1.4.1). This method could provide the large quantities of data required to construct these distributions.

For phenomenological studies of threshold variability, the instantaneous threshold method could be invaluable; however, further assessment is required to understand the variability associated with anemometer positioning. The method has not seen wide usage, and for this reason, I hesitate to recommend its use for practical threshold determination or as a standard.

3.7.3 Regression threshold

This method has similar assumptions to the TFEM and GTFEM, in that it assumes that threshold is static within the measurement interval. In addition, as all regressions were linear, the regression threshold assumes that mass flux linearly increases with wind speed. This assumption can be challenged from numerous angles.

First, the count rate from a Sensit H11-B piezoelectric sediment transport sensor was assumed to be proportional to sediment flux. Although similar sensors have shown linear relation between sediment flux and count rate (e.g., Gillette et al., 1997a; Baas, 2004), given the complexities encountered in Chapter 2 (Section 2.5.1), this assumption is tenuous, and further work is required to validate this relation.

Second, the linear regression threshold assumes that mass flux increases linearly with wind speed. Most transport formulae conceptualize this relation as cubic (see Chap. 1, Sec. 1.3). However, in conditions of intermittent transport many investigators have found the increase in flux with wind speed to be close to linear, rather than cubic (R. Davidson-Arnott, personal communication, 06 July 2010; Schönfeldt, 2004). In previous tests with this dataset, using regression models with higher order coefficients resulted in thresholds that were anomalously low or negative. Thresholds from a linear model were closer to those measured by other methods and more reasonable.

In light of the potential errors associated with the regression threshold, it is likely not a good choice for a standard. Although I have included it in this study, I hesitate to recommend its use, due to the numerous tenous assumptions.

3.8 Conclusions and recommendations

I compared four methods of calculating aeolian sediment transport threshold from identical raw field data. Results suggest that the majority of methods produce values that are similar but not commensurate. This inconsistency can affect predictions of mass transport.

To overcome some of the issues revealed in this research I tentatively suggest several recommendations. First, updating the semantics associated with threshold measurement is necessary. I suggest referring to these measurements as individual erodibility metrics (e.g., TFEM erodibility, etc.); otherwise these measurements could be mistaken as applicable and comparable threshold values. Thus, despite my ubiquitous usage of the term "threshold" throughout this thesis to refer to these erodibility metrics, the term "threshold" may be best reserved for theoretical or conceptual studies. Second, I believe that common protocols could improve inter-study comparison of field-based threshold estimates. The need for technical standards in various facets of aeolian geomorphology has also been discussed by Lal (1994, 2001), Visser, Sterk, and Ribolzi (2004), Stroosnijder (2005), Zobeck and Van Pelt (2006), and Ellis, Li, Farrell, and Sherman (2009). Of the methods discussed here, the TFEM has the most reliable assumptions and widest usage. Consequently, it may be the most promising method for selection as a standard. However, more work is required to substantiate this assertion, and it is important to note that threshold calculation method is only one of a series of measurement system configuration parameters that could affect threshold values. Any future technical standard would need to specify almost every aspect of the measurement system.

Threshold, in general, remains a parameter that is difficult to measure in the field. Despite this, it is necessary to venture into the field to gain a true picture of threshold and its controls and dynamics. Without the technology and methods available to measure the dynamics of threshold on long timescales under conditions of natural sediment transport, the reliability of wind tunnel and modeled threshold values can be questioned. As such, I hope that the research presented here will stimulate greater scrutiny of threshold measurement protocols and encourage research examining the applicability and commensurability of all threshold values (field, wind-tunnel derived, and modeled).

3.9 References

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CHAPTER 4: STANDARDS FOR AEOLIAN PROCESS MEASUREMENTS: MOVING BEYOND RELATIVE CASE STUDIES

> "There continues to be a lack of standard methods to measure and quantify soil erosion and its impact on productivity and environment. [] In fact, data reliability is one of the serious problems in soil erosion research. Erosion rates assessed by an unstandardized methodology are unreliable. Regrettably, the literature is polluted with such data."
>
> - Rattan Lal, on soil erosion measurement in general, wind and water (1994),
> in Soil Erosion Research Methods, p. 5.

