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UNIVERSITAT DE VALÈNCIA
2005

PREDICTING MAXIMUM AND MINIMUM AEOLIAN SAND TRANSPORT RATES TO PROVIDE A BASIS FOR ASSESSING MANAGEMENT ACTIONS FOR BEACHES AND DUNES

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Abstract
This paper presents simple methodologies for predicting rates of aeolian sand transport rates on beaches for the assessment of alternative management actions. The equations of Bagnold (1936), Kawamura (1951), and Zingg (1953) are used to predict maximum, moderate, and minimum rates of sand movement under dry conditions. The Belly (1964) and Hotta et al. (1984) equations are used to correct for wet conditions. Examples of data sources are described, and a protocol for using the methodology is detailed using data for a beach at Wildwood, New Jersey, USA. It is shown that there is reasonable agreement between predicted and observed transport values for the relatively uncomplicated conditions on a flat beach. More complex issues associated with transport in dunes and with other complicating factors presented. Potential applications for dune management and resource protection are discussed.
Key words: *dune management, aeolian models, sediment budget, wind blown sand.*

Resumen
Este artículo presenta metodologías para predecir las tasas de transporte eólico en las playas capaces de proporcionar alternativas a las acciones de gestión. Las ecuaciones de Bagnold (1936), Kawamura (1951) y Zingg (1953) se utilizan para pronosticar las tasas de movimiento de arena máximas, moderadas y mínimas en condiciones secas. Las ecuaciones de Belly (1964) y Hotta et al. (1984) se usan como correctoras para condiciones húmedas. Se describen ejemplos de fuentes de datos y se detalla un protocolo para utilizar la metodología, usando los datos de una playa en Wildwood, New Jersey, USA. Se demuestra que hay una razonable correspondencia entre los valores de transporte pronosticados y observados en playas llanas con condiciones relativamente no complicadas. También se presentan resultados más complejos asociados con el transporte en dunas y con otros factores más complicados. Finalmente se discute sobre su potencial aplicación para la gestión de las dunas y como recurso de protección.
Palabras clave: *gestión de dunas, modelos eólicos, presupuesto sedimentario, transporte de arena.*

Resum
Aquest article presenta metodologies per a predir les taxes de transport eòlic a les platges, qüestió molt important a l'hora de proporcionar alternatives de gestió. Les equacions de Bagnold (1936), Kawamura (1951) i Zingg (1953) s'utilitzen per a pronosticar les taxes màximes, moderades i mínimes de moviment de l'arena en condicions seques. Les equacions de Belly (1964) i Hotta et al. (1984) s'usen com a correctores per a condicions humides. A més, es descriuen exemples de fonts de dades i es detalla un protocol per a aplicar la metodologia, utilitzant les dades d'una platja en Wilwood, New Jersey, USA. Els resultats mostren que hi ha una correspondència raonable entre els valors de transport pronosticats i els observats en platges planes amb condicions poc complexes. També es presenten resultats més elaborats sobre el transport en dunes i altres factors més complicats. Finalment, es discuteix sobre el seu potencial d'aplicació en la gestió de dunes i en la seua protecció.
Paraules clau: *gestió de dunes, models eòlics, pressupost sedimentari, transport d'arena.*

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Introduction

COASTAL managers and planners are often required to predict the evolution and fate of coastal landforms as part of the process of developing strategic plans or environmental policy (e.g., Van Koningsveld *et al.*, 2002). Coastal landforms are inherently dynamic but humans tend to prefer stability, requiring knowledge of natural processes and ways of controlling these processes to achieve human goals without adversely affecting natural values. Knowledge of the processes and rates of landform change is important in determining the optimum locations for human habitation and use and ways of minimizing hazards while ensuring sustainability of natural habitats.

One of the most difficult locations to manage in the coastal zone is the region where the backbeach/dune contact occurs under natural conditions. This is a location of complex and dynamic interaction between wave uprush, aeolian transport and vegetation growth. In many developed areas, these natural interactions, and the landforms characteristic of them, are altered by humans by constructing shorefront buildings and protecting them with shore protection structures or grading dunes to create wider beaches for recreation. The resulting recreation platforms are often raked free of vegetation and litter, altering nutrient pathways, diminishing the potential for biodiversity and increasing the likelihood of damage to landward structures by storm wave overwash and wind-blown sand. As a result, coastal managers have called attention to the need to preserve dunes in locations undergoing human development and restore protective dunes in locations that are already developed. Many of these dunes are artificial landforms, constructed using earth-moving equipment and lacking the internal structure, outward appearance, dynamism, biodiversity, nutrient status, size, and evolutionary trajectories of natural aeolian landforms (Nordstrom, 2000). A key to effective management is determining to what extent natural aeolian transfers can be favored to create dunes and allow them to evolve into functioning habitats. Data are also required to make permit decisions on human adjustments that could increase rates of aeolian transport, such as destroying stabilizing vegetation or creating gaps in dunes to provide easy access to the beach or views of the sea from buildings and promenades.

