Journal of Coastal Research	13	3	962–966	Fort Lauderdale, Florida	Summer 1997

DISCUSSION

Discussion of: Bauer *et al.* 1996. Indeterminacy in Aeolian Sediment Transport Across Beaches. *Journal of Coastal Research,* 12(3), 641–653.

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INTRODUCTION

We should very much like to support the authors' proposition " . . . that the problem of aeolian sediment-flux prediction, as conventionally conceptualized, is indeterminate for situations other than the simplist ones . . . ," for that is also exactly our experience down here on the Gold Coast of Australia. Over the years we have often been attracted by the idea of mounting windblown sand measuring exercises like those reported by the Authors, but apart from a very small experiment where we collected windblown sand particles on sticky-tape (Matthews et al., in press) each time we have done nothing simply because the problem of aeolian transport is so indeterminate. On our Gold Coast, we monitor our beach every day and one thing that we particularly look for, is the height, form and volume of the collected windblow on the beach and in the dunes since the day before, particularly when allied with the windblow surface texture, area and the available fetch distance of entrainable sand across the beach. It did not take us long to appreciate that even this cluster alone of variables, demonstrated a range of uncertainty and variability, that completely smothered any possible deduction of simple cause and effect relationships.

FIELD OBSERVATIONS

If it was our daily field monitoring that lead us to abandon standard windblow sediment studies, it was also these daily monitoring beach sorties, that with continusing ongoing time, lead us to finally appreciate that all aeolian beach sand transport was indeed increadibly complex and, at least on our beach, quite different from the well published mathematical models and quantitative process formulae, that we all read in the literature.

So at this stage, let us discuss what we have seen and learned over our last 26 years of study of our Gold Coast beach and dune systems. The first item, based upon thousands of daily observations is that, at the most basic level, aeolian sand transport can, and does occur, within three escalating modes that develop one from the other in a fixed sequence that always stays the same whether the sand flow quantity is rising or falling. Firstly transport starts on the bed, then it expands to bed load plus saltating load and finally to bed, saltating and suspended load and this sequence is reversed as the wind drops back to no transport at all. Because we suspect that each class of transport is different, it is most likely that the transport "equation" for each class will also be different and we do have some evidence that the physical properties of the sand carried in each class *are* different. If this is so, we are addressing three variables before we even start, and not some mean overall average of all the wind/sand interactions.

It is widely reported in the literature, that a very common phenomenon that develops on the bed, is armouring, or selective winnowing that removes the fine easily transportable particles and leaves the heavier more resistant particles behind. This then introduces another variable that is governed by time as well as the wind force, for as the bed armours, the feedstock offered to the wind is not only changing in properties but also in the volume of sand that can be entrained. It is in fact reasonably common to see the bed armour-up enough to stop all sand blow, even for a nearly constant wind velocity. The transport of sand in streamers as discusses by Gares *et al.* (1996) leads to similar results, with the variable being mainly the percentage of beach area occupied by the streamers, and the degree to which they are continuous or intermittant, for these affect the continuity of both the feed and the transport capacity rates. We also find on our beach, that ripples on the surface of the sand can be variable structures, in that they themselves can migrate with the wind *i.e.*, they are not "fixed" friction inducers, they can vary with time in the way the troughs sort out, and then lose coarse lag deposits, and sometimes the very fastest wind gusts can erase, and flatten them all out in seconds. Our ripples are not extremely mobile, but they are nowhere near stationery either, so they do hold some finite variability.