4.1 Prologue

In Chapters 2 and 3 I examined how modifying the sediment transport sensor or calculation method could affect measured threshold values. With both issues, two challenges arose: (i) there is no standard or "correct" value to use as a benchmark for evaluation; different values arise from different interpretations of the measurement parameter, (ii) the poorly understood character of natural sediment transport resists reliable calibration (e.g., from sensor to sensor, method to method). Consequently, the end result is a number of possible measurement system configurations. When deployed, each measurement system produces a unique series of threshold values that could be similar in magnitude, but are fundamentally incommensurate.

A lack of comparability poses great challenges for reliable data comparison or integration. Ultimately, the studies that use field-based threshold measurement are case studies (e.g., studies listed in Table 3.1), where although measurements are used, the reported values are not useful beyond the context of the study. I believe that the "case study" mode of scientific discourse, although prevalent, could be improved.

A potential solution to improve inter-study comparison is the use of standard methods. Standard methods ensure commensurate data. However, such coordination and international cooperation is a daunting challenge. Standards are not the only barrier to data integration, for example, investigators may need to improve data sharing. However, there is little use sharing incommensurate data; consequently, the development of frameworks to ensure comparable data is of vital importance.

The objective of this chapter is to introduce the idea of technical standards to the aeolian geomorphology community, with the goal of improving inter-study comparison. I believe this challenge extends beyond threshold measurement, and as such have aimed this chapter at aeolian process measurements in general, with threshold measurement as an example. Although I clearly espouse standards, the overarching objective is to encourage discussion.

4.2 Chapter abstract

Collective progress in process-based aeolian sediment transport research is hampered by limited opportunities for data comparison, synthesis, and integration. This is partially due to a lack of reliable comparison methods. Many comparison methods are forms of calibration that are either restrictive (e.g., time-averages only) or non-existent (e.g., for field thresholds, mass flux profiles). In this commentary, I express concern for the future of process-based aeolian sediment transport research. I believe that the adoption of standard methods for common measurements could improve inter-study comparison, add value and longevity to data, and advance integrative modeling efforts. I review examples of approaches in allied disciplines where standards are used routinely and discuss how the mutual benefits

of standard data could outweigh disadvantages. Overall, the goal with this commentary is to encourage discussion, self-assessment, and forethought with regards to the measurement methods used in aeolian geomorphology.

4.3 Introduction

Quantitative comparison is a fundamental tenet of all studies involving measurement. Without comparison, measurements are meaningless. In general, there are two methods to compare measurements: (i) develop a relation to modify values measured with different methods so as to render them comparable (herein referred to as calibration, e.g., Goossens, Offer, & London, 2000), or (ii) use identical measurement protocols and instruments (herein referred to as standards). Calibration, in general, is less reliable than using standards, as calibration methods typically rely upon generalized assumptions. However, calibration requires less coordination among investigators.

Many different measurement protocols and sensors are used in aeolian sediment transport research. This has led to a variety of studies comparing various transport measurement systems (e.g., Goossens & Offer, 1994, 2000; Goossens et al., 2000; Baas, 2004; Goossens & Rajot, 2008; Van Pelt, Peters, & Visser, 2009; see Chap 2 and 3). Within a study, investigators typically use standard methods to ensure comparable data that are required to demonstrate differences and support scientific conclusions. However, to compare results *among* studies (with no standard method), investigators are forced to use a method of calibration.

Methods of calibration in aeolian sediment transport research have been developed for many parameters; however, it is important to stress the limitations and assumptions inherent in their use. In cases, these limitations can restrict their use to uncommonly ideal situations. For example, the primary method of comparing wind speeds measured at different heights (the "Law of the Wall") is only reliable when time-averaged wind speeds are compared and in the absence of topography (Bauer, Sherman, & Wolcott, 1992; Bauer, Houser, & Nickling, 2004). The current method of comparing sediment flux (calibration to kg s^{-1} per crosswind meter) is also only reliable as a time-averaged quantity. This has become apparent from high-resolution measurements demonstrating considerable variability in sediment transport across a span-wise meter over short timescales (e.g., 20 s), presumably due to turbulence and complex behavior in aeolian transport systems (e.g., Baas & Sherman, 2005, 2006; Baas, 2008).

