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Measurement and Prediction of Long-Term Sediment Supply to Coastal Foredunes

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ABSTRACT

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Sediment supply to coastal foredunes was measured over the period 1986–1992 at three sites along the accretional distal end of Long Point spit, Lake Erie. Sediment supply was determined from measurements of aggradation in the embryo and foredune made along transects perpendicular to the shoreline. Annual sediment deposition rates ranged from 2.6–10.3 $m^3 m^{-1}$. Measured sediment deposition at two sites over the period May–December, 1987 was 25% and 50% of sediment transport predicted using an equation developed by HSU (1974). Variations in sediment deposition from year to year, and between sites, were controlled primarily by variations in beach width, related to changes in lake levels and to local beach morphodynamics, rather than by variations in potential sediment transport based on wind velocity. It is argued that it is inappropriate to predict long-term sediment transport from instantaneous transport equations which make use of the wind shear velocity U_*. Furthermore, where beach width is typically less than 50 m, variations in beach width are a stronger control on rates of sediment supply to the foredune than the wind climate.

ADDITIONAL INDEX WORDS: *Aeolian sand transport, dune sediment budget, beach width.*

INTRODUCTION

The beach, and ultimately the littoral drift system, is the source of sediment supply for the creation of coastal dunes. The sediment transported from the beach to the foredune thus represents an output from the littoral sediment budget and an input to the dune sediment system (PSUTY, 1988a; NICKLING and DAVIDSON-ARNOTT, 1991). On a broad scale, differences in the rate of formation and form of foredunes will reflect differences in physical and biological factors, including: wind regime; wave climate; temperature and precipitation; littoral sediment supply; sediment size and mineralogy; and vegetation type and density (e.g. OLSON, 1958a, b; JENNINGS, 1964; DAVIES, 1972; RITCHIE, 1972; BORÓWKA, 1980; SHORT and HESP, 1982; PYE, 1982, 1983; HESP, 1989; KLIJN, 1990). Aeolian transport from the beach to the dune may be partially offset by transport from the dune system onto the beach and by erosion of the embryo dune and foredune by wave action during storms (LEATHERMAN, 1979; KRIEBEL and DEAN, 1985; THOM and HALL, 1991). Thus, the gross sediment supply to the dune can be seen as one important element of the complex set of processes that characterise beach/dune interaction (PSUTY, 1988b; SHERMAN and BAUER, 1993). The ability to predict the amount of sediment supplied to the dune from the beach can be seen as an important input into both beach and dune sediment budget calculations, and for modelling the long-term evolution of the dune field. It is also an important element in achieving an understanding of the evolution of embryo and foredune systems and the response of those systems to changes in sediment supply and local beach morphodynamics (HESP, 1983; CARTER and WILSON, 1990).

A number of recent studies have attempted to measure rates of sediment transport from the beach to the dune, and to compare measured rates with predictions based on a variety of sediment transport equations (e.g. KUHLMAN, 1958, SVASEK and TERWINDT, 1974; ROSEN, 1979; BERG, 1983; PYE, 1985; ILLENBERGER and RUST, 1988; SARRE, 1988; KROON and HOEKSTRA, 1990; CARTER and WILSON, 1990; GOLDSMITH et al., 1990). In most instances, rates predicted using the sediment transport equations have been much greater than the actual rates measured (SHERMAN and HOTTA, 1990; NORDSTROM et al., this volume; BAUER et al., this volume). A number of factors can contribute to differences between predicted and measured values over periods of weeks or months, including: 1) errors in measurement of the actual sediment transport; 2) errors or deficiencies in the data used to model input wind parameters, most notably in the determination of the wind shear velocity U_*, which is a key variable of most transport equations used; and 3) the inability to measure or model accurately a number of factors which may act to limit the actual transport rate—*e.g.*, moisture, development of crusts or lag deposits, and restricted source width.

The purpose of the study described here was to obtain accurate measurements of sediment transport from the beach

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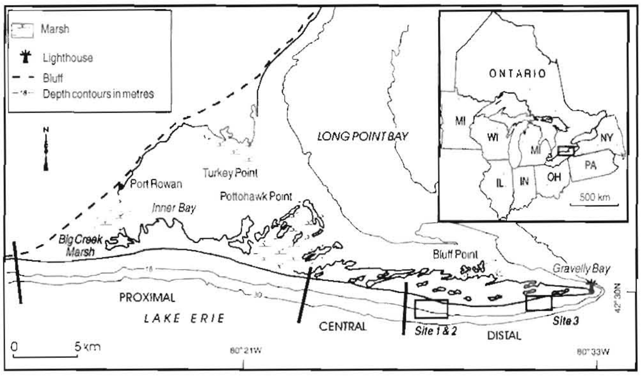

Figure 1. Map of Long Point showing locations of study sites.