The increasing use of beach nourishment to create wider beaches to provide for shore protection and recreational use creates new possibilities for the development of natural dunes and dune habitat, but it also creates potential problems. Several studies have called attention to the differences in rates of aeolian transport due to beach nourishment (Draga, 1983; van der Wal, 1998) and the opportunities lost in failing to allow natural processes to reshape the beach sediment into naturally functioning landforms (Nordstrom *et al.*, 2000). Knowledge of the rates of aeolian transport on nourished beaches is important to anticipate changes to the sediment budget caused by 1) sand losses to landward during onshore winds and to the sea during offshore winds; 2) the rate of growth of dunes if sand fences or vegetation plantings are used to trap sand; and 3) the time it takes to achieve target dune volumes. Once sand has been transported beyond the backshore into the dune environment, prediction of aeolian transport is substantially more difficult.

The purpose of this paper is to present simple methodologies for predicting likely rates of aeolian sand transport so that environmental conditions can be estimated and decisions can be made on alternative management actions, and to provide some cautionary notes on the estimation of sand transport in dune environments so that better, or at least more informed decisions can be made about aeolian sediment transport in more complex dune environments.

The operation of natural processes and the geomorphic responses to these processes are difficult to predict, especially over time and space scales of interest to managers (years to decades, and decameters to kilometers). Many sediment budget models rely on static data sources (such as maps and aerial photographs) to estimate volumetric changes in the sediment system. This historical approach frequently proves inappropriate for systems where the environmental controls – sets of processes and process rates – are changing, such as when dunes are leveled or beaches are nourished. Under such conditions, it would be valuable to employ process-based sediment budgets that are based on transport rate models.

Opportunities and constraints of transport models

The last several decades have been marked by the development of many sediment transport models, with at least some process information, to predict landform change. Transport based models that use the sediment budget concept have become especially promising tools for anticipating and planning for change in aeolian, coastal, and fluvial environments (e.g., Kostic and Parker, 2003; Lancaster and Bras, 2002). A vast array of models now can be used to allow managers to address the landform (and other) impacts of sediment transport, but the ambiguity of model performance clouds their use. Part of the ambiguity stems from the variety of models for each type of sedimentary environment; part stems from statistical uncertainty in the parameterizations used in the model and in the data used to power the models. For some sets of landforms, the difficulty in deterministic modeling has led to the use of probabilistic simulation models that are able to mimic natural forms, but not predict them (e.g., Baas, 2003). These models provide relatively little information of immediate practical utility to managers, although they can lend insight to the identification of critical process relationships and thus be of use to scientists operating in a basic research mode. For a given environmental type, application of a number of the pertinent models results in a range of predictions, and this range can be quite large. Many models require the kind of data or levels of expertise not available to local and regional managers. Selection of any particular model as the basis for predicting landform change is therefore often frustrating.

Although exact prediction is not possible, it is important to establish upper and lower limits for aeolian transport to place current conditions in perspective and provide a reasonable approximation of future changes. We outline a general approach to prediction based on obtaining reasonable transport rates for the relatively simple case of sand transport off the beach and backshore, and show how the results can be relevant to local and regional environmental applications. We use a series of models for the major components of the aeolian system to derive protocols for establishing maximum and minimum transport rate estimates. The protocols are developed with the presumption that minimal site and time specific data are available to the manager from generic sources.

We address the dichotomous cases of wind blown sand as a resource and as a hazard. In terms of resource potential, we consider the importance of blowing sand for the development of coastal dune systems, either as shore protection features or as habitat. For dune growth estimates, a conservative approach is to estimate the minimum likely sand-transport rate, thus, the minimum likely dune growth rate. In the case of blowing sand as a hazard due to the inundation of roads, buildings and private lots and loss of beach volume leading to beach erosion (Sherman and Nordstrom, 1994), a conservative approach is to estimate the maximum likely sand-transport rate.

Many of the aeolian sand transport models that can be used in a management context are reviewed in Sherman *et al.* (1998). The models most commonly used by scientists are those of Bagnold (1936), O'Brien and Rindlaub (1936), Kawamura (1951), Zingg (1953), Kadib (1964), Hsu (1973), and Lettau and Lettau (1977). All of these models require data describing only the wind and sediment systems, and most of the data for these models can be gathered quickly from readily available published sources. Differences between these models include the way they relate wind speed or shear velocity (a variable that represents wind speed and surface friction) to the transport rate and the way sediment size is treated. As a result, each model yields different predictions. These models ignore complicating local conditions, such as the effects of surface slope and moisture content, topographic steering and acceleration, vegetation cover, height and density, that are important in coastal environments.

The use of different models with different combinations of slope and moisture corrections can result in predictions that vary by several orders of magnitude, with little indication of what a true value might be. A manager who chooses to apply a specific model must do so with the understanding that there will be uncertainties in its application, which may be a source of frustration. The complex nature of sediment transport systems always will inhibit our ability to adequately specify all of the interactions affecting the transport process. The transport environment becomes even more complicated when we attempt to predict sediment transport within dune systems.