Some parameters do not have calibration methods. For example, to examine the dynamics of turbulence and its relation with sediment transport, many investigators in aeolian geomorphology are shifting to higher resolution measurements (Walker, 2005; Bauer, 2009). This has led to a variety of new parameters, for example: high resolution sediment transport and wind speed (e.g., Baas & Sherman, 2005), Reynolds stress (e.g., van Boxel, Sterk, & Arens, 2004), and field measurements of threshold and intermittency (e.g., Davidson-Arnott & Bauer, 2009, see Chap. 3). Methods of calibration do not exist for these parameters. Nor do methods of calibration exist for many other measurements in aeolian geomorphology (e.g., mass flux profiles, see Ellis, Li, Farrell, & Sherman, 2009). Consequently, inter-study quantitative comparison or meta-analyses are impossible.

With restrictive or non-existent calibration methods (especially for the newest measurements), I am concerned about the limited opportunities for data synthesis and integration in the future of aeolian geomorphology. Although several mentions of standards have been made in the literature, I believe that this issue requires further discussion (see Lal, 1994, 2001; Visser, Sterk, & Ribolzi, 2004; Stroosnijder, 2005; Zobeck & Van Pelt, 2006; Ellis et al., 2009; Panebianco, Buschiazzo, & Zobeck, 2010). A lack of comparability constrains collective progress and limits the applicability of data for developing and comparing models (e.g., Arens, 1996; Sherman, Jackson, Namikas, & Wang, 1998). In this commentary I argue that a viable solution is the development of technical standards. This would enable reliable inter-study comparison, resulting in a net increase in the applicability, comparability, and value of empirical measurements.

Standards are a practical solution to the "coordination problem", widely studied within the context of economics, politics, and game theory (see review by Harsanyi & Selten, 1988). Players (in this case scientific investigators) can realize mutual gains (commensurate data) with mutual cooperation.

I begin by reviewing two examples that highlight issues with quantitative comparison of measurements of aeolian sediment transport threshold and mass flux profile. I follow this with a discussion of how in several allied disciplines, the adoption of standards to enable reliable inter-study comparison has been beneficial. Finally, I briefly speculate on the future of empirical measurement in aeolian geomorphology. Although I espouse standards, the overall goal with this commentary is to stimulate discussion within the aeolian geomorphology community.

4.4 Difficulties with quantitative comparison

The first example concerns empirical measurement of sediment transport threshold. In Chapter 2 I examined the ability of four commonly used piezoelectric sediment transport sensors to detect the presence of transport. The relation between the presence or absence of sediment transport and wind speed can be used to derive sediment transport threshold (e.g., Stout, 2004, see Chap. 3), which is a fundamental parameter in sediment transport modeling. Results showed large discrepancies among sensors in duration of time transport was detected (despite approximately equivalent field conditions). This inconsistency is not unexpected as the sensors differ in sensitivity and size. My primary concern with this inconsistency is not with implying quality to any given response characteristic or sensor, but rather with the ability to compare measurements. Without consistent response, threshold measurements made with different sensors are incomparable. At present, there is no method to calibrate these results. This constrains progress, particularly in resolving how threshold varies spatially (e.g., Stout, 2007). While in Chapter 2 I found inconsistency among instrument types, inconsistencies amongst similar instruments have also been found (e.g., Baas, 2004). Therefore, with regard to threshold and high-resolution measurement of sediment transport presence/absence, it is suggested that studies employing piezoelectric sensors are only comparable qualitatively and the data have limited value outside of the study. Similarly, measurements of sediment transport threshold made with different calculation methods are incommensurate (see Chap. 3).