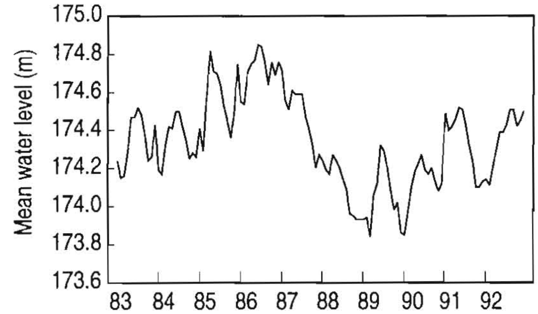

Figure 2. Mean monthly water levels in Lake Erie, 1982–1992.

to the foredune over a period of several years, and to use these data to evaluate the relative significance of incident winds, compared to supply-limiting factors such as moisture and beach width, in controlling actual sediment transport. The study was carried out over the period 1986–1992 at three sites in a progradational dune field at the distal end of Long Point, a large spit on the north shore of Lake Erie, Canada (Figure 1).

STUDY AREA

Long Point is a 40 km long spit on the north shore of Lake Erie (Figure 1). Sediment supply to the spit is derived from erosion of bluffs developed in glacial and glacio-fluvial sediments, and is estimated to be on the order of $10^6 m^3 yr^{-1}$ (RUKAVINA and ZEMAN, 1987). The sediment budget over the 10–12 km length of the distal end is positive and a progradational sequence of dunes over 3 km wide has developed. The area is characterised by beaches that are commonly 20–40 m wide and by the development of a foredune ridge 2–8 m high relative to the base of the windward slope.

The location at the distal end was chosen for this study because of the positive sediment budget, wide beaches and exposure to strong wind and wave action. The whole of this section of the spit lies within a natural wildlife area managed by the Canadian Wildlife Service which restricts public access. It was possible, therefore to carry out the study without the risk of human interference with the sites or the measurement stations. However, the area is accessible only by boat and bad weather forced cancellation of measurements in 1989.

Beach sediments are predominantly quartz and feldspar with a mean grain size of 0.20–0.30 mm. Heavy minerals, primarily garnet and magnetite, usually make up less than 10% by weight, but in some locations can constitute up to 20–30% by weight of berm sediments. In addition, there is a significant fraction of cobble material that travels primarily in the zone lakeward of the step. Some cobbles and pebbles are found on the beach, particularly following a storm, and the accumulation of the cobbles may be enhanced through deflation of sand by aeolian action to form a lag surface.

The beach width varies both temporally and spatially as a result of morphodynamic processs related to lake level fluctuation, storm wave activity, and the migration of longshore sandwaves (STEWART and DAVIDSON-ARNOTT, 1988). Annual changes in lake level of about 0.3 m occur as a result of seasonal variations in runoff and evaporation. There is usually a peak in late May or June, and occasionally a secondary peak in late fall, with lowest levels occurring during the winter months. Longer-term fluctuations result from climatically controlled variations in precipitation and runoff over the Great Lakes Basin and have a range of 1 m or more over periods on the order of a decade. The most recent period of high lake levels occurred in 1985–1986 (Figure 2). Water levels remained above 174.6 m in 1986 when this study was initiated, then decreased rapidly in 1987 and 1988 to below 174.2 m. Finally, levels rose about 0.3 m in 1991 through to the end of the study period (Figure 2). Storms during April and December, 1985 resulted in extensive dune scarping, overwash and inlet breaching over much of the spit (DAVIDSON-ARNOTT and FISHER, 1992). However, overwash only occurred at one location in the distal zone and new embryo dunes were established over much of the area in 1986. The dominant perennial colonisers are two species of grass, American beach grass (*Ammophila breviligulata*) and switch grass (*Panicum virgatum*), as well as well as American cottonwood (*Populus deltoides*).

Variations in beach width over periods of months are also controlled by the west-to-east migration of longshore sandwaves (STEWART and DAVIDSON-ARNOTT, 1988). The longshore sandwaves migrate at rates of 200–600 m yr^{-1} and produce variations in beach width on the order of 30–60 m or more. The migration of sandwaves relative to the three sites is depicted schematically in Figure 3, based on measurements from oblique aerial photographs obtained every year during the study. At sites 1 and 2 a large sandwave, documented by STEWART and DAVIDSON-ARNOTT (1988), moved through the area between 1986 and 1989, resulting in a considerable increase in the beach width at Site 2 in 1987 and 1988. The impact at Site 1 was not as great, because the widest part of the downdrift end was located just updrift of the site in 1986 and had moved well past it in 1987. From 1989–1992 no major sandwaves were located in the vicinity of sites 1 and 2, and the beach at both sites decreased in width during 1991 and 1992, reflecting the increase in lake level (Figure 2). At