Another problem is that managers may approach the use of quantitative models for aeolian transport with trepidation because they are not familiar with the mathematical basis for formulation of equations or uncertainties regarding the relationship between these equations and real-world situations. Existing models of sediment transport, when used in non-ideal environments, measure potential rather than active transport (Fryberger and Dean, 1979; Sherman, 1990). The complexity of natural beaches makes it difficult to apply these models without an appreciation of the limitations imposed by local conditions (Table 1) or the assumptions underlying the models (Nickling and Davidson-Arnott, 1990; Bauer *et al.*, 1996), but use of these models is valid to assess potential effects of future ad-

Natural factors	Human factors
Wind speed Expressed as shear velocity, is a primary determinant of quantity of sediment transported.	*Buildings* Change speed, direction, velocity profile of wind and locations of accretion/scour (Nordstrom, 2000). Eliminate source areas.
Wind direction Determines whether transport is onshore, offshore or alongshore. Determines effective width of beach source (Bauer and Davidson-Arnott, 2002).	*Sand fences* Change velocity profile; create obstacles and trap sand (Hotta *et al.*, 1987). Divide beach into smaller transport systems.
Air temperature and humidity Determines air density, efficiency of transport and velocity profile (Sherman and Hotta, 1990).	*Protection structures* Create obstacles to transport; separate sediment source areas from sinks.
Beach width Determines effectiveness of other surface variables restricting transport (Jackson and Cooper, 1999).	*Beach nourishment* Changes beach source width and quantity of sediment transported (Draga, 1983). Changes sediment density, size and sorting (van der Wal, 1998).
Storm wrack (litter lines) Traps sand, initiates foredunes (Nordstrom *et al.*, 2000); divides beach into smaller source areas.	*Surface shaping (grading)* Creates or eliminates topographic obstacles and changes width of source area (Nordstrom, 2000).
Slope Increases (downslope) or decreases (upslope) transport rates (Bagnold, 1973).	*Beach cleaning (raking)* Eliminates effectiveness of wrack and incipient surface vegetation (Nordstrom, 2000). Exposes finer grain sizes under surface gravels to deflation.
Sediment density, size and sorting Changes threshold velocity, likelihood of particle entrainment and momentum of moving sediment.	*Planting vegetation* Changes width of source area, velocity profile, threshold for sediment entrainment. Creates barrier to transport and new dune topography.
Moisture content of sediments Alters transport potential of surface sediments (Hotta *et al.*, 1984; Jackson and Nordstrom, 1997).	*Removing vegetation* Converts former sinks to sources (Swart and Reyneke, 1988). Increases likelihood of entrainment, transport and landform mobility (van Boxel *et al.*, 1997).
Salt crusts Make surface sediments resistant to entrainment (Nickling and Ecclestone, 1981).	
Vegetation Traps sand, builds up dunes, and changes velocity profile (Hesp, 1989); reduces beach source width.	

Table 1. Factors affecting prediction and application of rates of aeolian transport.

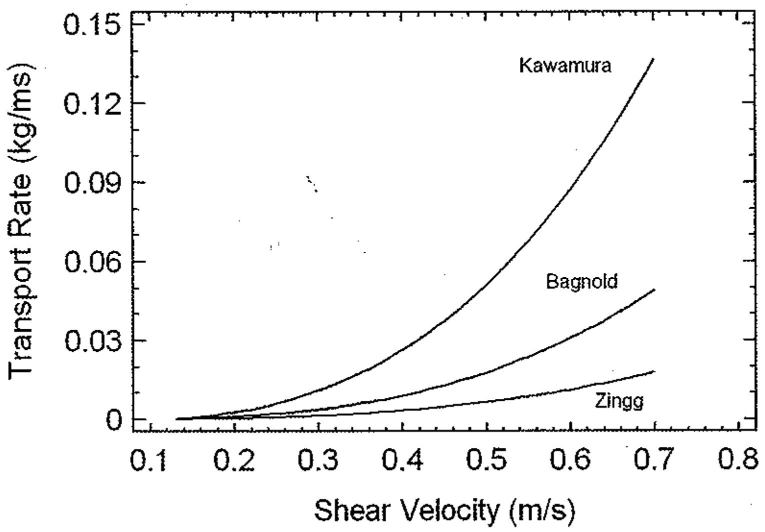

Figure 1. The range of transport rates associated with the Kawamura (1951), Zingg (1953) and Bagnold (1936) equations, as calculated for a 0.1 mm grain size.

justments, where real data are unobtainable. Despite the many conceptual and theoretical hurdles facing scientists, there is still a requirement to employ viable predictive models of utility to coastal managers.

Theoretical basis

Aeolian sand transport on beaches is a function of wind speed (usually expressed as shear velocity), grain size and density of surface sediments, grain size distribution (sorting in most formulations), moisture content of surface sediments, presence of cohesive agents including salt (Nickling and Ecclestone, 1981), microbial mats and algae (Pluis and de Winder, 1990), surface slope (Bagnold, 1973), and vegetation (Hesp, 1989). On human-altered coasts, transport is also influenced by human structures and management actions (Table 1). The significance of these variables to aeolian transport and landform evolution is reviewed in Horikawa (1988), Sherman and Hotta (1990), Nickling and Davidson-Arnott (1990), Pye and Tsoar (1990), and Nordstrom (2000). On most beaches, the primary controls are wind speed, grain size, and sediment moisture content, and we emphasize those variables in our protocol. Other factors that have the potential to influence aeolian transport on beaches can usually be ignored. For example, vegetation on beaches is typically unimportant because erosion/deposition cycles, the operation of storm waves and high spring tides, and salt stress, limit the growth of vegetation to locations above the storm and high spring tide line (Hesp, 2002). Slope affects are relatively minor for angles less than about 10 degrees, and so should be minimal on sandy beach and berm environments because gradients on those surfaces are usually lower than that. For example, using Bagnold's (1973) equation, an uphill gradient of 10 degrees would decrease transport rates by about 8%. For situations where transport is into or out of dunes, the use of a slope correction such as Bagnold's (1973) should be considered.

