ABSTRACT

EFFECTS OF HUMAN DEVELOPMENT ON AEOLIAN SEDIMENT TRANSPORT RATES WITHIN AN ADJACENT UNDEVELOPED BACKSHORE ENCLAVE

by
Kayla L. Kaplan

Sandy backshore enclaves are created where shorefront buildings are lost during high magnitude storms. Subsequent foredune growth in these enclaves is critical to providing protection to landward development. Conditions for foredune growth and sediment flux within an enclave can be influenced by the presence of adjacent buildings. The objectives of this research are to assess the following questions: what is the nature of sediment flux on a beach within an enclave, what are the potential constraints to transport on a beach within an enclave and, are natural processes alone able to sustain a foredune in an enclave. A field investigation was conducted within an enclave in Bay Head, NJ between 02 November and 25 December 2014. Four events were monitored during strong winds to assess wind characteristics and sediment transport across the Dune, Backshore and Foreshore.

Wind characteristics were measured using three anemometer towers each with four or five anemometers deployed at the Dune Crest, Dune Toe and Berm Crest. Total transport rates were measured using cylindrical traps emplaced during high wind events on 02 November, 18 November, 07 December and 25 December. Surface sediment moisture, grain size, fetch distance and topography were measured to assess potential constraints to transport.

Dominant direction of regional winds are WNW, but were NNW at the study site during the field investigation. The highest wind speeds and sediment transport rates

occurred at the Berm Crest during alongshore winds when fetch distances were greatest. Average wind speed of 7.67 $m\,s^{-1}$ resulted in a trapping rate of 21.32 $kg\ m^{-1}\,hr^{-1}$at the Berm Crest but trapping rates were an order of magnitude lower at the Dune Toe and Crest where average wind speeds were 6.26 and 5.62 $m\,s^{-1}$.

Sediment moisture content across the Dune and Backshore ranged from 0.0 to 4.6% during the four events. Fetch distances, ranged from 5 to 64m within the enclave and 61 to 65m at the Berm Crest. Fetch distance was limited by a sand-trapping fence at the Dune Toe and a house with perimeter sand-trapping fence located to the north. The longer fetch length at the Berm Crest was due to its seaward location relative to the house to the north. Overall average wind speeds and trapping rates were reduced during offshore winds.

Unsteady, low wind speeds within the enclave reduced the potential for sediment transport near the Dune Toe. The average grain size of surface sediment (0.68) mm and average fetch length (39 m) also contributed to lower aeolian sediment transport within the enclave. These results suggest that foredune growth within an enclave may require human intervention to reach adequate size for shore protection.

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by
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EFFECTS OF HUMAN DEVELOPMENT ON AEOLIAN SEDIMENT TRANSPORT RATES WITHIN AN ADJACENT UNDEVELOPED BACKSHORE ENCLAVE

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This thesis is dedicated to those who have helped me along my journey
and my husband, Dan.

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CHAPTER 1

INTRODUCTION

1.1 Statement of Objectives

Coastal dunes eroded during a storm by wave attack depend on wind to deliver sediment by aeolian transport to the foredune during post-storm recovery. On developed shorelines, natural processes alone may not be sufficient to rebuild dunes. The increased frequency of storms can reduce the amount of time natural processes have to rebuild dunes in between storms and leave coastal communities without a protective dune (Houser, 2009; Webster et al., 2005). Predicted rise in sea level increases risk to low-lying coastal communities to inundation and wave attack during storms (Nicholls et al., 2010). These risks create a need for coastal communities to manage dunes in a way that will protect houses and infrastructure from flooding and wave attack during storms.

Human infrastructure in close proximity to the beach can influence dune growth. Houses can be located on or near the backshore. Houses on the backshore are generally closely spaced with a uniform setback along the shoreline. Houses destroyed by storms can leave an open backshore area between remaining houses to be reworked by natural processes (Figure 1.1). The undeveloped backshore between houses is an enclave. The distance between houses defines the alongshore limits of the enclave. Houses are the most common structures creating enclaves, but other structures such as walk-overs and buildings may also bound enclaves.

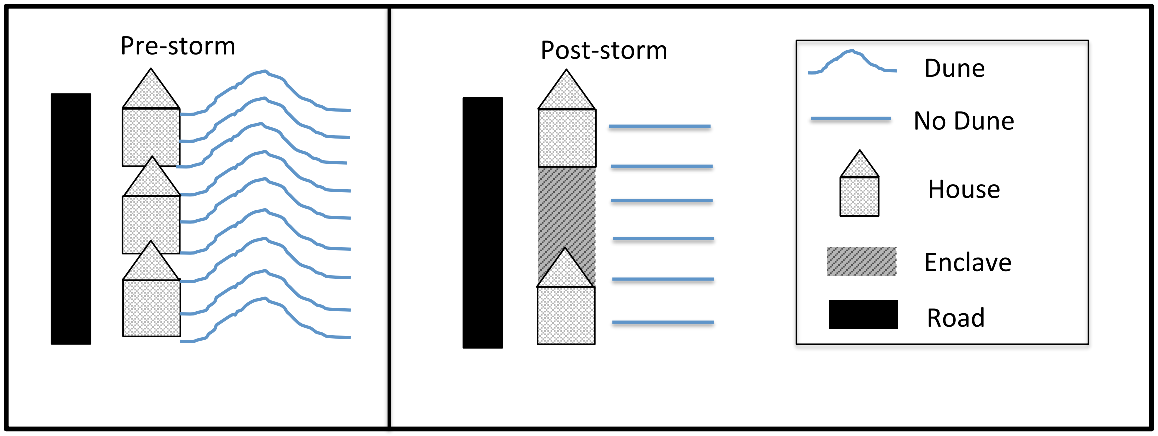

Figure 1.1 Formation of an enclave by former and existing houses.

Goggle Earth images from September 6, 2013 reveal 55 enclaves over 22 km of shoreline from Point Pleasant to Seaside Park, NJ. These enclaves have an average length of 43m and width of 28m. The width of an enclave is defined by the most seaward limit of the house of structure bounding the enclave. The majority (91%) of enclaves are located between two houses; the remaining enclaves are bounded by a combination of houses, recreational buildings and walk-overs. An increased number of enclaves may be created when shorefront homes are destroyed after a storm leaving an undeveloped vacant sandy backshore lot.

Structures and houses that create enclaves may influence sediment flux on the backshore by altering wind direction patterns, winds speeds and reducing fetch length. Nordstrom and Jackson (1998) identified a change in airflow by a deflection and recirculation of wind direction in the wake of a tall building landward of a foredune in Atlantic City, NJ. Landward development may also alter wind speed and direction (Nordstrom and Jackson, 1998; Mendis et al., 2007). Reduced winds created by landward structures may result in intermittent transport and reduced sediment flux (Davidson-Arnott and Bauer, 2009).

Aeolian transport can be facilitated or impeded by variables such as fetch, textural properties of sediment (i.e., size and sorting) and surface sediment moisture content (de Vires et al., 2012). Buildings on and adjacent to the backshore define the potential fetch length (the distance from the upwind margin of an erodible surface to a point of interest) for sediment transport (Delgado-Fernandez, 2010). Field studies have found that during average wind speeds of 8.5 and 13.9 $m\ s^{-1}$, sediment flux will increase with increasing fetch length of 0 to 30m (Davidson-Arnott and Law, 1990; Bauer and Davidson-Arnott, 2003). A restricted fetch created within an enclave can reduce sediment flux and potential deposition to the foredune.

Along with fetch, moisture content of surface sediment may also inhibit aeolian transport on the beach. Surface sediment moisture is the result of the beach water table intersecting the surface of the backshore, wave uprush, ocean spray or precipitation (Namikas and Sherman, 1995). The areas close to the shoreline, such as the Berm Crest and Foreshore, may have elevated moisture from wave spray and direct wave uprush (Namikas et al., 2010). Moisture restricts transport by creating a surface tension among grains (Namikas and Sherman, 1995). Several models predict that at 5% moisture sediment flux will shut down (Namikas and Sherman, 1995). Researchers at a site in the Skalligen Spit in Denmark found that the presence of surface moisture may increase the threshold of movement, requiring a greater wind velocity for sediment entrainment to occur (Davidson-Arnott et al., 2005). However, when mean wind speeds are high, (i.e., 11-12 $m\ s^{-1}$) a high capillary force due to moisture content may be over powered and result in sediment flux (Bauer et al., 2009). As a result, a dune system with consistently high moisture contents on the beach may grow more slowly than a dry system (Bauer et al., 2009).

Grain size distribution of surface sediment may limit aeolian transport by increasing the threshold for sediment entrainment. Large grain sizes will require a greater shear stress to become dislodged and enter the saltation cloud for a given wind speed (Namikas et al., 2009). The grain size diameter is a source of drag that may hinder entrainment (Valance et al., 2015). As a result, sediment flux may be reduced on a beach with large grain sizes (Valance et al., 2015; Durán et al., 2011; Creyssels et al., 2009).

To date, few studies focus on the relationship of infrastructure on or near the backshore and beach geomorphology, wind patterns and transport (Hernandez-Calvento et al., 2014; Smyth and Hesp, 2015; Nordstrom and Jackson, 1998; Nordstrom and McCluskey, 1985). Far more effort has been put into constructing buildings on beaches than determining the building's influence on the beach system (Nordstrom, 2004). As a result there is currently insufficient research on how infrastructure may affect aeolian transport on beaches (Jackson and Nordstrom, 2011).