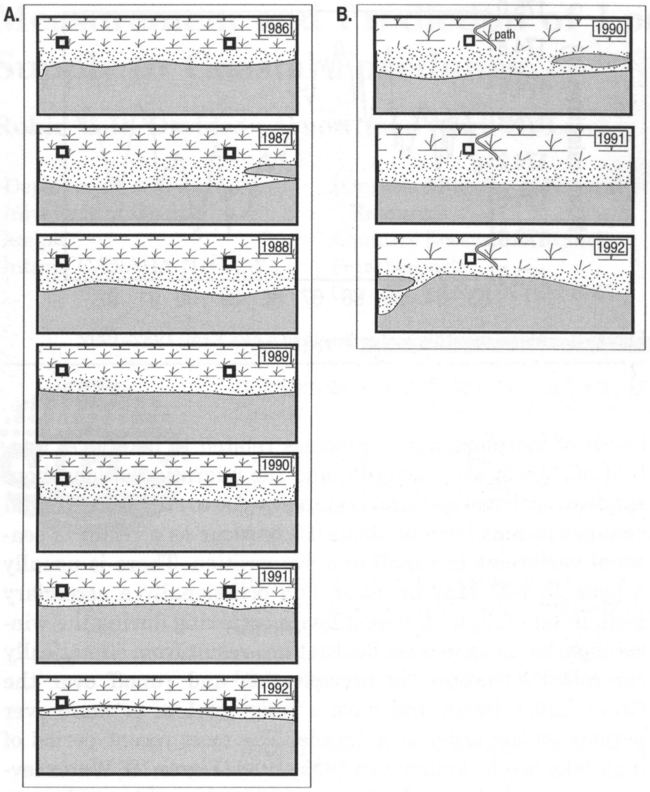

Figure 3. Sketches based on oblique aerial photographs of the position of longshore sandwaves relative to the study site (marked by squares): A) sites 1 (left) and 2 (right) 1986–1992; B) site 3 1990–1992.

Site 3 a sandwave greater than 1200 m in alongshore length migrated past the site in late 1989, producing wide beaches in 1990 and 1991 (Figure 3). However, beach width decreased significantly in 1992 as the erosional embayment between two sandwaves reached the site.

The prevailing and dominant winds are from the southwest and west, and this also coincides with the longest fetch of over 250 km. Typical storm waves have a period of 3–5 seconds and a significant wave height of 1–2 m, while intense storms can produce waves with periods exceeding 6 seconds and significant wave heights over 2.5 m (ONTARIO MINISTRY OF NATURAL RESOURCES, 1988). Because of the relatively shallow depth of Lake Erie winds blowing along the long axis of the lake can produce storm surges exceeding 2 m at either end (LIBICKI and BEDFORD, 1990), though surges at the end of Long Point are on the order of 1–1.5 m. Ice foot and extensive lake ice develop every winter in mid to late-December, and wave action is restricted until well into April. Snow cover and frozen beach sediments tend to reduce aeolian activity during the period January through March (DAVIDSON-ARNOTT and LAW, 1990). Because of the extensive vegetation cover in the foredune and embryo dune zones, there is limited offshore transport of sediment back onto the beach in this part of the spit.

Plate 1. Measurement using the bedframe device.

METHODOLOGY

Sediment deposition within the embryo and foredune zones was measured using a bedframe device (DAVIDSON-ARNOTT and LAW, 1990). This consists of a 2 m by 2 m square frame made from angle iron on which are mounted 13 rods which slide freely in sleeves and which are arranged in a uniform pattern to provide coverage of the area within the frame (Plate 1). Each of the rods has a 4 cm disc on the bottom to prevent penetration into the sand surface. Measurement stations consist of steel posts, 1 cm in diameter and 1.5 m long, embedded in the sand at the four corners of a 2 metre square and levelled at an initial height of about 0.75 m above the sand surface. The frame is placed on the four posts, which engage in corresponding sleeves on the frame, and the distance to the bed recorded at each of the 13 points (Plate 1). Changes in the bed elevation from one time period to the next are recorded by subtracting the distance to the bed from the previous measurement. In this paper values for change in volume are derived from the average of the 13 points measured at each station.

The frame is moved from one measurement station to the next, and is stored away from the site so that the measurement stations are marked only by the corner posts. There is thus minimal interference with wind flow or vegetation growth from the corner posts, and no disturbance to the vegetation within the plot from the measurement technique (see Plate 3a). The precision of each measurement is 0.1 cm and the accuracy better than 0.5cm. The technique has several advantages over simple profiling techniques: the same points are measured each time; it provides good spatial coverage—more than 100 points per line; and there is less disturbance to vegetation.

Measurements of sediment deposition were made along transects perpendicular to the beach and spaced 15 m apart. The transects extended inland a sufficient distance to ensure that all sand transported from the beach would be trapped by vegetation within the foredune zone. Measurements were made at three sites on the south shore of the distal end (Figure 1). Each site had a well-developed embryo dune/foredune area with dense vegetation cover. Sites 1 and 2 were initially established in May, 1986 and are about 1 km apart (DAVIDSON-ARNOTT, 1988; DAVIDSON-ARNOTT and LAW, 1990). Site 3 is located about 5 km east of Site 2 and was established in 1990.

Measurements at sites 1 and 2 in 1986–87 were made along one line at each site. In 1987–88 five new lines were established at each site as part of a detailed study of accumulation on a monthly basis (DAVIDSON-ARNOTT and LAW, 1990). Subsequently two lines were monitored through 1992. Measurement stations were spaced at 6m intervals along each line. Three transects were established at Site 3 in 1990 with stations spaced 7 m apart, and these were measured through 1992. In areas of rapid deposition new posts were inserted next to the old ones and re-levelled in order to keep pace with vertical accretion. Measurements were made at roughly 2–4 week intervals during the summer and fall in 1986 and 1987, and once a year thereafter. Rough weather at the end of the summer prevented access to the sites in 1989 and thus data were obtained for the period 1988–1990.