The second example concerns measurement of mass flux profiles with sediment traps. Time-averaged mass flux profiles are required to understand the physics of grain behavior, to model sediment transport rates (Panebianco et al., 2010), and to predict abrasion potential. Ellis et al. (2009) explored how inconsistent measurement of trap heights and bed elevation, and different regression analyses, influenced the calculation of flux profiles. It was found that substantial variation in results could occur if different measurement protocols and calculations were used. With this example, the use of a common protocol would vastly improve inter-study comparison and enable meta-analyses (e.g., Farrell & Sherman, 2006; Sherman & Farrell, 2008). In addition to highlighting the inconsistencies, Ellis et al. (2009) proposed a standard and described it in sufficient detail to enable others to follow. This type of approach represents a turning point, and should be espoused for resolving issues with incomparability in a number of process parameters.

I suspect the development of calibration methods to enable reliable inter-study comparison of threshold and mass flux profile would be exceedingly difficult. The chaotic and dynamic character of wind and sediment transport restricts straightforward generalization, and is far from being understood comprehensively (e.g., Baas & Sherman, 2005; Baas, 2008). With both of these examples, a standard method would improve comparability.

4.5 Experiences with common measurement protocols in allied disciplines

If aeolian geomorphology wishes to improve inter-study comparison by establishing technical standards, there are many lessons to be learned from allied disciplines. Developing standard methods requires effort, agreement, coordination, and funding. Any standard method requires a critical mass of researchers to adopt and maintain it. Although, in some cases, unofficial standards can emerge through the history of study (*de facto* standards), I believe it is important to formalize and maintain any given standard to ensure the social infrastructure is available for maintenance and development (Brazma, Krestyaninova, & Sarkans, 2006). There are several strategies that can assist with adoption and formalization of technical standards.

In most cases, recognition or affiliation with a technical society improves standard adoption. The most notable accomplishment in the development and implementation of standards in natural science is in meteorology (Edwards, 2004). The success of meteorological standards is in no small part due to the World Meteorological Organization (WMO), which is an agency of the United Nations with 189 member states and territories. Through the Instruments and Methods of Observation Programme (IMOP), the WMO actively promotes the standardization of meteorological measurements and related observations, while also ensuring the uniform publication of meteorological observations and statistics. The WMO *Guide to Meteorological Instruments and Methods of Observation*, which is available on-line[1], provides comprehensive and up-to-date guidance on the most effective practices for measuring and observing meteorological phenomena. Arguably, without this leadership and commitment to reliable comparison and integration, it is unlikely that the understanding of global climate change would be as it is today.

Standards can develop within groups of researchers that collectively realize the mutual benefits of data integration. These consortiums are commonly issue-driven. A notable example of this type of internationally-coordinated consortium is Fluxnet[2]. With a global network of micrometeorological sites, Fluxnet measures the exchanges of carbon dioxide, water vapor, and energy among terrestrial ecosystems and the atmosphere. Within the Canadian branch of Fluxnet (presently referred to as the Canadian Carbon Program), a measurement standards working group (Fluxnet-Canada Research Network; FCRN) was established to develop detailed protocols necessary to reliably collect commensurate data. In 2003 FCRN released a working draft report of measurement protocols for a range of micrometeorological measurements and sensor calibration procedures[3]. The report establishes a consistent framework for collecting data. Thus, Fluxnet researchers can reliably integrate results measured by many different investigators and examine spatio-temporal variability at large scales.

In some areas of science, standards are created and formalized, but not necessarily followed by all investigators. For example, ASTM (American Society for Testing and Materials) International develops voluntary consensus technical standards for a wide range of applications. There are methods for fluvial[4] and meteorological[5] processes, but none specifically designed for aeolian sediment transport. Compared to the issue-driven consortium approach, voluntary standards do not require international coordination. Investigators can pick and choose which standards they wish to follow. However, to ensure sustainability, voluntary standards require a critical mass of researchers.

The best approach for formalizing standards for process-based aeolian geomorphology remains unclear. Within aeolian geomorphology, Bullard (2010) describes how several issue-driven collectives have developed standards for integration of paleo-depostion records of dust, worldwide occurrences of dunes, and mapping of surface conditions in dust source regions. Unfortunately, aeolian process measurement does not have a central motivating issue. Consequently, I suspect that technical society affiliation may be important (with appropriate community involvement and formal peer-review). The newly formed International Society for Aeolian Research may be a logical starting point if aeolian geomorphologists wish to formalize process measurement standards.