The most useful procedures for predicting potential transport rates would be those that balance accuracy and ease of utilization and allow determination of reasonable maximum and minimum rates of transport and that place the effects of change within an envelope of plausibility. Many studies evaluate transport in terms of correspondence between actual and calculated rates, such as those of Gares (1998), Sarre (1989), Arens (1994), Davidson-Arnott and Law (1996) and Gomes *et al.* (2002). In their evaluation of transport models, Sherman *et al.* (1998) assessed the theoretical performance of five models to show that the Kawamura (1951) equation usually predicts the greatest transport rates, the Zingg (1953) equation the least, and the Bagnold (1936) equation about the average of the two extremes (Figure 1). The Kawamura equation predicts transport rates that are about 700% - 800% greater than those obtained with the Zingg equation.

The Bagnold (1936) equation is one of the most commonly used models. Sand transport rate (q) is:

$$q = C\sqrt{\frac{d}{D}}\frac{\rho}{g}u_*^{3} \qquad (1)$$

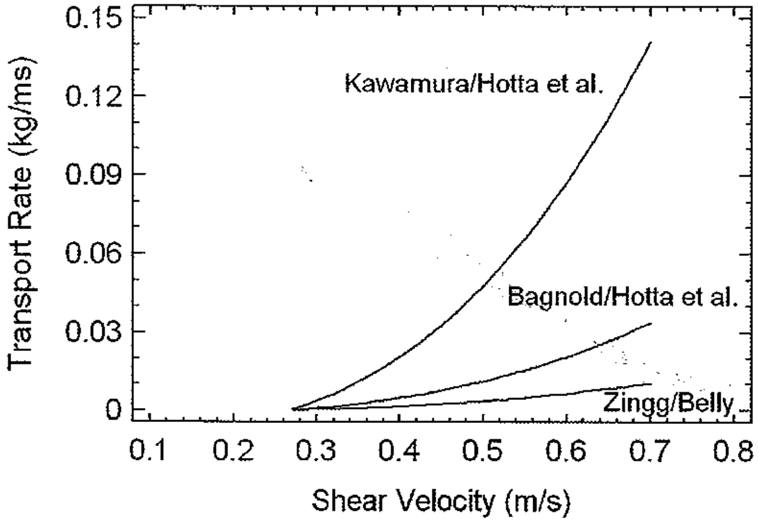

Figure 2. The effects on transport rates associated with 4% sediment moisture content, combining the Belly (1964) and Hotta *et al.* (1984) corrections with the Kawamura (1951) Zingg (1953) and Bagnold (1936) equations, and using a 0.1 mm grain size.

transport rates, the Kawamura transport equation should be used with the Hotta et al. moisture content correction. For the smallest likely transport rates, the Zingg and Belly equations should be used. The Bagnold and Hotta *et al.* equations can be used to obtain intermediate results. The concept of intermediate results does not imply that the values obtained are closer to predicting real conditions than those obtained from either of the extremes, but we can say that the maximum possible error is smallest using the intermediate predictions. Applying the moisture correction increases the range of predicted transport rates. Figure 2 depicts the effects of using a 4% moisture correction with the transport data used in Figure 1. Transport does not begin until the shear velocity exceeds about 0.27 ms^{-1}, as opposed to about 0.11 ms^{-1} under dry conditions, and transport rates under moist conditions are generally lower than under dry conditions. At faster shear velocities (greater than about 0.6 ms^{-1}), the Kawamura equation with the moisture correction predicts slightly increased transport rates relative to dry conditions. There are some complications associated with using the Belly or Hotta *et al.* corrections with the Bagnold or Zingg equations, as discussed below.

Data sources

Many publicly available data sets can be used for the methods we present. In the United States, wind data are available from the National Oceanic and Atmospheric Administration's National Climate Data Center. For many coastal weather station, wind direction and speed data are available in hourly, 3-hourly or daily formats (http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.htm). There is extensive coverage for coastal areas in the U.S., except where populations are sparse. In Spain, wind data are available in a slightly different format from the Instituto Nacional de Meteorología (http://www.inm.es). These data are organized according to monthly probabilities of occurrence, broken down by direction in 30° increments, and speed in 5 knot increments. In the Netherlands, hourly wind data are available for 70 stations from the Royal Netherlands Meteorological Institute (http://www.knmi.nl/samenw/hydra/meta_data/time_series.htm). For Australia, averages by month, for 9 am and 3 pm wind speeds for hundreds of locations, are available from the Commonwealth Bureau of Meteorology (http://www.bom.gov.au/climate/averages). Similar data are available for many other countries, and much of those data can be obtained at no cost from national agency web sites similar to those described above.

An estimate of shoreline orientation for the site of interest must be used to relate wind data to directions of potential transport for an understanding of local transport conditions (e.g., Bauer and Davidson-Arnott, 2002). For example, a northwest wind direction measured at JFK International Airport in New York will indicate onshore wind for the north shore of Long Island, offshore wind for the south shore, and alongshore winds for parts of the New Jersey coast. In Spain, a northwest wind measured at the *Aeropuerto de Murcia/San Javier* would indicate onshore winds for the where $C = 1.8$ for normal dune sands, d is sand grain diameter in mm, D is a reference grain size of 0.25 mm, ρ is air density (kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), and u_* is shear velocity (in m s^{-1}). In Bagnold's model, his use of shear velocity is only valid when sand is blowing.