A field investigation was conducted at a developed beach enclave in Bay Head, New Jersey to determine the potential constraints on aeolian transport. The following research questions were examined:

- What is the sediment flux on a beach within an enclave?
- What are the potential constrains on aeolian sediment transport on a beach within an enclave?
- Are natural processes alone able to sustain a protective dune in an enclave?

Data on wind speed and direction, temperature and relative humidity, backshore surface characteristics and sediment flux were gathered on four separate occasions across a foredune-backshore-foreshore transect within an enclave bounded by residential development.

CHAPTER 2

LITERATURE SURVEY

2.1 Review of Constraints to Aeolian Transport

Modifications to backshore environments include a range of physical structures to accommodate human occupation. Some of these structures include: walk-overs, residential and commercial buildings, piers, shore protection structures (i.e., shore parallel structures to trap sediment and shore perpendicular walls to prevent erosion and inundation), and sand fencing to build foredunes. Each of these structures is capable of influencing sediment transport to the foredune.

2.1.1 Houses

Houses built on or just landward of the backshore are common on developed shorelines. In some communities the natural location of the foredune will be replaced by residential or commercial structures and other recreational facilities (Martinez et al., 2013; Smyth and Hesp, 2015).

Houses on the backshore can have a direct influence on wind patterns surrounding them. Many studies focus on the impact wind has on the structure and how wind is influenced by the presence of the structure (Li et al., 2015; Mendis et al., 2007; Kubota et al., 2008). However, there is little research on the effect of structures on wind characteristics and sediment transport (Nordstrom, 2004; Nordstrom and McCluskey, 1985).

Wind flow around structures is commonly studied in wind engineering (Kubota et al., 2008; Holmes, 2007; Uematsu and Isymov, 1999; Macdonald, 1975). Kubota et al.

(2008) found wind velocities were reduced in areas of dense urbanization. On the leeward side of a single low rise building or house the wind speed is frequently reduced (Holmes, 2007; Nordstrom and McCluskey, 1985). A low rise building may create turbulence, gustiness and large gradients of wind speed in the surrounding area (Holmes, 2007; Heisler, 1990; Li et al., 2015).

A house on the backshore can act as an obstacle to wind flow and alter the downwind speed. A study involving high-rise buildings on a beach revealed an increase and reduction in wind speed downwind these structures (Nordstrom and Jackson, 1998). The reduction in speed was found directly downwind of the structure and the increase in speed was found downwind of the perimeter of the building (Nordstrom and Jackson, 1998). Nordstrom and McCluskey (1985) had similar results studying isolated houses on pilings in Fire Island, NY. The results showed a reduction in wind speed on the lee side of shorefront houses, but wind speeds were maintained underneath the house where scour pits formed. In 1984, Nordstrom and McCluskey also discovered houses on the ground act as a barrier to wind and moving sediment, which can reduce transport rates. Altered wind speeds created by the presence of houses may change the morphology of the beach and alter transport rates (Jackson and Nordstrom, 2011).

2.1.2 Sand Fences

Sand-trapping fences are commonly constructed in order to build new dunes or restore and stabilize existing dunes (Smyth and Hesp, 2015). The purpose of sand fencing is to trap wind-blown sand (Nordstrom, 2004). Fences can protect a dune by limiting human traffic and trampling of vegetation (Nordstrom and Arens, 1998).

The presence of a sand fence can aid in sediment deposition and have a direct impact on the dune morphology. A fence reduces wind speed resulting in deposition of entrained sediment (Li and Sherman, 2015). Sediment accumulation rates in areas with sand-trapping fences can be up to10-20 $m^3 m^{-1} yr^{-1}$, which is greater than areas without fences (Nordstrom and Arens, 1998).

Without sufficient sediment flux a sand-trapping fence may not achieve enhanced deposition near the foredune. Foredune growth due to sand fencing may be constrained in an enclave bounded by a house. The presence of a house may reduce wind speeds downwind, which can reduce transport rates. Without sediment flux near the sand-trapping fences, there will be no sediment deposition to the foredune. Therefore a fence inland that is bound by an enclave may have a reduced ability to assist in foredune growth.

2.1.3 Walk-overs

Walk-overs, comprising a platform and stairways are built over the dune crest to provide pedestrian access to the backshore. A walk-over protects the dune and vegetation from unnecessary foot traffic and deflation (Vallés et al., 2011). Research on coastal management in Spain found that walk-overs can prevent direct human impact on dunes by reducing foot traffic (Muñoz-Vallés and Cambrollé, 2014). A walk-over that extends over a dune to the backshore may protect the dune while restricting vertical growth of the dune.

A dune may be completely eroded during a high energy storm event like in the case of

Hurricane Sandy in 2012. If the dune underneath the walk-over is eroded, the walk-over may then impact sediment flux adjacent to the structure. A walk-over may reduce wind speed in its immediate surroundings. Similar to sand fences, a reduced wind speed can result in the accumulation of entrained particles. Around the pilings of elevated houses scour and accretion areas have been found as a result of the altered wind pattern (Nordstrom, 2004; Nordstrom and McCluskey, 1985). A walk-over supported by pilings with no dune may also have unique scour and accretion zones. The presence of a walk-over with no dune may restrict the potential fetch length during alongshore winds. Similar to many other beach structures, the presence of a walk-over may be able to alter the morphology of the surrounding area.

2.2 Review of Natural Constraints to Aeolian Transport

Sediment transport on a beach can either be transport or supply-limited (Nickling and Davidson-Arnott, 1990). A system is transport-limited by the sediment carrying capacity of the wind (de Vries et al., 2012). Therefore the transport rate is a function of the wind velocity profile (Davidson-Arnott et al., 2005). During supply-limited conditions there is not adequate sediment available to be transported by the wind. A supply-limited system may be created by the presence of surface moisture (Belly, 1964), restricted fetch, lag deposits or sediment characteristics (van der Wal, 1998; Davidson-Arnott et al., 2005). Coastal beaches are frequently supply-limited due to inhibited sediment mobility (Nickling and McKenna-Neuman, 2009; Williams and Lee, 1995).

The presence of an enclave may create both a transport- and supply-limited system. A reduction in wind speed in the lee of the house may diminish the sediment carrying capacity of the wind. If the winds are not strong enough to entrain sediment the system will be transport-limited. A supply-limited system may be created by a restricted fetch length created by the presence of an upwind boundary within an enclave. During alongshore winds the fetch length imposed by the upwind boundary may create supply-limiting conditions. Thus, transport rates in an enclave can be reduced by transport- and supply-limited conditions.

2.2.1 Wind Speed and Direction

Wind conditions are the main determinant for sediment transport. Winds may be steady or unsteady with periods of inactivity marked by periodic gusts of wind. Gusts may also occur under steady winds, but transport rates can be estimated from the average wind speed when the wind speeds are high. During unsteady or low winds, transport cannot be accurately determined by the average since gusts may not be significant enough to have an influence on the average wind speed (Stout and Zobeck, 1998).

A beach with intermittent winds will not be able to reach equilibrium saltation (Bauer et al., 2015) and may reduce transport rates. Sustained high wind speeds are frequently associated with elevated transport rates (Bauer et al., 2015). Fluctuating gusty winds may not have a high enough average velocity to exceed the threshold for entrainment. Intermittent winds frequently fall below threshold creating a pause in movement while a short strong gust may create a burst in saltation (Stout and Zobeck, 1997). These periods of inactivity marked by short bursts of movement are called intermittent saltation (Davidson-Arnott and Bauer, 2009). A system with unsteady winds and intermittent transport will rarely reach equilibrium and have reduced transport compared to sustained winds (Davidson-Arnott and Bauer, 2009; Bauer et al., 2015).

In a wind tunnel study, Butterfield (1993) found that short duration winds are capable of creating sediment flux. During periods of intermittent saltation, mass flux will be changed within one second to a positive increase in wind velocity (Butterfield, 1993). Therefore, one second of strong wind above the shear threshold is enough to initiate sediment transport. The researchers also found that gusty winds with a high shear velocity may initiate grain dislodgments that result in transport. Fluctuating or gusty winds transport sediment in a constant state of disequilibrium (Butterfield, 1993). Winds with a low average wind speed may still be capable of creating entrainment that is dependent on short gusts above the threshold.

The wind direction may be influenced by surrounding development. Dense urbanization may reduce potential offshore winds (Mendis et al., 2007; Roth, 2000). Therefore, a beach with dense urbanization landward may not have frequent offshore winds. Unlike offshore winds, alongshore winds are usually not restricted by major development. However, alongshore winds may be reduced and deflected by the presence of a house bounding an enclave (Mendis et al., 2007; Heisler, 1990). Development around a beach bound by an enclave may reduce the speed in its lee and result in predominately oblique or alongshore winds.

2.2.2 Grain Size

Textural properties of surface sediment (size and sorting) control entrainment and transport potential on the backshore. Based on Bagnold's (1936) widely accepted formula, the mean grain size diameter is a multiplying factor when estimating the shear threshold for entrainment. With all other factors remaining constant, larger mean grain sizes will require a higher shear stress in order for entrainment to occur.

A lag surface may be created by the favored transport of fine grain sediment, leaving the large particles behind on the surface (Nordstrom and Jackson, 1998). The lag has a large diameter and is less mobile than fine grain particles. Fine grain sediment that bounces on a lag surface during saltation may move faster due to the collision on the coarse lag surface (Nickling and McKenna-Neuman, 1995). However, if there is not a sufficient source of fine grain sediment the lag areas may decrease sediment transport.