Hourly mean wind speed and direction measured at a height of 10 m were obtained from a meteorological station maintained by Environment Canada at a lighthouse at the end of the spit, about 4 km east of Site 3 (Figure 1). The entire distal end of the spit is located near middle of Lake Erie, away from any topographic factors that could affect the wind field, and the station itself is completely exposed to winds coming off the lake from the west and south quadrants, i.e. the direction of all onshore winds at the three sites. Because of this, it was assumed that measurements made at the station would be representative of the wind field at the three sites. Furthermore, winds from these two quadrants recorded at a station set up between Site 1 and Site 2 during a four month period in 1987 showed no significant difference in speed or direction with those recorded at the weather station (LAW, 1989). Only data for April through December were used in the analysis since it was assumed that there would be very limited sediment movement during the winter months because of interstitial ice in the beach and dune sediments, and the presence of a snow and ice cover for most of the period.

Plate 2. Photographs of Site 1 taken in 1987 and 1992. (Top) Picture taken from the crest of the foredune looking east in May, 1987 showing the extensive vegetation cover established lakeward of the foot of the dune; (bottom) picture taken on the beach looking east in September, 1992. The embryo dunes are 1.5–2.0 m high and scarping in spring 1992 has resulted in recession of several metres.

RESULTS

Patterns of Sediment Deposition

At the time that sites 1 and 2 were established in 1986 lake levels in Lake Erie had peaked at their highest recorded level (Figure 2). Storm-generated waves during 1985 and 1986 removed most of the embryo dunes in the vicinity of the study area, accompanied by minor scarping of the foredune. However, the lakeward slope of the foredune generally remained vegetated, and vegetation quickly established itself on the backbeach during 1986 and 1987 as lake levels fell (Plates 2a, 3a). As a result, most of the sediment transported landward from the beach was trapped in the vegetation of the embryo dune and the lakeward face of the established foredune. This resulted in rapid accretion of the embryo dune and its coalescence with the older foredune over the course of the study (Plates 2b, 3b).

The pattern of deposition is illustrated by average aggradation recorded at stations along one line at each site (Figure 4). At Site 2 accretion over the period 1987–1992 exceeded 1.5 m within some parts of the embryo dune, averaging about 0.3 m yr^{-1} (Figure 4a). Accretion at Site 1, about 1 km to the west, was lower than at Site 2 but still exceeded 1 m (Figure 4b). At Site 3 maximum accretion over the two years 1990–1992 was on the order of 0.6 m (Figure 4c).

The three stations located on the foredune crest, lee slope and in the dune slack at sites 1 and 2 recorded little change in elevation from year to year and very limited accretion over the whole study period (Figure 4a, b). The small amounts of accretion recorded landward of the crest appeared to be derived from the development of small blowouts in a few locations along the crest (Figure 4a) rather than from sediments transported directly from the beach. The reduced sediment transport landward of the foredune crest was also reflected in a change in vegetation from *Ammophila breviligulata* and *Panicum virgatum* to grasses that are less tolerant of burial such as little bluestem (*Andropogon scoparius*) and several

Plate 3. Photographs of Site 2 taken in 1987 and 1992. (Top) view inland along line 3 taken in October, 1987 showing sediment accumulating in the embryo dune. The posts marking the stations are clearly visible; (bottom) view inland along the same line in September, 1992. Note the growth of the two poplar trees in the intervening period as well as the embryo dunes. Sediment supply is restricted by the development of a pebble lag and the embryo dunes have been slightly scarped by wave action in the spring.

species of shrub such as red osier dogwood (*Cornus stolonifera*). At Site 3 sediment supply was so large in 1990–91 that some sand was transported beyond the limit of the stations established in the embryo dune zone and thus the deposition recorded probably underestimates the total supply from the beach by 10–20% (Figure 4c). However, in 1991–92 sediment supply was much smaller, and all of the sand transported from the beach appears to have been trapped within the measurement zone.

At all three sites, with the exception of Site 3 in 1990–91, it appears that deposition recorded at the stations in the embryo dune and windward slope of the foredune accounts for almost all of the sand transported from the beach during the study period. Moreover, the dense vegetation cover on the foredune and in the dune slack at all three sites acts to limit the potential for offshore sand transport from the dune to the beach by northerly and north-easterly winds in the fall, and also in late winter. This is in contrast to conditions near the proximal end of the spit where the vegetation cover was more heavily disturbed by wave action during the high water period of 1985–86 (LAW and DAVIDSON-ARNOTT, 1990). Thus, while there will be some losses of sand from the dune to the beach due to wave action and aeolian transport, the net deposition measured here is likely to be very close to the gross aeolian supply from the beach over the study period.

Prediction of Short-Term Sediment Transport

During 1987 data were collected at sites 1 and 2 at intervals of 2–4 weeks during the summer and fall. Because bulk density measurements were made at both sites, the volume of sediment deposition can be converted to a weight per metre length of beach (Figure 5), and this permits comparison with transport rates predicted from hourly wind data measured at the meteorological station located the end of the spit. The bulk density of 40 samples taken from sites 1 and 2 ranged from 1700–2800 kg m^{-3}, with an average for the two sites of 2020 kg m^{-3} (Law, 1989). The high values and wide range reflect the presence of concentrations of garnet and magnetite of up to 30% by weight in the beach sediments along this section of the spit.