The Kawamura (1951) model has a derivation similar to that used by Bagnold, but it uses an explicit threshold shear velocity term, u_{*_t}, to indicate conditions at the initiation of grain motion:

$$q = C\frac{\rho}{g}(u_* - u_{*_t})(u_* + u_{*_t})^2 \qquad (2)$$

where $C = 2.78$, and u_{*_t} can be found using Bagnold's (1936) estimate:

$$u_{*_t} = A\sqrt{gd(\frac{\rho_s \quad \rho}{\rho})} \qquad (3)$$

where A is an empirical constant of proportionality with a value of 0.085 during saltation, and ρ_s is sediment density (in kg m^{-3}).

Zingg's (1953) transport model is similar to Bagnold's, but it is slightly more sensitive to the effects of grain size:

$$q = C(\frac{d}{D})^{\frac{3}{4}}\frac{\rho}{g}u_*^3 \qquad (4)$$

where $C = 0.83$.

The use any of these models requires only basic information concerning local wind conditions and sediment size. Wind data is typically available as wind speed rather than shear velocity. The conversion can be done using the law of the wall that describes the normal behavior of a wind profile:

$$u_z = \frac{u_*}{\kappa}\ln(\frac{z}{z_0}) \qquad (5)$$

where u_z is the wind speed u at an elevation z above the surface, κ is von Karman's constant that describes one aspect of turbulent mixing and which has a value of 0.4, and z_0 is the surface roughness length (a measure of "ruggedness" of a surface). The simplest way to estimate roughness length uses grain size, $z_0 = 2d/30$ (typically of the order of 0.01 – 0.1 mm) although this method yields a minimum value for z_0, and thus, a minimum estimate for u_*.

The major impact of moisture within the spaces between sand grains is to increase the shear velocity necessary to place the grains in motion. There have been many attempts to model this effect, with widely differing results (Namikas and Sherman, 1995). Cornelius and Gabriels (2003) found that Belly's (1964) model tended to over-predict the effects of moisture on u_{*_t}. The Hotta *et al.* (1984) model yielded the lowest predictions, but these predictions matched their actual measurements using initial moisture content. These two models are used here.

Belly (1964) developed his model from a wind tunnel experiment:

$$u_{*_{tw}} = u_{*_t}(1.8 + 0.6\log_{10} w) \qquad (6)$$

where $u_{*_{tw}}$ is the moisture-influenced threshold shear velocity, and w is the per cent moisture content by weight (note that the equation is reported incorrectly in Cornelius and Gabriels (2003).

The Hotta *et al.* (1984) model is also based on an analysis of wind tunnel data. They found:

$$u_{*_{tw}} = u_{*_t} + 7.5w \qquad (7)$$

Beyond the data requirements listed above, the use of either of these models requires only that a value for the surface moisture content, w, be specified.

Use of the moisture correction with the Kawamura equation is straightforward. The value for $u_{*_{tw}}$ obtained from either the Hotta *et al.* or Belly equation is substituted for u_{*_t}. The Bagnold and Zingg equations do not use an explicit term for threshold shear velocity; therefore the moisture correction is more complicated. The effect of increased moisture content is to decrease sand transport. This can be accomplished in the Bagnold and Zingg equations by changing the reference grain size, D. To do this, the chosen moisture correction is used to obtain a value for $u_{*_{tw}}$. This value is substituted for u_{*_t} in the threshold shear velocity equation, and that equation is then solved for a "moisture equivalent" grain size, D_w. The latter value is then used instead of D in solving the Bagnold or Zingg equations. For example, for $D = 0.1$ mm, and $w = 4\%$, and using the Belly equation, $D_w = 0.47$ mm.

If the intent is to estimate the largest likely sand dunes in the *Parque Regional Salinas y Arenales de San Pedro del Pinatar*, but offshore for the beaches and dunes in the *Parque Regional de Calblanque*. Numerous map resources are available for any coastal region, and measurements to acceptable limits of accuracy (<5 degrees) are easily obtained. USGS topographical maps, similar products from other nations, or many web-based maps, are adequate for this purpose.

Grain size data can be more difficult to obtain for a particular coastal reach, and there is usually no single source for data with wide area coverage for beaches or dunes. In the United States, grain size and other sediment data are commonly available in reports of beach nourishment or restoration projects or in regional or local reports compiled by the US Army Corps of Engineers (e.g., USACOE, 1987). Much grain size information is available in the scientific literature, and can be obtained through site-specific literature searches (e.g., Anfuso *et al.*, 2003 for SW Spain), or from regional studies (e.g., Sanjaume, 1985). Some agencies also maintain a local grain size data base. For example, the U.S. Geological Survey has compiled this kind of data for South Carolina as part of a pilot project (http://coastal.er.usgs.gov/scpilot-assessment/scarolina).