It is also well known, that the sand "fetch" is an important aeolian beach transport parameter, *i.e.* the length of trans-

96161 received and accepted in revision 11 January 1997.

portable sand measured along the "centreline" direction of the wind flow on the beach. The variability of the fetch is then affected by two major factors, firstly the width of the beach and secondly, the wind direction. The variability of the wind direction is then not at all trivial, if the wind is blowing at 45 to the beach, the fetch for the identical area of transportable sand is increased by 40% and theoretically if the wind was blowing *along* the beach, the fetch would be infinite! In addition to this the effective slope of the beach is also controlled by the wind direction all for a constant beach shape and form, the more oblique the wind to the beach the longer the distance for a given rise, so a flatter effective slope. Our Gold Coast beaches usually develop a dry sand fetch of between 5 and 50 metres, so the effects of wind direction on onshore windblown sand transport can be quite significant, yet strangely enough our maximum dry sand transport occurs under wind obliquities of between 40 and 45 from beach normal, although we do not know why this is so.

In general terms our local beaches under aeolian transport conditions appear to be quite nor ·.ǩ and during transport look like everybody else's beaches we have seen, and read about in the literature, but with one very major and baffling phenomenon, and that is the high rate transport of damp sand. Most of the literature advises that increasing moisture contents in beach sand depress and slow down all aeolian transport, but our beach is the very reverse, our highest rates of transport occur with markedly damp sand usually associated with rain and wind gust velocities exceeding 35 to 40 knots, and the damp transport is many times the maximum transport of any dry sand. The actual transport mode is also different from dry sand transport, in that it occurs as a well air entrained sheet flow generally less than 100 mm thick and with minimal saltation. The solids content is visably quite high nevertheless, since it is unpleasant to walk through the moving sheet with bare feet for it is often flowing fast enough to sandblast the skin very effectively. Near its peak, our damp wind blow can lift moist sand and blow it over the top of a dune with a crest level of +6.5 metres and ...at the top of the beach and nearly to the crest of the dune with an extra metre or more thickness of new sand in only a few hours. Why this moist sand transport should be so efficient, we do not know, but as a hint, we note that this class of sand transport seems to be associated with a beach accretion or building phase when all the beach from the top of the last high tide surfbeat runup down to the low tide runup is new and soft *e.g.* sand you sink +20 mm into when you walk on it and sand that has only arrived within a few hours, and has had no time to yet become compacted. It seems perhaps that when the beach is strongly accreting, the texture of the new soft sand being deposited, reacts with some special form of aeration input that allows the wind to disperse, lift and then transport the sand. Certainly we have seen 40 knot winds strip sand off the top of the swash zone between individual wave bore run-ups, an unforgetable sight to any coastal engineer! We should have loved Bill Carter to have seen it. Nevertheless, these observations are only general and we can offer no rational explanation of the real moist sand transport phenomenon that we see, but at least we can report it for others to ponder over perhaps, it is very certainly very different from conventional dry sand transport.

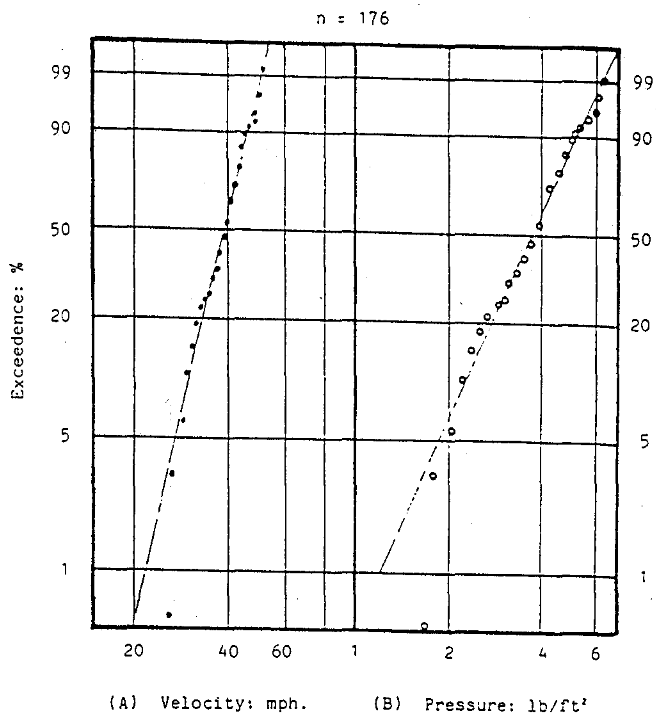

Figure 1. Wind Gust Velocities & Pressures—Weibull Plots. Data from Sherlock & Stout (1937). Data points more reasonable fit than Gaussian or Log-normal plots.