Surrounding development may influence the sediment budget and alter sediment transport. The littoral budget may be reduced down drift of common structures such as jetties, groin and harbors (Nordstrom, 2004; Smyth and Hesp, 2015). This may create a difference in sediment characteristics on opposite sides of the structure (Nordstrom, 2004). Differences in sediment characteristics can affect potential transport by wind. A reduced beach width created by houses and walk-overs decreases the source area for wind blown sand and will restrict aeolian transport.

2.2.3 Fetch

Fetch is the distance wind blows over an erodible surface or beach (Bauer and Davidson-Arnott, 2003). The fetch effect shows an increase in sediment transport rate as the distance downwind over an erodible surface increases (Delgado-Fernandez, 2010). Fetch has been studied extensively since 1974 (Svasek and Terwindt), with more recent studies focusing on the implications fetch has on transport rates and deposition to dunes (Bauer and Davidson-Arnott, 2003).

Longer fetch lengths lead to higher transport rates up until transport rates reach a maximum condition known as transport saturation (q_m)(De Vries et al., 2012). The width of a beach or alongshore distance can be constrained by the houses present. The critical fetch (F_c) is the distance where transport saturation (q_m) is able to occur. The maximum available fetch distance (F_m) is limited by the beach geometry since it is the maximum length of erodible surface over which wind is blowing. If $F_m < F_c$, the transport rate will be below its maximum potential and be fetch limited (Bauer and Davidson-Arnott, 2003). Houses on the backshore will limit the maximum available fetch during alongshore winds, which may reduce sediment transport to the foredune. In a field study done by Nordstrom, Jackson and Korotky (2011) a trapping rate of 24.23 $kg\ m^{-1}\ hr^{-1}$ is reached during an average wind speed of 6.3 $m\ s^{-1}$ with an unrestricted fetch. The high trapping rate is attributed to a long fetch distance due to a backshore with no houses or buildings.

Field studies and wind tunnel experiments to determine fetch length provide great discrepancies in the defined fetch length. Wind tunnel experiments show a critical fetch length of a few meters with natural critical fetch lengths exceeding 100m (Davidson-Arnott et al., 2005; Delgado-Fernandez, 2010). Bagnold (1941) suggested a fetch distance of 9m to reach saltation equilibrium in a wind tunnel experiment (Delgado-Fernandez, 2010). A field study on Prince Edward Island found maximum transport occurring at fetch distances of 50-150m (Bauer et al., 2009). In coastal areas there are several micro-scale temporal and spatial factors across the beach that make it extremely difficult to accurately predict and model fetch length such as lag, moisture, roughness and the availability of sediment (Jackson and Nordstrom, 2011; Bauer et al., 2009; Delgado-Fernandez, 2010).

A beach within an enclave will have a limited fetch length and result in reduced sediment transport. Development is known to change the patterns of aeolian transport

(Jackson and Nordstrom, 2011). Houses located on the backshore will limit the potential fetch of width of the beach that is a source for wind-blown sediment. An additional factor that may influence fetch and sediment flux is moisture. Moisture can contribute to the fetch effect and therefore increase the distance wind must blow to achieve saltation and intermittent transport of sediment (Davidson-Arnott et al., 2005).

2.2.4 Moisture

The fetch effect is likely to be more pronounced by the presence of surface moisture over an erodible surface (Bauer and Davidson-Arnott, 2003). Moisture is nearly always present in coastal systems due to wave uprush, capillary rise from the water table, wave spray and precipitation (Davidson-Arnott et al., 2009). In a study to determine the effect of moisture and fetch on a flat dry beach in Northern Ireland researchers discovered that at fetch lengths between 10-60 m there is no significant change in transport rates when moisture is very low (Jackson and Cooper, 1999). Moisture will increase the critical fetch distance and limit the aeolian sediment transport rate (Bauer et al., 2009).

The presence of moisture on beaches may inhibit sediment transport. As moisture content of sediment increases the wind speed and critical shear velocity required for saltation or transport increases as well (Davidson-Arnott et al., 2008; Namikas and Sherman, 1995). A study done by Bauer et al. (2009) found that high wind speeds up to 20 $m\ s^{-1}$ were required to reduce the cohesive effect of moisture and create sediment flux. At moisture contents between 8-10% several models such as Belly (1964), Hotta et al. (1984), Chepil (1956) and McKenna-Neuman and Nickling (1989) show transport rates of 0 $kg\ \ m^{-1}\ hr^{-1}$ at shear velocities of 0.80 $m\ s^{-1}$ (Davidson-Arnott et al., 2008).

In order for sediment transport to occur, the motion-inhibiting force of moisture must be offset by a greater shear stress (Namikas and Sherman, 1995). The complexity is increased because the threshold has been found to vary over as little as 10 seconds in response to drying of the sediment (Davidson-Arnott et al., 2005). Researchers have found on a back beach in Wildwood, NJ spatial variations of moisture of 2.9-9.2%, which makes accurately modeling transport extremely difficult (Jackson and Nordstrom, 1997). Evaporation and drying of surface sediment is a function of wind speed and time, high winds result in a rapid drying of sediment (Nordstrom and Jackson, 1993). Evaporation rate and sediment transport has yet to be accurately modeled and is another factor that contributes to the uncertainty of transport rate.

In this study, we aim to provide insight on how anthropogenic changes and the development of a beach enclave influences sediment flux across the foreshore and backshore. Data on wind speed and direction, temperature and relative humidity, surface sediment characteristics (size, sorting, moisture) and fetch are analyzed to account for differences in sediment flux during four sediment transport events.

CHAPTER 3

METHODOLOGY

3.1 Study Area

The New Jersey shoreline is nearly 130 miles in length and is primarily used for recreational purposes (Figure 2.1A). The shoreline is highly developed with high density infrastructure landward of the backshore. Some of the common structures near the beach are boardwalks, promenades, walk-overs, houses and other recreational buildings (Jackson and Nordstrom, 2011; Nordstrom, 2004). Such landward structures are able to prevent landward migration of the dunes.

Our study was conducted on a recreational beach in Bay Head, New Jersey (Figure 2.1B). The beaches in Bay Head are exposed headlands with sediments in the range of medium to coarse sand (McMaster, 1954). This particular site has never been nourished. The site was chosen due to the presence of an enclave bounded by a house surrounded by a sand-trapping fence to the north, a road to the west that bounds the landward limit of the foredune, a shore parallel wall and walk-over to the south (Figure 2.1D).

The house occupies a lot seaward of the Dune Crest on the backshore that is 48 m long and 30 m wide. The house is bounded by a bulldozed sand embankment with a sand-trapping fence at the Dune Toe. South of the house is a walk-over that was once over a dune before Hurricane Sandy 2012 (Figure 2.1C). At the time of the field investigation in 2014 the walk-over was over the Backshore with no foredune (Figure 2.1D). A bulldozed dune, located at the landward limit of the backshore, was created in the aftermath of Hurricane Sandy. On the landward side of the Dune Toe was a sand-trapping fence.

Figure 3.1 A-D Location map showing New Jersey coastline (A), the study area of Bay Head, NJ (B), the study site in 2010 showing the foredune prior to Super Storm Sandy (C) and in 2013 after the storm (D).
(Source: Google Earth)

At the beginning of the study the dune was 5.76m relative to mean sea level with a seaward slope of 10.2 degrees. The enclave at the site had an alongshore length of 93m. The shoreline is oriented NNE-SSE. Dominant winds from the WNW approach offshore at the study site. High velocity winds that are likely to move sediment are commonly from the north-northeast direction and are often accompanied by rain.

3.2 Data Collection

The field site was occupied from 31 October to 26 December 2014. Data on wind direction, speed and sediment flux were gathered on a cross-shore transect from the Dune Crest to the Upper Foreshore (Figure 3.2). The transect was located 60m south of the house bounding the north end of the enclave. Trapping of sediment in transport occurred on four separate occasions: 02 November, 18 November, 07 December and 25 December during periods of high speed winds. Topographic surveys and upwind sediment moisture samples were collected on the days that sediment was trapped.

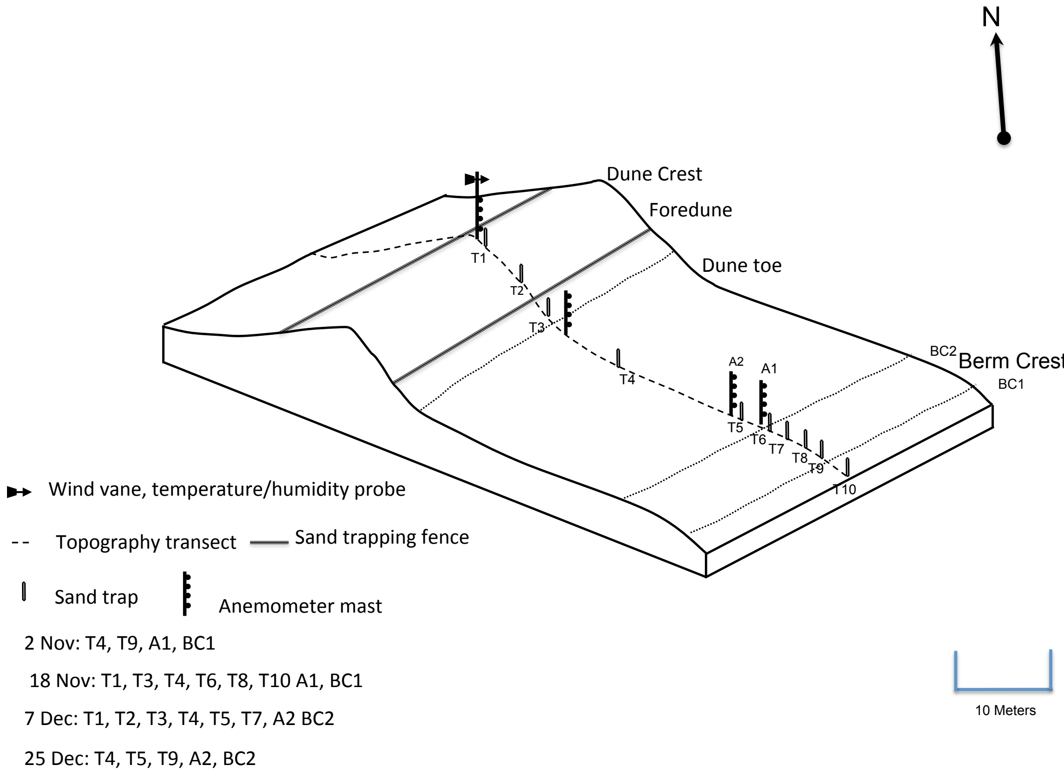

Figure 3.2 The field setup showing the instrument transect and location of sand traps during each of the four monitoring events.