Obtaining generic sediment moisture content data is impossible, because the moisture conditions changes rapidly through time and space. In order to use moisture information, it is more prudent for the manager to have an idea of the potential range of moisture content values. On any beach, the maximum possible moisture content, by percent weight, is about 25%. A minimal moisture content for a "dry" beach berm, with onshore winds capable of moving sand, is about 1%. Deflated higher reaches of a foreshore that have not been subject to recent tidal inundation or substantial rainfall may vary from about 2.5% to 4%. A value of 4% (similar to the cutoff indicated by Belly, 1964, or Hotta *et al.*, 1984) could be used.

Application

The way the procedures identified above can be applied at a local level are demonstrated using Wildwood, New Jersey as a test case. Wildwood is a resort community located near the north end of a barrier island. The subaerial beach (berm) is approximately 200 m wide with a 0.06 deg slope, and lacks vegetation because it is raked to provide a wide recreational platform during the summer. Factors such as vegetation, width of the beach as a sand source, or slope that influence the transport rate do not need to be considered in this application. Prevailing winds are from the west; northwest winds blow with the greatest velocity; but high-speed winds are also associated with northeast storms that approach onshore. Knowledge of the range of onshore sediment transport is important for controlling sand inundation to private property fronting the boardwalk or the rate at which dunes could form if the municipality decided to build them. The following procedure identifies the steps required to determine the values for onshore sediment transport using publicly available sources of information. The month selected is March, because onshore winds are frequent then. The estimates are calculated for 1994 so they can be meaningfully compared to data gathered in the field on 13 March 1994 by Jackson and Nordstrom (1999).

The first step is to estimate the threshold shear velocity term, u_{*t}, using Equation (3), for dry sand, and for moisture contents of 1% and 4% using Equations (6) and (7) from the following data:

d = 0.16 mm
x_s = 2,650 kg/m3
g = 9.8 m/s2
x = 1.2 kg/m3
A = 0.085

The threshold shear velocity for dry sand is 0.16 m s^{-1}. For sediments with a moisture content of 1%, the threshold shear velocity rises to 0.28 m s^{-1}. using Equation (6) and 0.22 m s^{-1} using Equation (7). For sediments with a moisture content of 4%, the respective threshold shear velocities are 0.34 m s^{-1} and 0.46 m s^{-1}.

The second step is to gather applicable wind speed data. For Wildwood, local climatological data (NOAA 1994) from the nearby airport in Atlantic City is used. Maximum and minimum daily onshore winds are derived from the 3-hr means and the fastest 1-min onshore wind speed. Wind direction is determined from the resultant direction of the winds (obtained from the Local Climatological Data) relative to the orientation of the shoreline (obtained from a USGS topographic sheet or a bathymetric chart). The orientation of the Wildwood shoreline reach is northeast-southwest with an azimuth of 66‰. All daily wind speed values with resultant wind directions from 67‰ to 245‰ are used to identify the maximum and minimum daily fastest

1-minute wind speeds. Table 2 presents the maximum and minimum onshore winds during March 1994.

The third step is to estimate the shear velocities, which are calculated for each day during the month of March 1994 using the daily onshore 3-hr maximum and fastest 1-minute onshore wind speed using Equation 5, with z = 19.5 m and z_0 = 0.00001 m. The height of the tower at Atlantic City is 19.5 m. The roughness length is $z_0 = 2d/30$ (d= 0.00016 m). Onshore winds occurred 23 of 31 days when the 3-hr wind speeds are used and 14 of 31 days when the fastest 1-minute speed is used. There is little difference in most of the matched pairs of maximum 3-hr and fastest 1-min wind speeds (Table 2). Shear velocities are below the threshold shear velocity for dry sand when wind speeds are below 4.2 m s^{-1}.

The fourth step is to estimate the potential rates of sediment transport. These rates are calculated for both the 3-hr wind speed and the fastest 1-min wind speed for each day when winds were onshore. For this exercise, the models of Bagnold (Equation 1), Kawamura (Equation 2) and Zingg (Equation 4) are used to calculate the transport rate assuming dry sand conditions to obtain a maximum transport estimate (Table 3) and moisture conditions of 4% to obtain minimum transport estimates. The latter transport values were derived by first determining the threshold velocity at 4% moisture content using Equations (6) and (7). For Equation (6), u_{*tw} = 0.34 m s^{-1}; for Equation (7) u_{*tw} = 0.46 m s^{-1}. These values were used in Equation (3) to estimate the revised grain size (*d*) for the new threshold velocities. The revised grain size is 0.747 mm when u_{*t} = 0.34 ms^{-1} and 1.34 mm when u_{*t} = 0.46 ms^{-1}. The grain diameter of 1.34 mm was used in Equation (1) to represent the reference grain size (*D*), and D = 0.747 mm was used in Equation (4).

The minimum and maximum rates of transport for surface sediment moisture conditions of <1% and 4% (Table 3) reveal that there are nine days when the calculated shear velocities were lower than the threshold shear velocity yielding no sediment transport when moisture contents are <1%. The highest rate of transport predicted by all three equations is on 2 March when winds blew nearly shore-parallel. There is no equivalent value representing the fastest 1-min wind on 2 March because the wind blew slightly offshore at that time. The range in potential transport, when moisture content is <1%, is 56.7 $kgm^{-1}s^{-1}$ (Kawamura equation) to 10.5 $kgm^{-1}s^{-1}$ (Zingg equation). When 4% is used for the sediment moisture content, all of the models predict that there would be no sand movement – clearly a minimum estimate.