THE IMPACT OF GUSTS

Most aeolian beach transport studies measure the wind by using sets of anemometers spaced vertically apart on poles, with a row of poles spaced across the beach and up into the dunes. In consideration of our discussion on wind direction above, it may be noted that most pole rows are laid out a right angles to the waterline of the beach, only the sand traps are aligned facing directly into the wind, but the results of measuring winds and trapping volumes along different directions, may not be based upon quite the same thing. However, to return to the point, the use of anemometers set out along a single line array, provide wind climate data that is strictly only two dimensional, but we all know that wind fields, particularly those close to the ground are three dimensional, and many wind cells, often those touching the ground being of markedly, circular form. The anemometers only read one assumed directional vector for most of the time, but when you walk on a windblown transport beach you can readily see that the mobile sand reads much more than this, as demonstrated by the complex contorted ripple fields on the surface of dry sand plus their often highly variable ripple axes shapes and directions. Wind gusts are three dimensional and near the boundary layer, they can come in trains aligned along preferred flight paths.

It is possible that near suface wind gusts are of similar

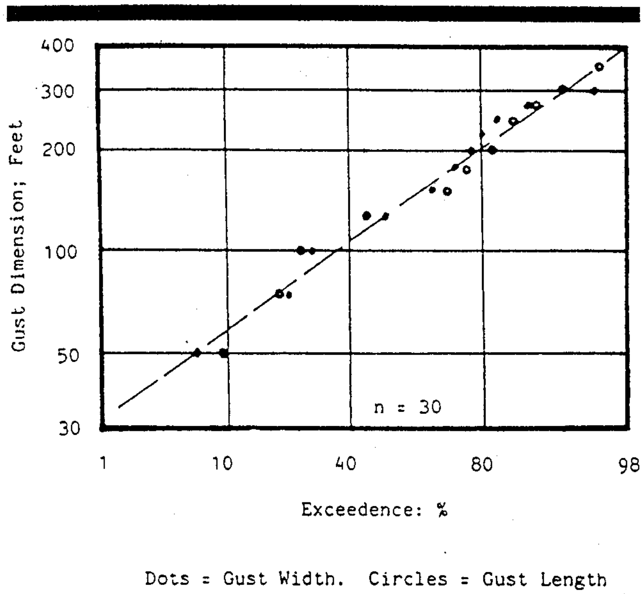

Figure 2. Wind Gust Dimensions: Log-normal Plot. Data from Sherlock & Stout (1937). Gust width and depth taken 50ft. above smooth ground.

"shape" in plan as vertically, in which case a vertical anemometer array would ultimately average out the gust shape field, but instinct would suggest that this would be unlikely. The only data suite that we hold that depicts wind gust contours in horizontal and vertical sections, is that of SHERLOCK and STOUT (1937). These researchers set up a very large anemometer array that measured gusts on vertical sections to 250 ft. high and horizontal sections across a width of 660 ft. during two winter storms in Ann Arbor, Michigan. The immediate wind fetch had a gentle slope of 175 ft. in 4 miles and contained occasional farm buildings and groups of trees so the measured wind fields would not be far removed from storm winds flowing landwards over a beach. The most obvious feature of their diagrams, is that in both cases, the vertical gust contours in the overall, are of much smaller "size" *i.e.* in "quasi-diameter," than the horizontal, and with the contour spacings often much closer on the vertical. This of course, is only one study, but it might well give us something to think about. Unless proven otherwise, we suggest that wind gust shape should be taken to be a variable and not a constant.