Most transport equations are based on the bed shear velocity U_*, rather than wind speed at a single height, and this in turn requires either measurement of the velocity profile or knowledge of the roughness length Z_0. In this case, the velocity profile was not measured, and it is likely that Z_0 varies considerably both temporally and spatially, thus making it inadvisable to use any of the commonly used equations. However, HSU (1974) proposed a simple equation for predicting sediment transport from hourly wind data based on the relationship between U_* and U from field data taken from a number of sites. The transport rate is given by:

$$q = 1.16 \times 10^{-4} U^3 \qquad (1)$$

where: q = rate of sand transport (g cm^{-1} s^{-1}), U = wind speed at a height of 2–10 m (m s^{-1}), (Hsu, 1974).

Because measurements were made of sediment deposition in the dune per metre length of beach, the potential sand transport based on wind speed must be modified to account for the angle of wind approach along the shoreline (DAVIDSON-ARNOTT and LAW, 1990) in order to compare the predicted with the measured values. The predicted sediment transport into the dunes per metre length of beach thus becomes:

$$Q_D = 0.1q \cos \alpha \qquad (2)$$

where: Q_D = rate of sand deposition (kg m^{-1} s^{-1}), α = angle of wind approach from shore perpendicular.

Values of the volume of sediment deposition can be converted to a total sediment transport based on the relationship:

$$\frac{1}{\gamma}\frac{dq}{dx} = \frac{dh}{dt} \qquad (3)$$

where q = bulk density of sediments (2,010 kg m^{-3}), h = change in elevation, x = distance along profile.

Predicted sediment transport can then be compared to measured values in each period (Figure 5) for all onshore

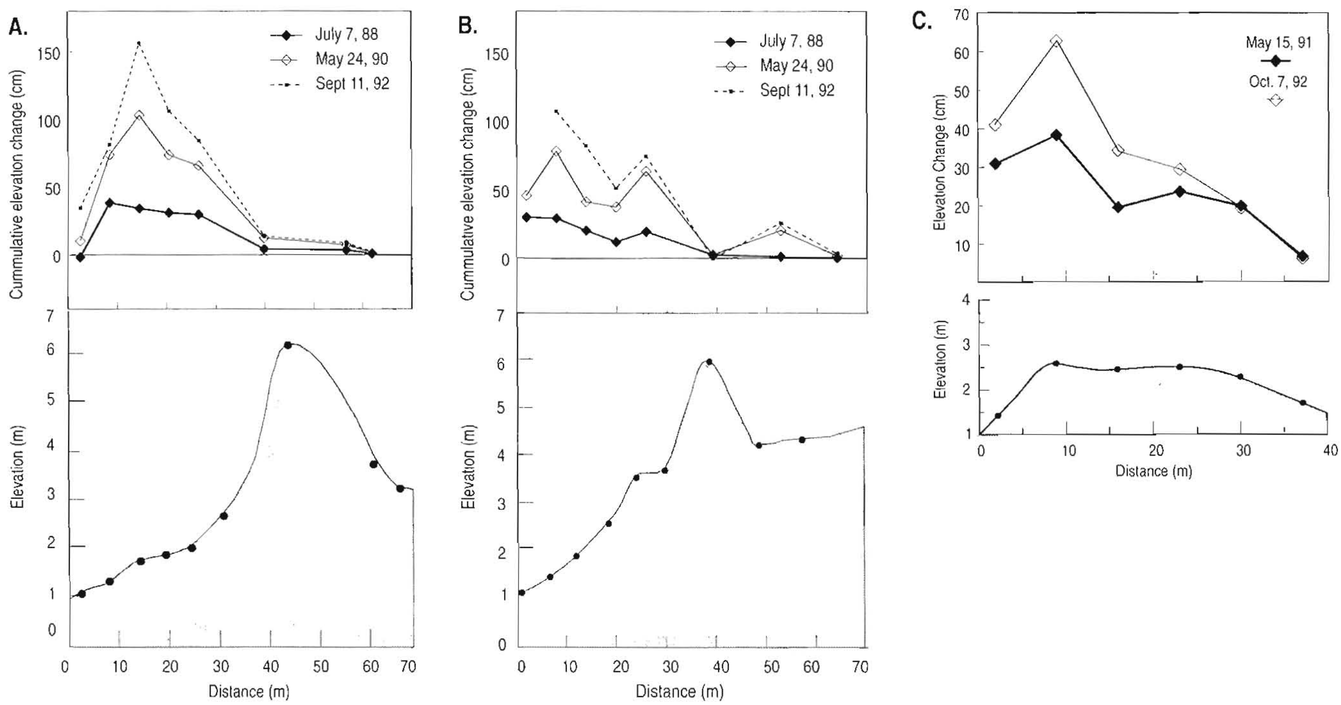

Figure 4. Cumulative sediment deposition at each site: A) Site 1 Line 5 profile surveyed in May, 1987 and cumulative elevation changes measured at stations along the line 1987–1992; B) Site 2 Line 3 profile surveyed in May, 1987 and cumulative elevation changes measured along the line 1987–1992; C) Site 3 Line 1 profile surveyed in July 1990 and cumulative elevation changes measured along the line 1990–92.