4.6 Challenges of technical standards

There are some important disadvantages of standards. The process of choosing appropriate methods is tedious for researchers and does not pay in publication volume. This can be alleviated somewhat with technical society afflilation and citation, which legitimizes the work.

Some aspects of aeolian geomorphology measurement are insufficiently mature for standards. For example, high-resolution measurement of transport does not have a satisfactory sensor for consideration as a standard (Baas, 2008; see Chap. 2). Nevertheless, in these cases, discussion of standards (although unimplemented at present) will improve sensor assessments, because each new candidate is forced to be tested with sufficient rigor to be considered as a standard. Sensor properties such as consistent response, low cost, and worldwide availability become paramount.

It can be argued that standards discourage development of new methods or sensors. At present, in aeolian geomorphology, the lack of standards limits development because assessments are difficult or un-publishable without a benchmark to compare against. Finally, in some cases, standards can become outdated and irrelevant for researchers. This is where societal recognition can help, as the socio-political infrastructure is developed to maintain and update technical standards, as needed.

4.7 Concluding remarks

At present, I believe that the future of measurement in aeolian process research requires some discussion. Many new measurements (e.g., turbulence metrics, field threshold) could shed light on old problems (e.g., sediment transport prediction), but have no method of reliable inter-study comparison. Many old measurements (e.g., mass flux profile) are exceedingly difficult to synthesize. A viable solution could be the development of standards. Standard methods have been used in aeolian geomorphology in the past, perhaps with little recognition. For example, the widely used "Fryberger method" (Fryberger, 1979) provides a standard method of quantifying the potential for aeolian transport at a given site. The Fryberger metrics are reliably integrated into a framework of comparison that extends internationally.

Reliable inter-study comparison with standards would allow greater quantitative integration. Quantitative integration is occurring rapidly in many disciplines in earth surface science. Large datasets can now be easily shared via the internet, reused and integrated with other data. For example, environmental modelers can now use empirical data directly (see Murray et al., 2009). Furthermore, the capacity to analyze large volumes of data is unprecedented (Zimmerman, 2008). I believe that without integration, aeolian geomorphology may not have the same opportunities for scientific progress that exist in other disciplines.

My goal with this commentary is to stimulate discussion of the future of measurement in aeolian geomorphology. My hope is that others follow what I perceive to be a major concern. The urgent problems of global environmental change and mounting societal pressure on science to provide solutions are a modern reality. Aeolian geomorphology is not immune, and to address societal-relevant questions the research area must be prepared to function efficiently. Efficiency, with respect to reliable integration of process measurements, may require collective and cooperative action. I hope this commentary can provide a catalyst for the beginning of a community dialog on the topic of inter-study comparison and data integration. Undoubtedly this discussion, regardless of the outcome, will better prepare aeolian geomorphology for the future.

4.8 Notes

[1] WMO *Guide to Meteorological Instruments and Methods of Observation* (7th ed., 2008): http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO_Guide-7th_Edition-2008.html. (Accessed: 30 August 2010).

[2] Fluxnet: http://www.fluxnet.ornl.gov. (Accessed: 30 August 2010).

[3] Fluxnet Measurement Protocols, 2003: http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf. (Accessed: 30 August 2010).

[4] ASTM International fluvial protocols: http://www.astm.org/Standards/water-testing-standards.html#D19.07. (Accessed: 30 August 2010).

[5] ASTM International meteorological protocols: http://www.astm.org/Standards/atmospheric-analysis-standards.html. (Accessed: 30 August 2010).

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CHAPTER 5: CONCLUSIONS AND FUTURE DIRECTIONS

> "When aeolian scientists lift their sights from their wind tunnels and experimental plots to the horizon or the decades ahead, they find new challenges."
>
> - Andrew Warren, in Sustainability in aeolian systems, Aeolian Research 1, p. 95.