Day	*Fastest onshore wind speed (m s^{-1})*		*u_* (m s^{-1})*	
	3-hr	*1-min*	*3-hr*	*1-min*
1	4.12		0.11	0.11
2	12.35	5.81	0.34	0.16
6	4.63	8.94	0.13	0.25
7	6.18		0.17	
8	3.60	8.05	0.10	0.22
9	6.69	6.26	0.19	0.17
10	7.72	7.15	0.21	0.20
12	6.18	5.81	0.17	0.16
13	7.21	7.60	0.20	0.21
14	5.66	7.15	0.16	0.20
15	7.72	7.15	0.21	0.20
16	3.09		0.09	
18	7.21	6.26	0.20	0.17
21	4.12	7.60	0.11	0.21
22	4.12	11.18	0.11	0.31
23	5.66		0.16	
24	3.09	6.26	0.09	0.17
25	5.66		0.16	
26	9.27		0.26	
27	2.06		0.06	
28	3.60		0.10	
29	3.60		0.10	
30	6.18		0.17	
31				

Table 2. Daily onshore wind speeds and shear velocities for March 1994 using data from the weather station at Atlantic City, New Jersey, USA (NOAA, 1994).

Data from 13 March (Tables 2 and 3) can be compared to field data gathered at Wildwood by Jackson and Nordstrom (1999) to assess the ability of the approach outlined above to reflect actual conditions on the beach. Shear velocity, derived from the maximum 10-min average wind speed measured in the field at an elevation of 6 m and a surface roughness calculated from the wind velocity profile on the backshore, was 0.30 ms^{-1}. Transport rate determined from the quantity of sand trapped on the backshore during this 10-min interval was 16.02 $kgm^{-1}s^{-1}$ and is comparable to, although larger than, the calculated range in transport derived from the Kawamura and Zingg equations using remote data from Atlantic City (Table 3).

Day	*Bagnold*				*Kawamura*				*Zingg*			
	3-hr		*1-min*		*3-hr*		*1-min*		*3-hr*		*1-min*	
	dry	*w=4%*	*dry*	*w=4%*	*dry*	*w=4%*	*dry*	*w=4%*	*dry*	*w=4%*	*dry*	*w=4%*
1	—	—	—	—	—	—	—	—	—	—	—	—
2	25.5	—	—	—	56.7	—		—	10.5	—		—
6	—	—	9.7	—	—	—	18.2	—	—	—	4.0	—
7	3.2	—			1.8	—			1.3	—		
8	—	—	7.1	—	—	—	11.6	—	0.3	—	2.9	—
9	4.1	—	3.3	—	4.0	—	2.1	—	1.7	—	1.4	—
10	6.2	—	5.0	—	9.5	—	6.3	—	2.6	—	2.0	—
12	3.2	—	—	—	1.8	—	8.8	—	1.3	—	—	—
13	5.1	—	5.9	—	6.6	—	6.3	—	2.1	—	2.5	—
14	—	—	5.0	—	—	—	6.3	—	2.6	—	2.0	—
15	6.2	—	5.0	—	9.5	—		—	—	—	2.0	—
16	—	—			—	—	2.1		2.1	—		
18	5.1	—	3.3	—	6.6	—	8.8	—	—	—	1.4	—
21	—	—	5.9	—	—	—	40.8	—	—	—	2.5	—
22	—	—	18.9	—	—	—		—	—	—	7.8	—
23	—	—			—	—	2.1		—	—		
24	—	—	3.3	—	—	—		—	—	—	1.4	—
25	—	—			—	—			4.4	—		
26	10.8	—			20.9	—			—	—		
27	—	—			—	—			—	—		
28	—	—			—	—			—	—		
29	—	—			—	—			1.3	—		
30	3.2	—			1.8	—				—		
31												

— Shear velocity is equal to, or less than the threshold for sediment entrainment.

Table 3. Potential transport rates (KGM^{-1} hr^{-1}) for March 1994 using data from the weather station at Atlantic City, New Jersey, USA (NOAA, 1994).

A similar approach may be used to estimate sediment transport in coastal dune environments but complicating factors become significant in reducing or enhancing sand transport. Plant cover, height, density, distribution and species will all affect the rate of transport and deposition. So too will dune height, roughness, and the degree of topographic complexity. Calculations of sand transport for different directions over a given period can be useful for rough determinations of just how much sand might potentially be moved to a location from a given direction. These estimates are commonly reported through the use of a sand rose (fig. 3) – analogous to a wind rose. The numerous problems associated with models for predicting transport in complex aeolian environments are outlined below and are provided not to dissuade the manager from utilizing the models, but rather to place limits on expectations of accuracy of estimates.