Table 3.1 Variable Identification and Method of Measurement

Variable	**Measurement**
Topography – (m)	RTK GPS
Mean Grain Size(mm and Φ)	Surface sediment and trap samples
Sediment Sorting (ϕ)	Sieve Analysis
Wind Speed (ms^{-1})	Gill 3-cup Anemometer
Wind Direction (True North)	Gill Wind Vane
Fetch Length- (m)	Measured Distance Upwind Trap to boundary
Gravimetric Moisture Content (m)	Bulk Sediment Samples
Sediment Flux ($kg\ m^{-1}\ hr^{-1}$)	Leatherman Traps

3.2.1 Topography

Surveys of the beach and dune were conducted on 02 November, 18 November, 07 and 25 December using a RTK GPS. Using the GPS we also identified positions of traps after deployment, the topography and geometry of the site.

3.2.2 Sediment Characteristics and Flux

Sands traps were deployed (02 November, 18 November, 07 December and 25 December) to collect wind-blown sediment. The shortest trapping duration trapping event occurred on 02 November, traps were deployed from 14:29 to 15:24 for a total of 56 minutes. The longest trapping event was on 18 November, traps were deployed from 10:31 to 12:46 for a total of 136 minutes. On 07 December traps were deployed from 9:39 to 11:13 for a total of 95 minutes. On 25 December traps were deployed from 13:51 to 14:57 for a total of 67 minutes.

Leatherman traps were deployed, which are vertical total load traps made from PVC pipe with two slits cut in (Leatherman, 1978). The traps used had a trapping height of 0.37 m and a 43.0 mm width. One of the slits is open and the other has a screen to provide maximum flow of wind through the trap. These traps have efficiencies reported to be between 30-70% (Marston, 1986; Greeley et al., 1996). These traps are able to give a total transport rate, but do not provide instantaneous trapping rates or height distribution of transported sediment. Vertical traps have the advantage of being portable and easily installed and are extremely useful in evaluating spatial differences of transport rates (Nordstrom and Jackson, 2011).

Sediment traps were placed along the transect line at the Dune Crest, Dune Toe, Backshore, Berm Crest and Foreshore (Figure 3.2). Traps remained in place until a change in wind direction, a reduction in wind speed or both. Bulk surface sediment samples were gathered 10m upwind of each trap at the end of each transport event. These samples were used to quantify differences in upwind source characteristics and moisture content. The moisture samples were collected, sealed in plastic bags, weighed and taken back to the lab where they were oven dried and reweighed. There is no current standard on the preservation of moisture samples, but it is best to keep them in airtight containers in order to prevent evaporation (Namikas and Sherman, 1995).

'Honey Cards' were used in order to collect sediment directly on the surface. A 4 by 6 inch index card, covered with a thin layer of honey, was laid on the surface of the backshore upwind of the traps. The card was then put in a plastic bag and brought back to the lab for processing. Cards were washed in water and all of the bound sediment was collected and washed. Honey is inexpensive and soluble in water making it a good substance to use for collecting surface sediment.

3.2.3 Wind

Three masts were deployed during each trapping event in order to collect wind speed data. Each tower consisted of a vertical array of four Gill 3-cup anemometers mounted at 0.25, 0.5, 0.75 and 1m. Prior to sampling the anemometer heights were measured and recorded to insure accuracy. These masts were placed along the transect on the Dune Crest, Dune Toe and Berm Crest (Figure 3.2). The mast at the Dune Crest had an additional anemometer and an RM Young wind vane mounted at 2.46m above ground surface. A probe measuring temperature and relative humidity was mounted 1.9m above the ground surface. Data from the field instruments were recorded continuously at 1 Hz on a Campbell 3000 data logger during each event. The instruments at the Dune Crest were sampled continuously at 1Hz during the entire field deployment.

3.3 Data Analysis

3.3.1 Topography

Using the survey data collected from the GPS-RTK we were able to observe changes to the beach profile over time. The surveys were also used to obtain the height of the existing Foredune, change in slope of the backshore and foreshore and change in the width of the backshore. Using the GPS coordinates of our traps we were able to calculate the potential fetch based on wind direction. Fetch was calculated using Google Earth by measuring upwind to the nearest structure that would restrict the fetch.

3.3.2 Sediment Characteristics

Surface and bulk sediment samples and trapped sediment were taken to the laboratory and analyzed for estimating sediment flux, grain size statistics and moisture content. All samples were washed, dried and sieved at $\frac{1}{4}\phi$ intervals. Mean grain size (m_z) and sorting (σ_1) were calculated using graphic measures (Folk, 1974).

The threshold for sediment entrainment was estimated using the equation of Bagnold (1936):

$$U_{*t} = A\sqrt{gd\frac{\rho_s - \rho}{\rho}} \tag{3.1}$$

with A being an empirical constant taken at 0.085. The air density is represented by ρ, the sediment density of quartz is ρ_s, the acceleration due to gravity is g and the average grain diameter is d. This value represents the shear stress required for sediment entrainment by wind.

Moisture content w of sediment samples is calculated gravimetrically by percent weight of the sample:

$$w = \frac{(w_s - w_d)}{w_d} \tag{3.2}$$

where w_s is the total sample weight at the time of collection and w_d is the dry weight.

Sediment collected in the traps was weighed to determine the trapping rate and evaluate spatial differences of transport across the beach. Trapping rate ($kg\ m^{-1}\ hr^{-1}$) was calculated using the dry weight of the trapped sediment, duration of deployment and the width of the trap:

$$q = \frac{w}{t}\frac{1\,meter}{0.043} \tag{3.3}$$

where w is the weight of the trapped sediment in kilograms, t is the time in hours multiplied by 1 meter (shoreline width) over the width of the trap in meters.

3.3.3 Wind Speed

The relative wind strength for each mast was calculated for 5-minute intervals for each day. The relative wind strength allows us to compare spatial wind speed differences across the beach. The relative wind strength is a non-dimensional parameter calculated by taking the difference mean wind speed and threshold wind speed from the surface sediment and then dividing it by the standard deviation of the wind speed. The use of the standard deviation will depend on the intermittency and gustiness of the wind. Intermittent winds will have an elevated standard deviation and reduce the magnitude of the relative wind strength (Stout and Zobeck, 1997):

$$S = \frac{\bar{u} - u_t}{\sigma} \tag{3.4}$$

The threshold wind velocity (u_t) is subtracted from average wind speed ($\bar{u}$) and divided by the standard deviation of the wind speed (σ). The relative wind strength is a non-dimensional value and allows us to compare wind strength for each day data was collected at different locations on the beach. A positive S implies that the mean wind speed is greater than the threshold wind speed and saltation is likely to occur. A negative S indicates that the average wind speed is lower than the threshold wind speed and thus the transport will depend on individual gusts to entrain sediment (Stout and Zobeck, 1997).

Wind speed velocity profile is used to estimate the shear velocity, which is the primary determinant of aeolian transport. To estimate the shear velocity a velocity profile is created using the velocity measurements and the heights of each anemometer, as done by Namikas et al. (2003), Sherman and Li (2012) and Bauer et al. (1992). Linear regression is performed using the measured wind speed against the logarithm of the anemometer height. The shear velocity estimates are derived from the log profile of the law of the wall, which relates the wind speed to the shear velocity:

$$U_z = \frac{u_*}{k} \ln \left(\frac{z}{z_o}\right) \tag{3.5}$$

where U_z is the corresponding wind speed at height z, z_0 is the roughness length and k is the Von Karman constant of 0.4. The Von Karman constant relates flow speed profile in a wall bounded shear flow to stress on the surface (Andreas et al., 2005). The data is put on a log linear plot and the formula of the linear regression line has the equation $y = mx + b$. The slope and y intercept of the line are then used to estimate the shear velocity u_* and roughness z_o.

$$m = \frac{u_*}{k} \qquad b = -\frac{u_*}{k} \ln(z_o) \qquad (3.6, 3.7)$$

In order to avoid any faulty readings not all profiles were used in data analysis. Shear velocities associated with an r-squared value less than 0.95 were omitted from analysis.