5.1 Summary of conclusions and contributions

In this thesis I examined methods for field-based measurement of aeolian sediment transport threshold. Threshold is essential for modeling of aeolian sediment transport and provides a practical metric to describe the relation between the presence of transport and a given wind speed. New field-based methods provide an opportunity to examine threshold in conditions of natural sediment transport. However, some aspects of these methods require consideration. Overall, I have several key conclusions:

(1) Results from Chapter 2 suggest that commonly available piezoelectric sensors do not consistently detect the presence of sediment transport. This constrains comparability of threshold measured with these sensors. This has not been previously shown. Previous workers have briefly mentioned the challenge of defining the presence of sediment transport (Lyles & Krauss, 1971; Nickling, 1988; Zhen-shan, Xiao-hu, & Wen, 2008), my study adds to this by demonstrating the problem extends to field-based studies. In Chapter 2 I suggested the use of a standard sensor, which is a viable and practical solution.

(2) Many methods are available to calculate threshold from raw field data. Data from Chapter 3 illustrated that each method could produce similar results; however, as the underlying generalizations are different, the threshold values are fundamentally incommensurate. I proposed the use of technical standards to improve inter-study comparison and recommended the time fraction equivalence method of Stout and Zobeck (1996, 1997) as a practical standard method.

(3) Standards are widely used in other disciplines as a method to ensure commensurate data. Many aspects of aeolian geomorphology would benefit from such an approach as the calibration methods available are either restrictive (e.g., time averages only), or non-existent (e.g., among different measurements of sediment transport threshold). I introduced the idea of technical standards and briefly discussed strategies to aid adoption. Several previous workers have briefly suggested that standards would benefit various aspects of aeolian transport measurement (Lal, 1994, 2001; Visser, Sterk, & Ribolzi, 2004; Stroosnijder, 2005; Zobeck, & Van Pelt, 2006; Ellis, Li, Farrell, & Sherman, 2009; Panebianco, Buschiazzo, & Zobeck, 2010), but none have introduced the idea to the community in a dedicated commentary, a format that encourages discussion.

5.2 Summary of recommendations

I have made several tentative recommendations throughout this thesis. These recommendations are tentative because I believe that the aeolian geomorphology community needs to discuss threshold measurement, rather than depend on the opinions or findings of one investigator. However, I realize that at times a recommendation is necessary to start the discussion; consequently, I have made recommendations where appropriate.

With respect to sediment transport sensors, none of the sensors I tested in Chapter 2 are suitable. The cylindrical design modifies the sampling area, causing great issues for reliable determination of sampling area. Furthermore, investigators have reported poor control over the sensitivity of piezoelectric crystals (Baas, 2004; John Stout, personal communication, 08 July 2010). Sensors need to be consistent. For this reason, I recommend investigating the use of photo-electronic sensors such as the Wenglor YH03PCT08 (Barchyn & Hugenholtz, unpublished data). These sensors are consistent, low cost, and accurate; however, further field testing is required.

The four methods for calculating aeolian sediment transport threshold closely match in magnitude, but are fundamentally incommensurate (Chap. 3). Similar to previous authors (Wiggs, Atherton, & Baird, 2004), I recommend the use of the time fraction equivalence method (TFEM) of Stout and Zobeck (1996, 1997). To quote an anonymous reviewer of a previous version of Chapter 3, "[The TFEM] provides a practical device for an impossible situation, if one threshold value is required". I agree, and recommend its use as a standard for practical studies of threshold variability. I also recommend some clarification to the semantics of threshold determination (detailed in Section 5.3).

In Chapter 4, I recommend the use of technical standards for common measurement protocols in process aeolian geomorphology. Although the discussion in Chapter 4 is aimed at implementing standards, my underlying recommendation is for the beginning of a discussion on the topic.

5.3 Revisions to threshold semantics

The findings from this thesis suggest that some revision to the semantics of threshold determination may be useful. In Chapter 3 I found that many interpretations of the threshold concept resulted in a series of measurements of threshold that were similar, but fundamentally incommensurate. The problems could be avoided if each of these methods were referred to as individual erodibility metrics (e.g., TFEM erodibility, etc.). Erodibility metrics could be presented with a suite of metadata (sensor type, sensitivity, anemometer, etc.). This would dissociate the results from being applicable threshold results. The word "threshold" may be best reserved for theoretical treatments. Such a revision does not result in commensurate data; however, it does help limit the arbitrary application of these values in transport formulae. I acknowledge that I have used the word "threshold" ubiquitously throughout this thesis to refer to these erodibility metrics. I have done this to maintain consistency with the semantics used presently in the literature.