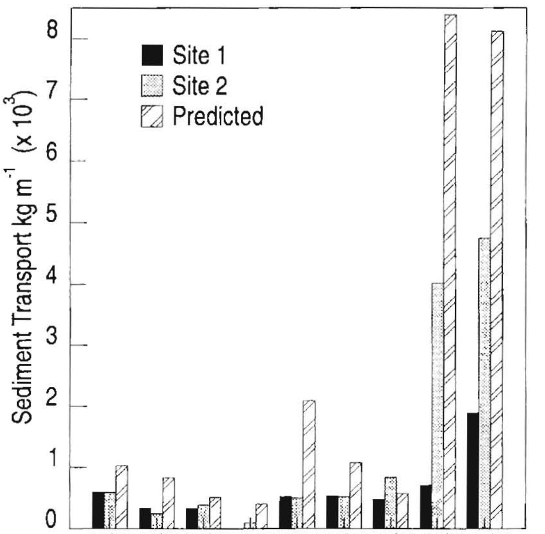

Figure 5. Sediment deposition (kg m^{-1}) measured at sites 1 and 2 for nine periods during 1987. Data are based on averages for five lines. Also shown is the sediment transport predicted for the sites based on the equation of Hsu (1974).

winds exceeding the threshold (19 km hr^{-1}). Over the whole period of measurement total sediment transport predicted is 2.3×10^3 kg m^{-1} compared to values of 0.5 and 1.2×10^3 kg m^{-1} for Sites 1 and 2 respectively. Thus, the measured values are roughly 25% and 50% of the predicted values for the two sites. Predicted values are always higher than the measured deposition at Site 1, but on one occasion measured deposition at Site 2 was higher than the predicted value (Figure 5). In addition, while the general temporal pattern of predicted values follows that of the measured deposition, for two of the periods measured values increased from the previous period while predicted values decreased.

Beach and dune form can influence wind flow and boundary layer development, and thus the potential rate of sediment transport (e.g. SHORT and HESP, 1982; HSU, 1987; BAUER et al., 1990; BAUER et al., this volume). Profiles for the beach and inner nearshore at the two sites measured on September 18, 1987 show the differences in beach width and form typical of the two sites (Figure 6). Site 2 has a steep berm with a remnant runnel just landward of the berm crest, a form similar to the reflective subaerial beach of SHORT and HESP (1982), while Site 1 has a relatively gentle slope without any major inflections and more closely resembles the dissipative sub-aerial beach type. On the basis of form the model of SHORT and HESP (1982) predicts higher transport values for Site 1 whereas the reverse is the case. At this location, therefore it would seem that the influence of beach width outweighs that due to profile form. Because of the very low

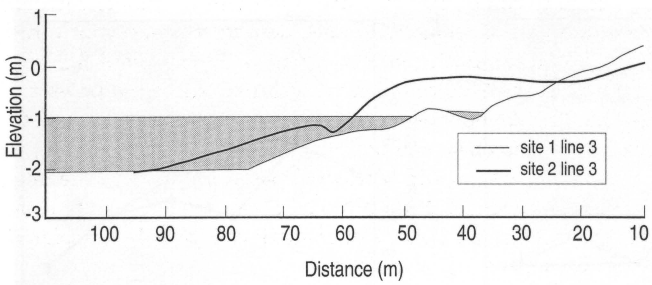

Figure 6. Profile of the beach and inner nearshore at sites 1 and 2 on September 18, 1987.

form of the embryo dunes it seems unlikely that the dune form itself influenced wind flow on the beach (HSU, 1987) and thus contributed significantly to a reduction in the potential transport.

Annual Rates of Sediment Accumulation

Deposition measured on an annual basis for the period 1986–1992 shows even less correspondence with wind data than was the case for the much shorter periods during 1987. Sediment accumulation in the foredune over the study period is summarized for the three sites in Figure 7a. Data for Sites 1 and 2 are averages for 1 line at each site in 1986–87, 5 lines in 1987–88 and 2 lines for 1988–92. Data for Site 3 are based on averages of three lines. Note that no measurements were obtained in 1989, so that results are presented for deposition over the period 1988–90 and the values have been halved in order to permit comparison with the other annual data.

Because bulk density measurements were only obtained in 1987, the data are presented as volume data, rather than as the weight of sediment transported. Total sediment accumulation over the period 1986–1992 was 33.33 $m^3 m^{-1}$ for Site 2 and 25.42 $m^3 m^{-1}$ for Site 1. Total accumulation at Site 3 over the period 1990–1992 was 14.62 m^3m^{-1}. If the value for bulk density of 2010 kg m^{-3} obtained for sites 1 and 2 in 1987 is used, the corresponding weight of sediment transport is 50,840, 66,600 and 29,240 kg m^{-1} for sites 1, 2 and 3 respectively. The annual deposition measured at the three sites ranged from 2.6–10.3 $m^3 m^{-1}$, values that are similar to those measured on many mid-latitude beaches (e.g. GARES, 1988; CARTER and WILSON, 1990; THOM and HALL, 1991), though lower than those reported for some very large dune fields (e.g. HUNTER et al., 1983; ILLENBERGER and RUST, 1988).