Certainly common sense and ordinary observation lead to the conclusion that the highest sand transport occurs under the gusts of highest velocity, much as the largest waves are manufactured by the fastest winds, which leads to the consideration of what wind velocity rating should be selected for aeolian sand transport models. If most transport occurs under the strongest gusts, then it would be illogical to adopt the mean velocity, particularly since most high wind fields, (except tropical cyclones perhaps) are Weibull and not Gaussian, but the Weibull distribution is very much skewed, and cyclones being Gumbel, are even more so. Our feeling is that windblow sand transport models should recognize maximum gust behavior by using not the mean wind speed, but by analogy with wave dynamics, the velocity of say Vsig. or in other terms V 84% meaning 84% of the winds are less than this value, we call it V 84% passing. Before calculating this class of statistical value however, it could be necessary to crop out from the data, all wind speeds lower than that of the sand entrainment value for each specific site and its specific sand properties. The problem then, would be should you keep the overall Vsig and crop out all the below threshold values in terms of the lengths of time the velocity was below threshold, or should you crop the below threshold values and then calculate a new truncated or "rump" Vsig? We have no idea, but intuitively we might expect the former. We should always remember that wind force calculations are extremely sensitive to the selected "design" velocities, wind pressure in closely proportional to V^2.

PROBABILITY DISTRIBUTIONS

As discussers who are very much in agreement with the authors' propositions, we think that their most important alternative concept, to accepting simple deterministic models, is their suggestion that instead, we should investigate probablistic models. For 25 years, all of our Gold Coast basic research, has been based entirely upon concepts of uncertainty and the detection of probability distributions for every coastal process that we have ever been able to measure, or detect, for example, see SMITH and PIGGOTT (1993), but we have been able to rationalize only part of the approach. The authors set out their alternative as "... Instead of simplifying conditions ... (our) ... approach advocates sampling the range of variability within the system with the intent of obtaining statistically robust estimates of the means and variances of the relevent variables, and ultimately estimates of their probability distributions." Whilst we heartily agree with their sentiments, we might suggest that they might perhaps reverse the order of their study parameters. In fact, the detection of any particular natural process probability distribution is by far the easiest part, and the one that can, and should, be the first, and not the "ultimate" step in the process analysis. Quite simply all that is required, is to plot up the natural process data on the usual sequence of exceedence probability papers until a straight-line fit is attained, and this *is* your probability distribution, see again SMITH and PIGGOTT (1993).

The next step, or the ultimate step, in the authors' philosophy, involves just how you can use these probability distributions in a sensible practical way. To repeat again, the authors say that they should be seeking "... robust estimates of the means and variances of the relevent variables ...", but all skew probabilities do not have a "mean", they only exhibit a 50% passing value, and these perhaps can be somewhat different things. Likewise, the common theoretical concepts of statistical standard deviations and co-efficients of variation are only applicable to Gaussian distribution. The basic problem is just how to assess and combine a suite of different physical parameters that may hold several different statistical populations of markedly different skewnesses and apply a weighting to the importance of any individual, or group, of parameters.

Table 1. *Probability distributions.*

Element	Source	Reported By	Probability Distribution
(1) Wind Gust Velocity	Sherlock & Stout	Discussers. Fig. 1A	Weibull
(2) Wind Gust Pressure	Sherlock & Stout	Discussers. Fig. 1B	Weibull
(3) Wind Gust Plan Dimensions	Sherlock & Stout	Discussers. Fig 2	Log Normal
(4) Wind Direction	Smith	Smith & Piggott (1993)	Gaussian
(5) Dry Beach Width	Smith	Smith & Jackson (1992)	Weibull
(6) Beach Slope	Smith	Smith (1990)	Gumbel
(7) Sediment Properties	Smith	Smith (1992)	Log Normal
(8) Ocean Sea Levels	Smith	Smith & Piggott (1993)	Gaussian