3.3.4 Wind Direction

A wind rose is a common way to depict wind direction and velocity (Nordstrom and Jackson, 1998; Liu and Zimbelman, 2015; Rodriguez et al., 2013). Data gathered from the anemometer and vane at the top of the mast on the Dune Crest were used to construct a wind rose for the period of the field investigation. Data from the Monmouth Executive Airport (16 km NW of the site) for the period of the field investigation were analyzed for comparison. The plots were constructed in MATLAB using code published by Daniel Pereira (March 2015).

3.3.5 Fetch

Fetch length was calculated using data from the trap locations, the wind direction and the position of the upwind boundary. Using Google Earth the erodible surface upwind of each trap was measured. Each trap had a specific GPS coordinate that was recorded during its deployment. The wind direction used to measure the fetch distance was from the wind rose for that specific trapping event. The middle value of the most prevalent bin on the wind rose was used to calculate fetch for each event.

CHAPTER 4

RESULTS

4.1 Beach Topography

Figure 4.1 presents profiles after each of the four trapping events monitored. The beach profile reveals the topography during the collection period of 02 November to 25 December. There was little to no net change across the foredune during the monitoring period. The Dune Crest elevation ranged from 5.8m on 02 November to 5.7m on 25 December. Surface elevation seaward and landward of the sand fence near the Dune Toe did not change. The Berm Crest increased in elevation from 2.6m on 02 November to 3.1m on 07 December. Due to high-energy events on 06 December and 24 December the backshore decreased in elevation and width during the deployment. The elevation of the backshore decreased between 18 November and 25 December from 2.9 to 3.9m. Between 02 November and 25 December the backshore width decreased 5m from erosion of the foreshore.

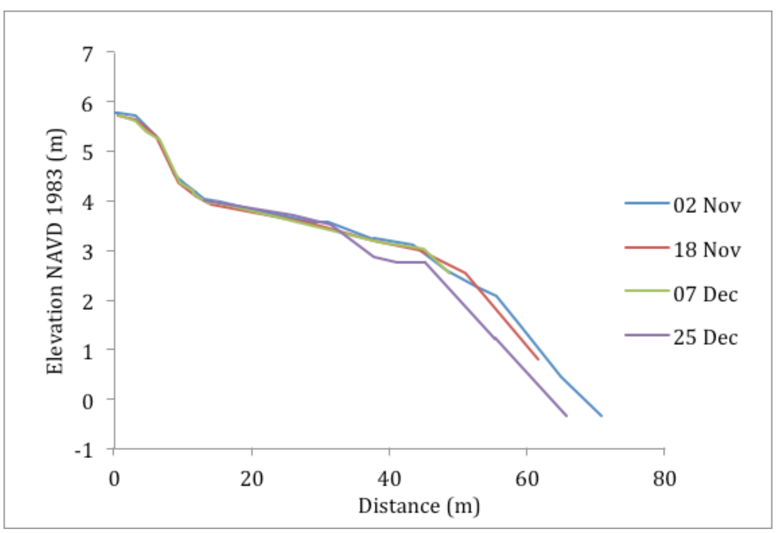

Figure 4.1 Beach profiles on the instrument transect during each trapping event.

4.2 Wind Characteristics

The dampering effect of the residential development on wind characteristics at the study site are revealed in a comparison of the regional wind conditions (Figure 4.2 A-B) from an airport tower 16 km NW and the data gathered on the Dune Crest at the field site. The regional wind direction shows greater variation with dominant winds from the WNW. Winds from the NNW are dominant at the field site but the highest velocity winds are from the NNE, approaching the study site from alongshore. The surrounding development and high elevation houses may be restricting the wind direction at the site.

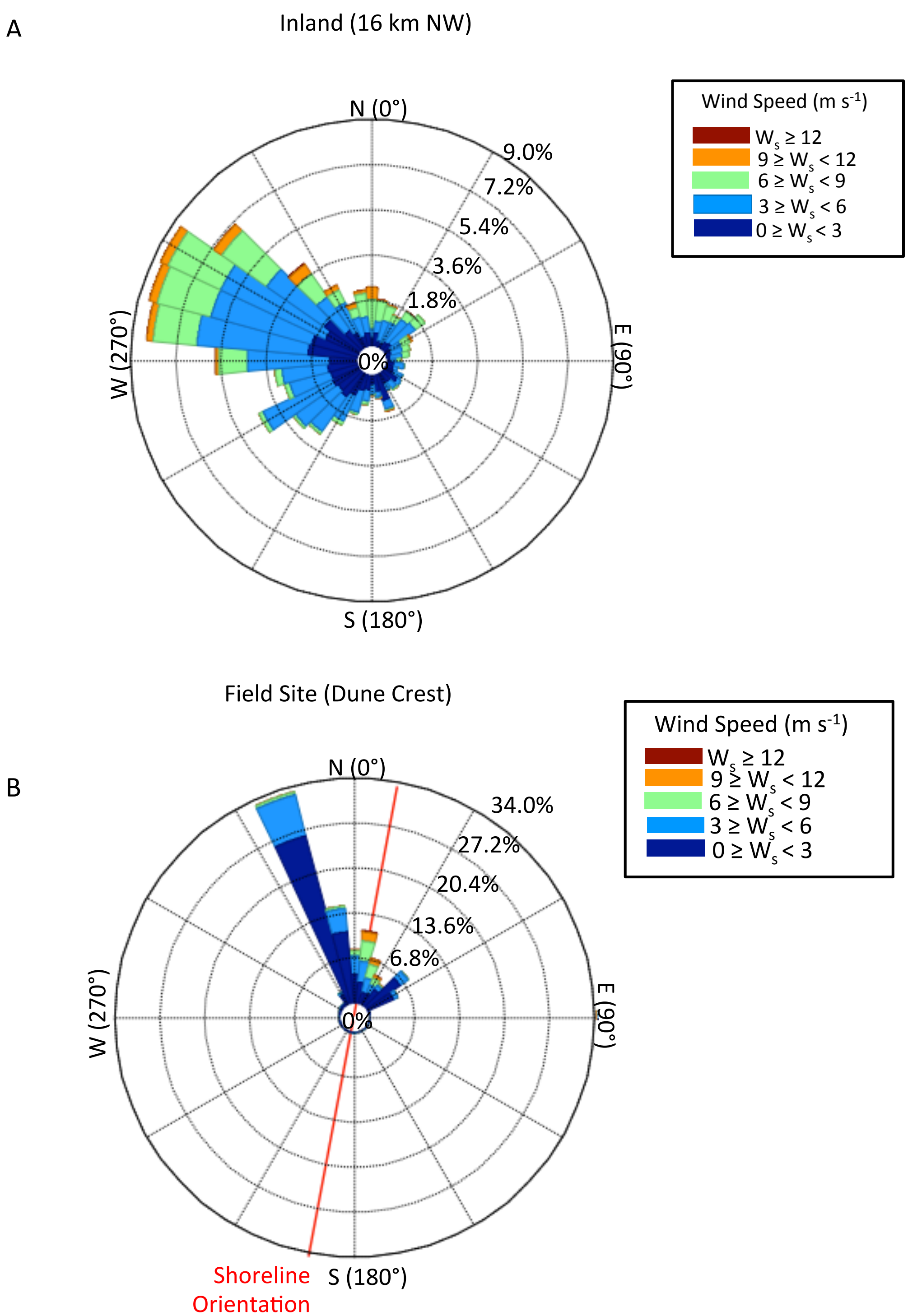

Figure 4.2 A-B Wind rose of regional (A) and site conditions (B) throughout deployment.

A wind rose was also created for each trapping period for data gathered at the field site (Figure 4.3 A-D). Winds from the north were the most frequent during each trapping event. The highest frequency wind speeds for each event were between 3.5 and 7.5 $m\,s^{-1}$. On 02 November 60% of the winds approached from 350 to 0 degrees and these winds were associated with the highest frequency wind speeds above 7.5 $m\,s^{-1}$. On 18 November wind direction was predominately from the north, but this event had the largest range (NW to NE) in variation among trapping events. Wind direction on 07 December approached from the NNE with 87% of the winds from 0-10 degrees. The winds on this day were the strongest with nearly half the winds from the 0-10 degree bin greater than 7.5 $m\,s^{-1}$. The most offshore winds occurred on 25 December with about 50% from 340-350 degrees followed by 330 to 340 degrees. Compared to the other trapping events 25 December had the highest frequency of wind speeds less than or equal to 3.5 $m\,s^{-1}$ and the lowest frequency of wind speeds greater than or equal 7.5 $m\,s^{-1}$.