Sediment accumulation at Site 1 was consistently lower than Site 2 from 1986–1991, ranging from 62% to 87%, but they were similar during 1991–1992. The temporal pattern at both sites was similar, with relatively small variations from year to year between 1986–1991 and then a decrease in 1991–92 to about half of the values recorded during the preceding years. Sediment accumulation at Site 3 during 1990–1991 was 2–3 times greater than that recorded at the other two sites, and it too recorded a dramatic decrease during the period 1991–1992.

The annual variations in sediment supply to the dunes at

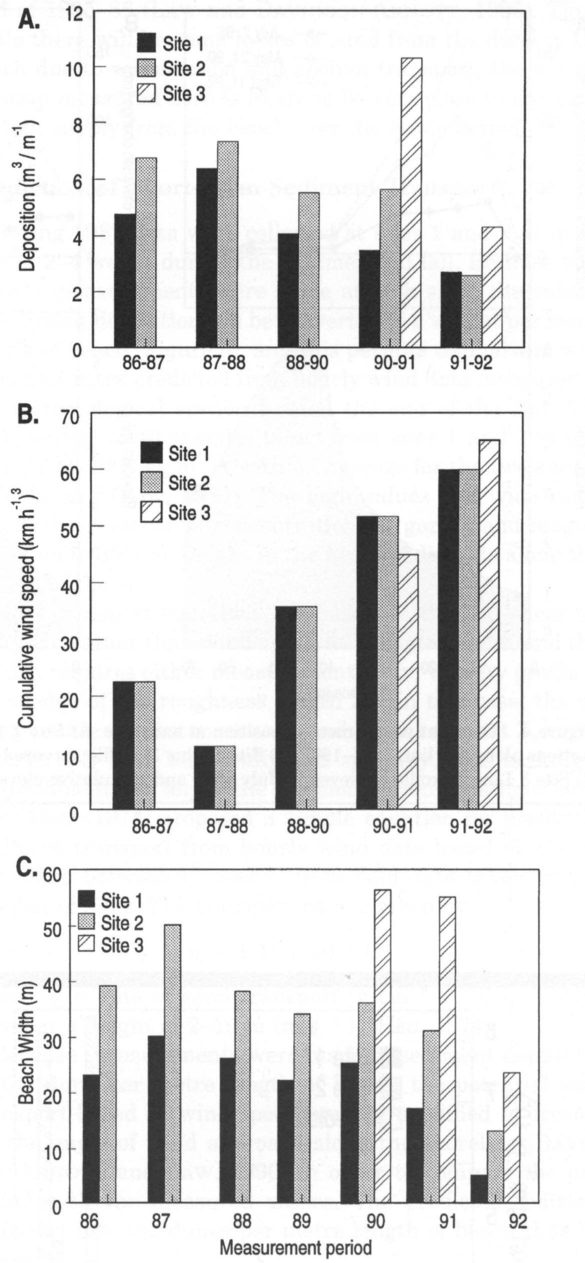

Figure 7. A) Average annual deposition at each site over the study period. Note that total deposition recorded for the period 1988–90 at sites 1 and 2 has been divided by two to permit comparison with the other annual measurement periods; B) wind potential for each measurement period based on equation 4; C) beach width at each site from field surveys carried out at the same time as measurement of deposition.

the three sites can be compared to potential transport based on hourly wind data recorded at the meteorological station located at the lighthouse. Because of the uncertainties introduced by the length of the period of measurement and the effects of snow and below freezing temperatures in the winter, no attempt is made to predict actual rates of sediment transport. Instead, the onshore component of sand transporting wind was calculated from:

$$U_{tot} = \sum_{i=1}^{N} \cos\alpha_i U_i^3 \quad (4)$$

where: U_{tot} = total onshore component of wind, α_i = wind angle (relative to shore perpendicular) at hour i, U_i = average wind speed (km hr^{-1}) for hour i for all U > 19 km hr^{-1}.

The equation is based on the premise that sediment transport is proportional to U^3 or U_*^3, since this is common to most aeolian sediment transport equations, but otherwise makes no attempt to predict actual transport rates. Note that the wind potential, based on equation 4, is the same for sites 1 and 2 because they have the same orientation. A comparison of the measured deposition at the three sites with the pattern of potential transport based on equation 4 (Figure 7a, b) shows little in the way of similarities. At sites 1 and 2 the highest deposition occurs in 1987–88, which corresponds with the lowest wind potential. Conversely, the lowest deposition occurs in 1991–92 which corresponds with the highest wind potential. Actual deposition amounts decreased each year from 1987–88 while the wind potential increased. Similarly, at Site 3 measured deposition in 1991–92 was about half that of 1990–91, but the potential transport indicated by winds actually increased.

A number of recent studies (DAVIDSON-ARNOTT and LAW, 1990; NORDSTROM and JACKSON, 1992; ARENS, 1994) have shown that sediment transport rates can be considerably reduced where the source width is small. While the actual source width for a given transport event depends on both the beach width and the angle of wind approach, over periods of months or years it is evident that average source width will vary directly with the beach width. Beach width measured at the time of site surveys are plotted for the three sites in Figure 7c. Where possible, values for surveys made in September or October are used, coinciding with the period of maximum beach width and highest sediment transport rates, but the 1988 widths are for July when beaches are somewhat narrower.