5.4 Future directions

The experiments in this thesis were designed to test aspects of measurement systems used to measure aeolian sediment transport threshold. There are many future directions that could be taken from these studies. First, many of these studies could be repeated for other aspects of the threshold measurement system: for example, anemometer type, anemometer height and positioning, sediment transport sensor height, sampling interval, measurement interval, etc. However, I suspect that all of these studies would have similar results to those in this thesis.

Some research on the anemometers used in aeolian studies would be worthwhile. At present, wind measurements from different instruments are all implicitly treated as commensurate in aeolian research (e.g., sonic, propeller, cup, and thermal). Simple kinematics support the presumption that anemometers with some mechanical element (propeller, cup) will suffer from some inertial or lag effects. Comparing these measurements to sonic or thermal anemometers (with little to no inertial response) may be questionable. It could be possible to develop an analytical calibration if one were comfortable with making assumptions regarding boundary layer turbulence spectra (see e.g., Horst, 1999).

The temporal intervals of field-based threshold measurement systems could be systematically investigated. These comparisons approach an investigation of the spectra of threshold variability and are likely to be very deployment specific. However, these analyses could be useful to assist investigators pick measurement or sampling intervals for a standard method. I suspect that no perfect measurement or sampling interval will be found, and believe some compromise will be required.

It is clear that aeolian geomorphologists need better instruments. The lack of reliable and consistent sensors for measuring the most basic parameter of interest (sediment transport) at a high resolution is concerning (Baas, 2008), and I believe this to be one of the most pressing challenges in process-based aeolian geomorphology today. Research into sensor design and development is a top priority for aeolian investigators at the present time.

With regards to my recommended revisions to semantics (Section 5.3), one may ask: if all field based measurements are simply erodibility metrics, how can these erodibility metrics be integrated with transport formulae? I don't claim to have the answer and suggest that this is a viable avenue for future research. However, I will note that understanding the reliability of integrating field-based threshold measurements (as erodibility metrics) into transport models is vastly simplified if a standard measurement protocol were available. With a standard protocol, the process only needs to be completed once, rather than multiple times for each unique combination of sensor and method.

The topic of standards in science could be covered in more detail from a social scientists perspective. I have deliberately avoided extensive study as I am not a social scientist. Standards are becoming very important for other disciplines in science (e.g., see for genomics: Brooksbank & Quackenbush, 2006, for biology: Vogt, 2009; also see Brazma, Krestyaninova, & Sarkans, 2006). Similar to these investigators, I believe it to be vital that a majority of investigators be behind the *idea* of standards for any standard to survive. Here, I believe the social aspects of scientific communities requires careful consideration. For example, many social structures (science included, I suspect) are pseudo-hierarchical (Sherman, 1996; see Sperber, 1990). As such, some would argue that the best method to achieve anything in science is to convince the key leaders of the discipline (the "fashion dudes" of Sherman, 1996). The rest of scientists are much more likely to follow with some approval from the leaders of the discipline. Overall, some research into the potential influence of social aspects of scientific communities on scientific progress could be very enlightening. I suspect much of the research has been completed, but perhaps requires some pre-digestion into a format and language that the average earth scientist can understand and apply.

5.5 Concluding remarks

Many investigators have noted that geomorphology is a philosophically sedate discipline (e.g., Schumm, 1991; Sherman, 1996; Slaymaker, 2009). Some argue that the culture places little importance on self-reflection and assessment (Smith, 1993; Warren, 2010). Throughout this thesis, I have discussed issues with limited opportunities for quantitative integration in the future of aeolian studies. In effect, many aspects of this thesis can be regarded as a self-assessment. With threshold measurement, I suspect even a little integration would go a long way. For example, a common definition (or standard sensor) for the presence of "sediment transport" (Chap 2) would greatly improve the applicability of measurements of threshold. Such integration is not unachievable. As such, I view the future of aeolian studies as bright and sincerely hope this thesis has made a contribution (however small) to beginning a discussion that will arm the future investigators of tomorrow with better tools to understand aeolian systems worldwide.

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