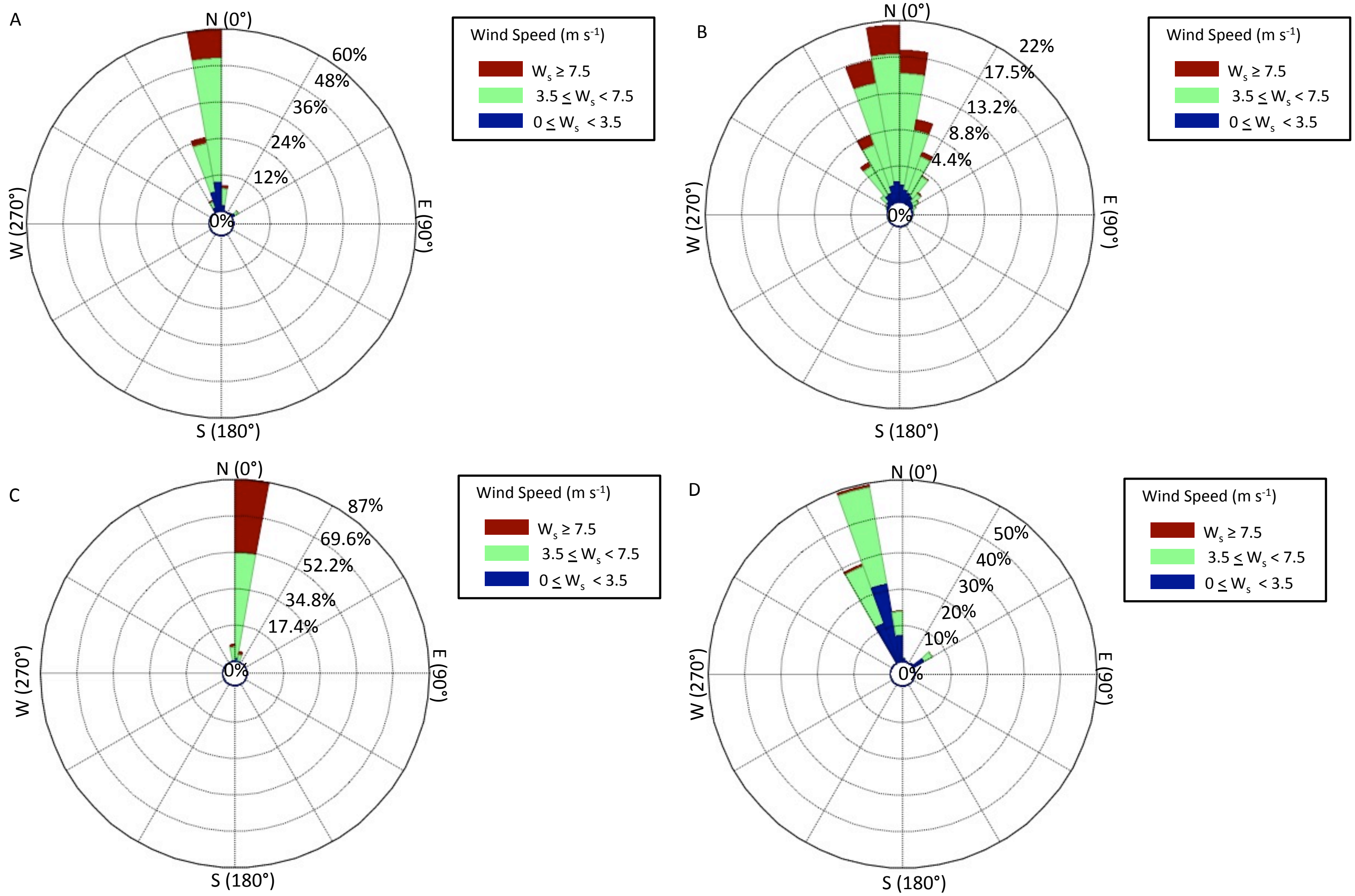

Figure 4.3 A-D Wind rose for each trapping event on 02 November (A), 18 November (B), 07 December (C) and 25 December (D).

Average wind speeds during each trapping event measured at 1 m elevation reveal the majority of the trapping events had low to moderate winds (Table 4.1). The highest 5-minute average wind speed at the Dune Crest, Dune Toe and Berm Crest all occurred on 07 December. The highest maximum wind speeds also occurred on 07 December at the Dune Crest and Berm Crest. The greatest maximum wind speed on the Dune Toe occurred during the 25 Dec trapping event.

Table 4.1 Average, Standard Deviation and Maximum Wind Speed From Data Gathered at 1m Elevation During the Total Duration of Each Trapping Event

Date	**Location**	**Average** $m\,s^{-1}$	**Standard Deviation** $m\,s^{-1}$	**Max** $m\,s^{-1}$
02 Nov	Dune Crest	3.29	1.61	11.44
	Dune Toe	3.70	1.71	11.26
	Berm Crest	4.39	1.89	12.50
18 Nov	Dune Crest	3.14	1.36	11.19
	Dune Toe	2.87	1.39	10.49
	Berm Crest	5.31	1.80	14.77
07 Dec	Dune Crest	6.26	1.87	13.81
	Dune Toe	5.62	1.51	10.95
	Berm Crest	7.67	1.76	15.11
25 Dec	Dune Crest	2.33	1.05	7.72
	Dune Toe	2.06	1.19	11.91
	Berm Crest	4.14	1.50	9.28

Comparison of average wind speed at the Dune Toe and Dune Crest relative to the Berm Crest on 02 November reveals a 16% and 25% reduction in average wind speed respectively. During the alongshore winds, on 18 November the reduction in average wind speed at the Dune Toe and Dune Crest relative to the Berm Crest was 46% and

41%. On 07 December the reduction in wind speed at the Dune Toe and Dune Crest was 27% and 18%. On 25 December the reduction of average wind speed relative to the Berm Crest was 44% and 50% at the Dune Toe and Dune Crest.

During each event, the average wind speed is lower at the Dune Crest and Dune Toe in comparison to the Berm Crest. During some trapping events, the Dune Crest had higher reductions in speed than the Dune Toe. On 02 November and 25 December the reduction in wind speed was greatest at the Dune Crest. The lower wind speeds at the Dune Crest may be a result of the landward residential area.

During trapping events on 18 November and 07 December, the Dune Toe had the highest reduction in wind speed. These two events produced the highest wind speeds at the Berm Crest and had some of the most alongshore winds. Therefore, the house directly north of the site may have reduced the wind speeds at the Dune Crest during these events. The presence of a dune may shelter and reduce wind speeds at the Dune Toe.

4.3 Relative Wind Strength

The relative wind strength calculated from the five-minute averages of wind speed at 1m elevation across the beach and dune reveal that average speeds did not exceed the threshold for sediment entrainment on all but one occaision (Figure 4.4 A-D). On 02 November the shear threshold used to calculate the relative wind strength at the Dune Crest, Dune Toe and Berm Crest was 0.25, 0.30 and 0.30 $m\ s^{-1}$ respectively. Relative wind strength ranged from -0.63 at the Berm Crest to -4.66 at the Dune Toe. There was no time period when the relative wind strength was > 0.

On 18 November, the shear threshold used to calculate the relative wind strength for the Dune Crest, Dune Toe and Berm Crest was 0.29 $m\ s^{-1}$ for each location. The highest value for the relative wind strength is -0.62 at the Berm Crest and the lowest is -5.05 at the Dune Crest with no relative wind strength exceeding zero.

On 07 December, the shear threshold used to calculate the relative wind strength for the Dune Crest, Dune Toe and Berm Crest was 0.31, 0.29, and 0.29 $m\ s^{-1}$. This was the only trapping event when the relative wind strength was greater than 0. The highest value for S occurred on the Berm Crest (0.615) and the lowest on the Dune Toe (-2.74).

On 25 December, the shear threshold used to calculate the relative wind strength for the Dune Crest, Dune Toe and Berm crest was 0.32, 0.32, and 0.24 $m\ s^{-1}$. The highest relative wind strength was -0.84 on the Berm Crest and the lowest was -7.23 at the Dune Toe.

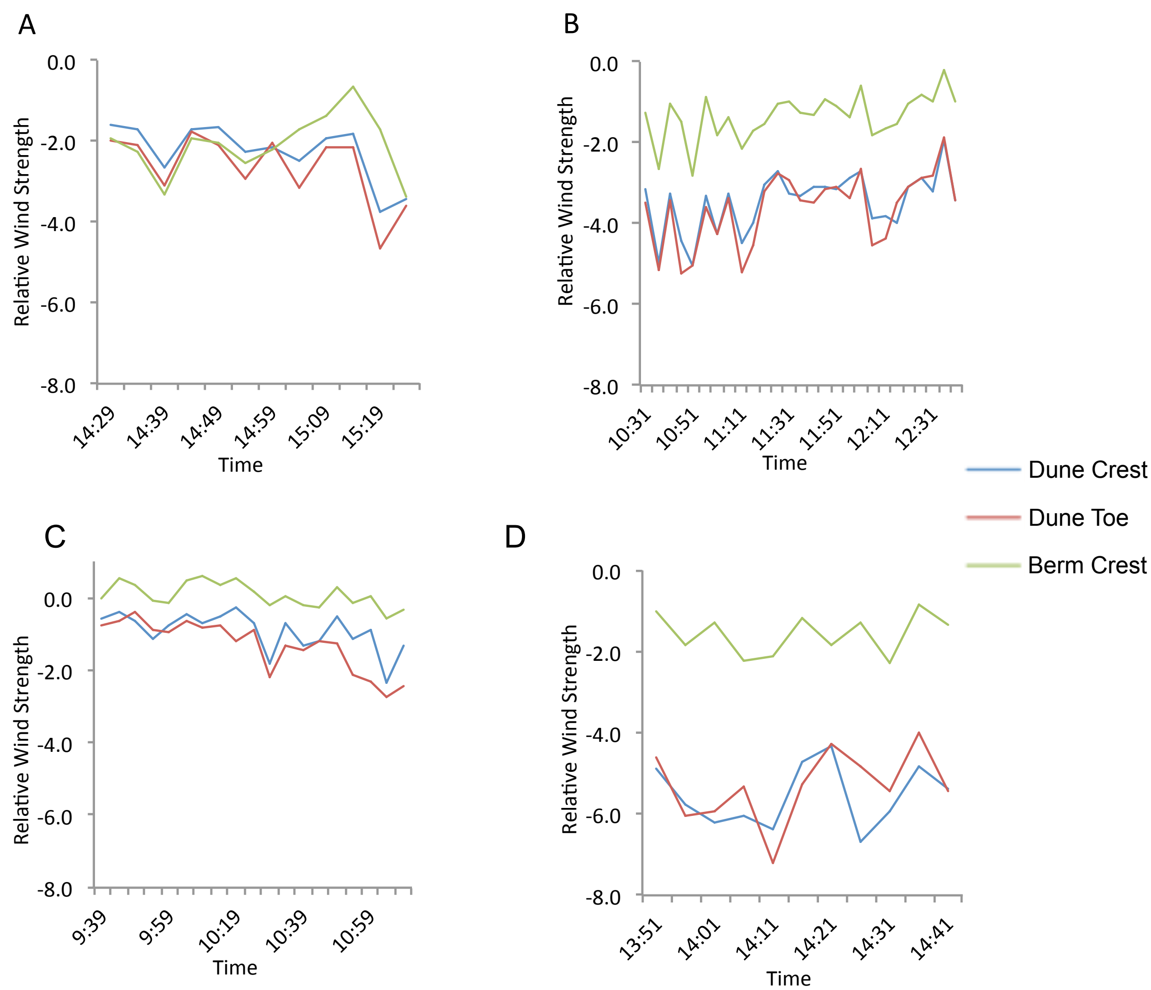

Figure 4.4 A-D The relative wind strength for each trapping event on 02 November (A), 18 November (B), 07 December (C) and 25 December (D).