A comparison of measured sediment deposition (Figure 7a) with variations in beach width at the three sites (Figure 7c) suggests that beach width is a much better predictor of the spatial and temporal patterns of deposition than is potential transport due to wind alone. The highest deposition recorded at each of the sites is associated with the greatest beach width; in 1987–88 for sites 1 and 2, and in 1990–91 for Site 3. Measured deposition was greatest at sites 1 and 2 during 1987–88, corresponding to the lowest potential transport based on winds. Sediment deposition actually increased over that recorded in 1986–87 despite the fact that the potential transport based on winds was less than half that recorded for the previous year. The greater deposition at Site 2 compared to Site 1 during the period 1987–1991 reflects a generally greater beach width there. Similarly, the very marked decrease in deposition from 1990–91 to 1991–92 reflects both an increase in lake level and the large reduction in width at Site 3 due to the movement of a longshore sandwave (see Figure 3b).

The patterns in Figure 7 are confirmed by simple correlation analysis of measured deposition with beach width and wind potential. Both the correlation with beach width is significant at the 95% confidence level and with wind potential at the 90% confidence level. However, while there is a positive correlation between beach width and deposition, there is a negative relationship with wind potential. Clearly the negative relationship has no physical meaning and results from the overwhelming impact of reduction in supply associated with decreasing beach widths.

DISCUSSION

There are now a number of reported studies of measurements of sediment transport to coastal dunes over time periods of days, months or years in which the measured values have been compared to values predicted from one or more of the standard aeolian sediment transport equations (e.g. SVASEK and TERWINDT, 1974, ROSEN, 1979; SARRE, 1988; GOLDSMITH et al., 1990; BAUER et al., 1990; DINGLER et al., 1992; WAL and MCMANUS, 1993; ARENS, 1994). In a few rare cases the measured and predicted values are similar, but in most cases the actual transport values are considerably lower than predicted values.

Where conditions are simple and only a few transport events are involved, it may be possible to adjust some of the constants in the sediment transport equations (e.g. DINGLER et al., 1992), or to optimise the actual equation used (CHAPMAN, 1991). On most beaches this cannot be done because the steady, uniform conditions required for accurate estimation of U_* from wind measurements based on a vertical array of sensors are rarely met (BAUER et al., 1990; BAUER et al., this volume). Moreover, as is the case in this study, long-term predictions are often based on measurements from a single weather station, requiring detailed knowledge of beach form and roughness in order to estimate U_* However, the results of a number of studies (e.g. PLUIS, 1992; NORDSTROM and JACKSON, 1992; WAL and MCMANUS, 1992; ARENS, 1994; GARES et al., this volume) indicate that on most mid-latitude beaches aeolian transport is seldom transport limited, but rather the influence of factors such as moisture, limited fetch width and lag development reduce the sediment supply from the surface. Thus, even if improvements are made in predictions based on wind speed alone, it is likely that the overall impact on transport prediction will be small compared to the potential that would arise from significant improvement in our ability to predict the impact of the factors that limit sediment supply.

The data presented for sites 1 and 2 during the summer and fall of 1987 show that, even over relatively short time periods, variables other than incident wind velocity play an important role in controlling sediment transport from the beach. Some of the difference between predicted and measured values may reflect the presence of heavy minerals in the beach sediments. These could account in part for the lower measured values for deposition, while temporal variation in the proportion of heavy minerals on the beach due to wave action may contribute to differences in the temporal pattern of observed versus predicted deposition. However, it is likely that the most significant factor accounting for the observed differences between the two sites is variation in beach source width (DAVIDSON-ARNOTT and LAW, 1990).

The effect of beach width also appears to be the dominant factor in explaining both temporal variations at a site and the variations between sites on an annual basis over the period 1986–1992. During this time measured beach width ranged from a few metres to over fifty metres. Previous work (DAVIDSON-ARNOTT and LAW, 1990; NORDSTROM and JACKSON, 1992; NORDSTROM et al., this volume) indicates that supply limited conditions will exist where beach fetches are less than 30 m for winds just over the threshold, and that much longer fetches are required during periods where winds exceed 10 m s^{-1}. While fetch length will be greater than the beach widths presented here for oblique winds, the actual beach widths during strong winds will be much smaller because of the effects of storm surge and increased wave run up.

Finally, it is evident that beach width influences the total volume of sediment transport into the foredune/embryo dune zone in three ways: 1) together with wind direction, it determines the source width and thus the instantaneous rate of sediment transport for a given wind speed; 2) together with the thickness of sediment above the beach water table, it determines the total volume of sediment available for transportation under a given set of conditions; and 3) it indirectly influences sediment transport through its effect on beach form and slope (e.g. SHORT and HESP, 1982). In many areas, successful prediction of sediment supply for input into beach and dune sediment budget calculations will require explicit inclusion of source width into predictive models and this in turn will require the collection of data on temporal variations in beach width. Further work in developing expressions for predicting the effect of source width, therefore, must be a high priority if we are to improve the level of our overall ability to model beach and dune sediment budgets.

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