As a quasi-practical example of a typical set of property and process probability distributions that might be involved in constructing a mathematical model of aeolian transport on a beach, Table I sets out a reasonably representative suite of physical parameter elements together with their population probability distributions. We use the prefix "quasi" because not all the data have come from the same place, the data for the first three elements come from Michigan U.S.A., the next four from the Gold Coast Australia, and the last from Sydney Australia, to the total suite might not be suitable for say an aeolian transport model for our Gold Coast. On the other hand, it is the principle that we are trying to demonstrate, not the detail, and the mathematically vexing problem is that we are addressing four significantly different population distributions in only eight variable elements, in all: Gaussian, Log normal, Weibull *and* Gumbel, only is the Log-Gumbel population missing in this example. This represents an extremely wide range of population variability, for just one single coastal process. But this then simply returns us to our final central theme, how *do* we make robust estimates of the means and variances of highly skewed probability distributions? Certainly, we can read-off from a probability population plot any particular "% passing" value that suits our study, but the variance may be quite another matter. The actual variance for a skewed population is graphically demonstrated by the slope of the plot, and perhaps the slope may offer a surrogate for the variance, the steeper the plot, the higher the variability, but how this might be applied in practice, currently escapes us.

In fact, we think that the distributions shown in Table 1, well *could* be used to construct a Gold Coast aeolian transport mathematical model, the data from Sherlock and Stout that indicate a Weibull distribution for storm wind velocities and pressures, have also been substantied in many other areas of the world *e.g.* fine weather wind is Log-normal, normal storms are Weibull and tropical cyclones are Gumbel, so the probability distributions of Table 1 would still apply to a Gold Coast sandblow model. It would only be that the *slope* of the Gold Coast wind Weibull that would be different, and that would require local site data to elucidate. Likewise, we only included the variation in ocean sea levels (as element 8), as a possible element contender, because it has become so popular for coastal researchers to emphasize the probable impact of sea level rise, when predicting all future coastal processes, so we would expect coastal planners involved in aeolian transport, to do the same, or at least try to.

THE UNPREDICTABLE NATURE OF SEDIMENT TRANSPORT

A problem pervasive to studies in any facet of coastal processes is the margin of error involved in measuring these processes. This is especially true when attempting to quantify sand transport. As an example, it can be reasonably expected that a large percentage of the average net annual littoral drift will be moved during a single storm on the Gold Coast. Our Nerang Seaway bypassing system annually pumps a volume of 500,000 m^3 to South Stradbroke Island on an intermittent basis, which is equal to our average volume of net littoral drift. When operating at full capacity during storms, it is designed to accomodate this volume in one week. Likewise, active sand transport around the Point Danger headland only occurs during major storm events, which may span several years. During extreme cyclones we have witnessed 1,000,000 m^3 sweep around Point Danger at one time.

The unpredictable nature of these threshold occurrences renders a deterministic approach to modelling or forecasting sediment transport utterly useless. Even if we could accurately predict transport under a given set of wave and wind conditions, it is still our experience that two "identical" storms having the same wave heights and wind speeds always produce different effects on our beaches. Every storm is unique, and so we must also expect our beach processes to respond differently in accordance. And they do so in a manner which we do not understand and cannot predict.

It is a common procedure, both in the literature and in engineering application, to evaluate volumetric gains and losses on a beach by measuring beach and nearshore profiles. We frequently do not even know how or where the sand is moving, but these analyses are performed nonetheless. Every geologist learned how to measure beach profiles in Geology 101, probably still puzzled about how beaches were even remotely connected to geology. The appeal lies in the simplicity and the visual impact of profiles.

On the Gold Coast it may be possible to utilize profiles of our subaerial beach and dunes to estimate eolian transport on our beaches. We are fortunate to meet two important criteria which make this possible: 1) we have a beach in dynamic equilibrium that is not experiencing long term erosion, and 2) we have black heavy mineral seams in our dunes that serve as natural "marker beds" from which to measure dune accretion. The mineral seams are left at the top of the storm swash beach, and buried as the dunes are rebuilt in fine weather.