4.4 Intermittency of Winds

During all trapping events, winds were intermittent and there were few times when the average wind speed exceeded the threshold for entrainment for extended periods of time. Table 4.2 depicts the percent of time the threshold was exceeded and for how many continuous seconds at the Dune Crest, Dune Toe and Berm Crest. Individual gusts exceeding the threshold for entrainment are capable of entraining sediment over short durations. The Berm Crest and Dune Crest had the greatest number of instances when shear velocities exceeded the threshold. Most frequently, the Berm Crest and Dune Toe had the highest number of exceedances. For each event, the Dune Toe had the lowest frequencies of exceedances.

The most common duration of wind gusts exceeding the threshold velocity was for one second (Table 4.2). For three out of the four trapping events, the Berm Crest had the highest number of exceedances followed by the Dune Crest and Dune Toe. The Berm Crest also had longer duration gusts in comparison to the Dune Crest and Dune Toe. The short duration of gusts indicates that there was a consistent lull in wind speed marked by short bursts of wind.

The 02 November trapping event had a reduced percentage of threshold exceedances, with the Dune Crest having the most exceedances. The 18 November trapping event had the highest number of exceedances at the Dune Crest. This is the only event that the Dune Crest and Dune Toe had higher frequencies of exceedances than the Berm Crest. The alongshore wind on 07 December produced the highest frequency and duration of wind gusts exceeding the threshold at the Berm Crest. Compared to the other trapping events 25 December produced the fewest exceedances of the threshold for all locations. The reduced winds during this event created few gusts strong enough to exceed the threshold for entrainment.

For most trapping events (02 November, 07 December, 25 December), the Berm Crest had the most frequent bursts of wind. The Berm Crest was directly east of the enclave and not bound by the house north of the site. The lack of a barrier north of the Berm Crest may be the reason the wind gusts were able to exceed the threshold for a longer period of time. The house may also deflect oncoming winds and potentially increase the wind velocity in its lee.

Table 4.2 The Percentage, Duration and Frequency of Wind Exceeding the Threshold Velocity

Date	**Location**	**Threshold Exceeded %**	**1 Seconds**	**2 Seconds**	**3 Seconds**	**4 Seconds**	**5 + Seconds**
02 Nov	Dune Crest	18	175	28	10	3	3
	Dune Toe	7	132	21	6	2	3
	Berm Crest	9	200	90	34	12	11
18 Nov	Dune Crest	28	631	292	144	64	38
	Dune Toe	10	390	102	43	13	6
	Berm Crest	5	327	32	3	0	0
07 Dec	Dune Crest	9	375	55	6	1	0
	Dune Toe	6	278	27	0	0	0
	Berm Crest	23	589	203	56	14	15
25 Dec	Dune Crest	8	58	18	9	5	1
	Dune Toe	5	53	14	3	2	0
	Berm Crest	8	87	24	3	2	0

4.5 Sediment Characteristics

The sediment at the site was predominatley medium to coarse sand and generally well to moderately well sorted. There was a difference in grain size among trapped, bulk and surface sediment.

The mean grain size and sorting of trapped, bulk and collected sediment are presented in Table 4.3. The location of traps are identified in Figure 3.2. The bulk sediment can be described as coarse sand with a mean size of 0.65mm. The mean grain size of the collected bulk samples ranged from 0.38 to 1.38mm. The Dune Crest had two samples that can be desribed as very coarse sand. The bulk sediment was moderately well sorted sediment, but ranged from well to poorly sorted sediment.

The trapped sediment was more fine than the bulk sediment with an average grain size of 0.44mm. The trapped sediment can be desrcibed as medium sand. On average the the collected sediment was well sorted ranging from well to moderately well sorted. There was low varability (0.34-.53mm) in the grain size of the trapped sediment. Only one trap that collected coarse sediment. This trap (T3) was located at the Dune Crest during the 18 November trapping event.

The trapped and bulk sediment samples have a difference in grain size. The trapped sediment was more fine than the bulk samples. This indicates a potential selective entrainment of only the small diameter grains took place.

Using the honey card method the surface samples had an average of very coarse sand. Seaward of the Dune Crest the grain size of the surface samples drecreased from 1.71 to 0.81mm. The sorting of the surface sediment was very poor at the Dune Crest, seaward the sorting improved to very well sorted at the Foreshore. The sediment collected using the honey cards at the Dune Crest and Dune Crest with no fence had 31% and 46% gravel. The very poor sorting and presence of gravel indicates possible lag deposits near the Dune Crest.

The honey cards collected coarser material than the bulk samples. Both methods collected very coarse sand at the Dune Crest. While the grain sizes are different both methods also show a seaward decrease in grain size. The bulk sediment represents a sample of the overall sediment characterisitcs while the honey cards specifically sample the upper layer of surface sediment.

The threshold for sediment entrainment was calculated based on trapped sediment and bulk sediment. The average shear threshold is 0.26 $m\ s^{-1}$ for trapped sediment and

0.30 $m\ s^{-1}$ for the bulk sediment. The average difference between the shear threshold for the trapped and surface sediment is 0.04 $m\ s^{-1}$. A paired t-test reveals the shear threshold for the surface sediment is significantly higher at the 95% confidence level.

Table 4.3 Mean Grain Size and Sorting of Collected, Bulk and Surface Sediment From Each Trapping Period

Date	Collected	Trap ID	Mean Grain Size mm	Mean Grain Size ϕ	Sorting ϕ
02 Nov	Trapped Sediment	T4	0.46	1.13	0.50
		T9	0.43	1.22	0.43
18 Nov		T1	0.37	1.42	0.73
		T3	0.53	0.92	0.66
		T4	0.48	1.06	0.49
		T6	0.42	1.24	0.42
		T8	0.44	1.18	0.49
		T10	0.49	1.02	0.54
07 Dec		T1	0.45	1.17	0.44
		T2	0.50	1.01	0.50
		T3	0.44	1.17	0.47
		T4	0.35	1.50	0.47
		T5	0.42	1.24	0.44
		T7	0.50	1.01	0.42
25Dec		T4	0.38	1.40	0.54
		T5	0.34	1.57	0.49
		T9	0.50	1.01	0.58
02 Nov	Bulk Sediment	Top of unfenced dune	1.08	-0.11	1.37
		Dune Crest	0.39	1.37	0.39
		$T4_{upwind}$	0.58	0.78	0.45
		$T9_{upwind}$	0.57	0.82	0.50
18 Nov		Crest of Bulldozed Dune	0.62	0.68	0.99
		$T4_{upwind}$	0.54	0.88	0.50
		$T6_{upwind}$	0.52	0.95	0.47
		$T8_{upwind}$	0.56	0.83	0.47
		$T10_{upwind}$	0.58	0.78	0.43
07 Dec		$T1_{upwind}$	0.60	0.74	0.90
		$T2_{upwind}$	0.70	0.52	0.76
		$T3_{upwind}$	0.55	0.87	0.72
		$T4_{upwind}$	0.56	0.83	0.54
		$T5_{upwind}$	0.56	0.85	0.46
		$T7_{upwind}$	0.59	0.77	0.36
		$T1_{upwind}$	1.38	-0.46	1.51
25 Dec		$T4_{upwind}$	0.67	0.57	0.46
		$T5_{upwind}$	0.38	1.38	0.52
		$T9_{upwind}$	0.49	1.04	0.43
07 Dec	Surface Sediment	Upwind unfenced Dune Crest	1.71	-.078	1.14
		Backshore	1.18	-0.24	0.70
		Berm Crest	0.79	0.34	0.36
		Foreshore	0.87	0.20	0.24

4.7 Fetch, Moisture and Trapping Rate

For each trap that was deployed the fetch, sediment moisture content 10m upwind of the trap and trapping rate were calculated. The fetch distance was limited by the sand fences bounding the site at the Dune Crest and Dune Toe and surrounding the house north of the site.

The fetch distance, moisture content and trapping rates are presented in Table 4.4. The fetch distance increased across the beach seaward from T1 to T10 with the foreshore having the longest fetch length. The longest fetch distances were found at the foreshore and Berm Crest ranging from 65 to77m. The limiting factor to these fetch lengths was the sand fence surrounding the house north of the site. The shortest fetch lengths were at the Dune Toe ranging from 5 to 8m. The fetch length at the Dune Toe was restricted by the fence located west of the traps at the Dune Toe.