If the wind is blowing over a foredune, the higher the dune, the greater the acceleration in wind speed up the slope (Arens *et al.*, 2002). If wind approach is oblique, flow is topographically steered to cross the foredune approximately normal to the crestline (Svasek and Terwindt, 1974; Rasmussen, 1989). Maximum deflection of the wind occurs when the approach angle is between 30° and 60°. Thus, estimates of potential sand transport for a given direction may also be in error when applied to transport across a

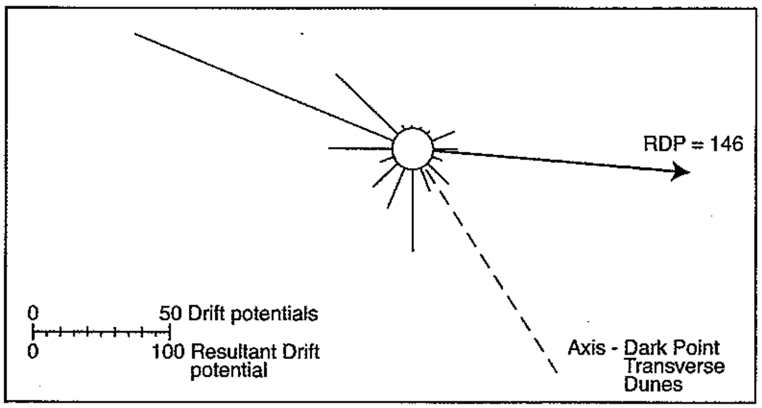

Figure 3. A sand rose constructed for the Dark Point, Australia dune field (using the Fryberger and Dean (1979) model) showing the Resultant Drift Potentials.

foredune (Hesp, 2002). As an approximation, it may be assumed that any wind approaching the foredune at angles up to 60° from the crest orientation will transport sand across the dune.

Blowouts (wind eroded troughs, hollows, bowls and saucer-shaped depressions) are common in coastal dunes and provide a major corridor for wind blown sand. Hesp and Hyde (1996) found that the wind direction within the blowout was strongly controlled and steered by the internal topography and wind speed was dominated by topographic accelerations and was highly turbulent, often displaying corkscrew vortices. Comparisons of wind speed between instruments located outside the blowout at 10 meters height (the typical meteorological tower height) and within the blowout showed that wind speeds are 60 to 80% faster in the blowout. In addition, calculations of sand transport estimated outside the blowout were up to two orders of magnitude lower than those calculated within the blowout (Hesp and Pringle, 2000).

Implications for management

The calculation procedure identified here allows a manager to estimate temporal variations in transport potential at a number of time scales (e.g., diurnal, annual, seasonal, or storm cycles). The minimum and maximum rates of aeolian transport provide limits that can be used to narrow the number of options required to address problems and opportunities associated with blowing sand and thus facilitate decision-making. One of the principal uses of the minimum rate of transport is to identify options that will not be viable because an insufficient volume of sediment will be moved. An example would be whether a dune could form by aeolian accretion (such as at a sand fence) or whether earth-moving equipment would be required to supplement natural processes. Knowledge of the maximum rate would be important in locations where rapid dune construction is critical, such as where a storm-damaged dune must be repaired or replaced prior to the occurrence of the next damaging storm. In this case, the option of using earth-moving equipment may be selected if it is predicted that a dune of sufficient volume could not form in the interval expected between storms. Determining the maximum transport rate through time would be useful in anticipating the frequency at which new fences should be placed within the desired dune zone or how high structures should be raised to prevent inundation or maintain views over the tops of accreting or migrating dunes.

Accelerated rates of transport often follow beach nourishment operations, due to the great width of the nourished beach and the presence of fine materials (Draga, 1983). Knowledge of these rates is important to estimate the loss of protective beach and the hazard to shorefront communities due to besanding. The former application would be useful in specifying overfill ratios for beach nourishment volumes. The latter application would help decide on the types and time of implementation of strategies to modify the hazard potential by designing compatible structures, covering vulnerable surfaces, or adjusting to the loss by investing in labor or equipment to clear properties.

Regulatory officials are continually confronted by private interests with requests to build near or on beaches and dunes or to modify these environments to facilitate recreational or commercial use. Calculation of sediment budgets provides data useful for assessing potential changes in aeolian transport caused by 1) the

To assess the feasibility of changes in management actions

Calculate rates of dune building to select methods of enhancing accretion.

- Determine if protective dunes of adequate dimensions will evolve by aeolian transport alone.
- Determine number of rows and lifts of sand fences required for specific dune dimensions.

Determine whether eliminating dunes will adversely affect landward buildings and infrastructure.

Determine the effects of suspending (or initiating) beach cleaning operations.

Determine the side effects of new protection structures, access paths, crowd control structures.

Assess future beach nourishment projects.

- Calculate offshore and onshore losses to specify fill volumes.
- Determine the type and scale of strategies for alleviating inundation of landward structures.

To make permit decisions

Anticipate temporary effects of new construction (including site preparation and construction phases).

Anticipate permanent reductions in source widths due to replacement of beach by structures.

Evaluate use of vegetation and other landscaping elements used on private lots.

Table 4. Application of predictions of aeolian transport rates to management needs.

creation of new bare land to facilitate the construction of buildings and facilities; 2) restrictions to source width as a result of replacing sand surfaces with structures; or 3) the effect of selecting alternative vegetation types that have different tolerances to burial or different effects as barriers to transport farther inland.

The most useful procedures for predicting potential transport rates are those that balance accuracy with ease of utilization. We provide such a protocol that allows the manager to obtain an estimate of sand transport off the beach and backshore given minimal data. The determination of reasonable minimum and maximum rates of transport provides managers with another decision-making tool for the manipulation of landscapes, and for the definition of an envelope of plausibility for assessment of the results of changes in policy.

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