On a steadily retreating beach there is usually a permanent scarp developed in the dune which would make this method more difficult to employ. From our daily monitoring and experience we know that dune scarps on the Gold Coast almost always recover between storm seasons. There is a well developed primary dune which has been stable over time and which is seldom subject to erosion. During long periods of fine weather which occur from late autumn to early spring, a small foredune is usually developed in front of the primary dune. The foredune is often eroded during the summer storm season.

We can gain a crude estimate of the net annual eolian budget by calculating the volume of sand in the foredune which has accumulated above the previous year's heavy mineral seam. Although we have not yet tested this method it offers some apparent benefits over other methods. First, a profile provides a continuous surface from which real sand volumes can be calculated. There is no need to extrapolate sediment trap data through space or time. The data measurements stand independent of the variables which often hinder aeolian transport studies. We should still like to monitor such variables, as we discussed earlier, which affect aeolian transport. We cannot understand the transport processes without monitoring the variables, but it is somewhat earier to interpret the relative importance of the variables if we can backtrack from an answer that we already have in hand.

There are also some disadvantages to this method. Particularly, we cannot measure gross transport rates over short time periods. On the Gold Coast this still interests us because we have several "hot spots" where wind-swept sand is periodically removed from roads and parking areas. We are not sure why we have higher eolian transport rates on some of our beaches, but it is a major problem at times. We also cannot measure aeolian transport that does not settle into the dunes. Any transport that occurs parallel to the beach or offshore, or that is deposited beyond the dunes (such as happens during storms) cannot be accounted for. A third problem is separating swash deposition from wind deposition on the beach. During any period of beach progradation, swash deposits will be preserved beneath subsequent aeolian deposition. Simple profiles cannot distinguish between the two.

Despite the various drawbacks, the usefullness of the profile method lies in calculating sediment budgets. The volume of sand which accumulates in the dunes represents the total volume completely removed from the littoral system. Regardless of what the real gross transport rate is, the net loss of sediment to aeolian processes will be recorded in the dunes.

Our foredune at Station 2a, our daily monitoring site, is generally 25 m wide and 2 m high, so it can be assumed that the minimum rate of net aeolian transport would be no less than 25 $m^3/m/yr$. GOLDSMITH (1989) quotes net transport rates of a similar magnitude on beaches in South Africa and Oregon. This translates to 35,000 m^3/yr over 1.4 km, which is our average distance of littoral transport in a year. So in our budget, 7% of the sediment is removed from the littoral system by aeolian processes, although much of it will be reclaimed during storms. It is our experience that over time, the dunes have neither gained nor lost a significant volume, but have been dynamically stable. Thus, we feel that on the Gold Coast, this method could serve a useful purpose. By no means do we suggest that it should work anywhere else.

The method may appear an awful lot like a quick and dirty back-of-the-envelope calculation. It is precisely because we do not receive confusing signals from multiple variables that it appears that simplistic. Yet through all our experience, the most simplistic models have anways been of greatest value to us. Let us not forget the degree of uncertainty inherent in measuring coastal processes. As scientists and engineers, we tend to hold ourselves to the same standards of precision as the laboratory chemist who can detect a molecule of PCB at a concentration of one part per billion. In our field this is simply not possible. Rather, we need to acknowledge the variability as real, and maintain a proper perspective on the scale of the overall system we study. In the world of sediment transport an error of 10% should be regarded as remarkably accurate. After all, on our beaches we have seen deviations from the average by greater than 100%. In this sense sediment transport is truly indeterminate.

CONCLUSION

In this discussion, we have no conclusions, only a terminal statement. We greatly admire the "Aeolus Project" and the work that all the authors, and their co-workers have put into this basic research project, so *our* conclusion is that we agree with *their* conclusions and perhaps that they may find our additional data of some interest perhaps.

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