The moisture content of the sediment ranged from 0 to 4.6% during trapping. The highest moisture contents were found on 07 December and 25 December. The relative humidity during those trapping events was 53 and 41%, respectively. The elevated moisture contents are due to rain that occurred within 24 hours prior to trapping. Elevated moisture contents on the Foreshore and Berm Crest are likely due to sea spray or direct wave uprush.

The trapping rates during the alongshore winds on 07 December at the Berm Crest are an order of magnitude greater than all other trapping events. On 07 December the range of trapping rates was .01 to 21.32 $kg\ m^{-1}\ hr^{-1}$. Traps on the Mid-Backshore and Upper Foreshore also had significant trapping rates of 7.44 and 6.53 $kg\ m^{-1}\ hr^{-1}$, respectively. The elevated trapping rates at the Berm Crest could be due to the combined effects of frequent gusts exceeding the threshold (Table 4.2), a long fetch, a positive relative wind strength (Figure 4.4C) and the deflected winds from the fence surrounding the perimeter of the house to the north. The Berm Crest trap is seaward of the house and 5m landward of the seaward limit of the sand-trapping fence. The elevated trapping rate at the Berm Crest may also be a result of entrained sediment being deflected by the fence surrounding the house towards the Berm Crest downwind. The 07 December trapping event also had the highest average wind speeds among all events.

The trapping events on 02 November, 18 November and 25 December produced low trapping rates ranging from 0.003 to 1.62 $kg\ m^{-1}\ hr^{-1}$. The highest trapping rates of 1.62 and 1.50 $kg\ m^{-1}\ hr^{-1}$ were on the Berm Crest and Upper Berm Crest on 02 November and 18 November. These relatively high trapping rates may be due to the greater fetch distances along with the more sustained, higher velocity winds found at the Berm Crest during these two trapping events. The low trapping rates on 25 December may be a result of the high moisture contents and low wind speed throughout the trapping event.

Table 4.4 Trap Location, Fetch Distance, Moisture and Trapping Rates During Trapping Events

Date	Trap ID	Fetch (m)	Moisture %	Trapping rate $kg\ m^{-1}\ hr^{-1}$
02 Nov	T4	64	0.4	0.08
	T9	65	0.0	1.62
18 Nov	T1	21	1.1	0.01
	T3	5	-	0.01
	T4	58	0.3	0.11
	T6	65	0.4	1.50
	T8	65	0.7	1.32
	T10	77	0.5	1.01
07 Dec	T1	45	2.0	0.20
	T2	61	1.0	0.10
	T3	8	3.3	0.15
	T4	61	0.9	7.44
	T5	61	1.2	21.32
	T7	77	2.4	6.53
25 Dec	T4	32	0.8	0.02
	T5	60	4.0	0.21
	T9	66	4.6	0.003

CHAPTER 5

DISCUSSION

5.1 Relative Wind Direction

Winds that approach alongshore are influential in delivering sediment to the foredune (Lynch et al., 2008; Jackson and Nordstrom, 2011). Alongshore winds are responsible for the majority of sediment flux due to the unrestricted fetch and lack of dense development on the backshore (Heathfield and Walker, 2015). Development that restricts these winds will create a reduction in sediment transport.

A house can reduce the wind velocity in its lee (Nordstrom and McCuskey, 1985; Heisler, 1990). The enclave at the field site results in reduced wind speeds that are gusty and turbulent downwind the house from the Dune Crest to Backshore. As a result, the transport rates are reduced from the Dune Crest to backshore during alongshore winds. The Berm Crest is not restricted by the house and is able to achieve higher wind speeds that are more sustained. The elevated standard deviation of wind speed at the Berm Crest may be due to frequent bursts of wind in between periods of low winds. The house deflects alongshore winds and creates areas of overspeed downwind of the corners of the house (Heisler, 1990). The sand-trapping fence surrounding the house also deflects entrained sediment towards the Berm Crest. The deflection and overspeed created by the presence of the house and fence north of the trapping area resulted in enhanced transport rates at the Berm Crest during alongshore winds.

WNW offshore winds are the predominate winds for this segment of the NJ shoreline. These winds frequently deliver sediment towards the water (Bauer et al., 2015). Due to the presence of a residential area west of the site the offshore winds are deflected and reduced (Li et al., 2015; Heisler, 1990). As a result the majority of the winds at this site are from the NNW.

Comparing the wind rose of the site in Bay Head to a regional site about 16 km NW at Monmouth Airport shows a deviation in wind direction. The regional wind rose shows dominant winds are from WNW and range from 275 to 305 degrees. These winds approach offshore at the field site. The Bay Head wind rose shows the majority of winds are NNW and range from 335 to 345 degrees. Wind engineering studies have found that series of buildings are able to reduce the local wind speed or wind pressure by drag force (Li et al., 2015). The dense residential development west of the site reduced westerly winds resulting in predominately northerly winds.

The dense residential area directly west of the site creates a drag force and reduces westerly offshore winds (Li et al., 2015). The buildings create eddies that result in gusty turbulent wind (Mendis et al., 2007). Offshore westerly winds that reach the site may then be further reduced since the Dune Crest is effective in reducing wind velocity in its lee (Nordstrom and McCluskey, 1985; Mendis et al., 2007).

5.2 Transport

For each event besides the 07 December event, the average wind speed never exceeded the required threshold for entrainment. Due to the low average wind speeds, there was likely no continuous transport, but mainly intermittent sediment transport due to intermittent wind. Although the average wind speeds are low, during trapping events intermittent winds were able to transport sediment. Field studies have found that transport rates are directly influenced by gustiness even over very short time scales (Davidson-Arnott et al., 2005). The most frequent duration of wind above the threshold for each day was recorded as one second, which may reduce the overall transport.

The alongshore winds on 07 December had the highest average wind speeds, with the highest speeds at the Berm Crest (Table 4.1) along with a positive relative wind speed value (Figure 4.4C). The threshold of entrainment was exceeded most frequently at the Berm Crest with 23% of the winds exceeding the threshold (Table 4.2). The elevated wind speed at the Berm Crest is created by the house on the backshore deflecting the alongshore winds. It has been found that single houses can deflect wind and create an overspeed downwind (Heisler, 1990). The deflected winds in lee of the house may enter the enclave due to the creation of vortices with an increased speed relative to the upwind speed (Peterka et al., 1985). The overall high wind speeds during this alongshore event are a product of the lack of dense urbanization to the north and the overspeed created by deflected winds.

The Berm Crest and Foreshore had a longer fetch length during the 07 December trapping event. Spies and McEwan (2000) predict a critical fetch of 50m to reach saltation equilibrium. A sufficient fetch will allow sediment transport to be influenced more by the magnitude of the wind (Davidson-Arnot et al., 2005). The unrestricted fetch from the Berm Crest and Foreshore contributed to the elevated transport rates in the area.

A combination of sustained elevated wind speeds (Table 4.2) and long fetch resulted in high trapping rates from the Mid-Backshore (T4) to the Foreshore (T7) on 07 December (Table 4.4) (Jackson and Cooper, 1999; Davidson-Arnott et al., 2005). Although the foreshore had an elevated moisture content, strong winds and adequate fetch length may overcome the binding forces of moisture and create transport (Cooper and Jackson, 1999; Davidson-Arnott et al., 2005; Bauer et al., 2009). The trapping rate on the Berm Crest (T5) of 21.32 $kg\ m^{-1}\ hr^{-1}$ is an order of magnitude greater than all other events.

The wind speed at the Dune Crest and Dune Toe was reduced during the 07 December alongshore winds due to the house to the north. The winds in lee of a building are frequently reduced and turbulent (Nordstrom and Jackson, 1998; Mendis et al., 2007). The fetch was limited by the sand-trapping fence at the Dune Crest and Dune Toe. The combined effects resulted in a reduced transport rate from the Dune Crest to Backshore during alongshore winds.

The 18 November event had a high frequency of wind gusts exceeding the threshold (Table 4.2) and an average wind speed at the Berm Crest of 5.38 $m\ s^{-1}$ (Table 4.1). During the 18 November event the wind exceeded the threshold 28% of the time at the Dune Crest with sustained winds of 5 seconds or more (Table 4.2). The Dune Crest also had a low moisture content (Table 4.4). The high frequency of exceedances and low moisture content is not reflected in the low 0.01 $kg\ m^{-1}\ hr^{-1}$ trapping rate at the Dune Crest during the 18 November event (Table 4.2).

The restricted fetch length may have constrained the sediment flux at the Dune Crest during the 18 November event (Table 4.4). Critical fetch may limit the magnitude of sediment flux on a beach, which may have reduced transport west of the Berm Crest (Bauer and Davidson-Arnott, 2003). The restricted fetch can reduce the potential for equilibrium saltation to occur and reduce the transport rates (Delgado-Fernandez, 2010). The presence of a surface lag can increase the threshold for entrainment and reduce sediment transport. Although the threshold was exceeded, the restricted fetch length resulted in reduced transport rates at the Dune Crest.

The low average wind speeds on 02 November and 25 December are due to extended periods of low winds. Although short bursts of wind occurred, they were not significant enough to raise the overall average. While sediment flux is able to respond to gusts in wind from 1 to 2 seconds, saltation equilibrium may not occur (Li and Neuman, 2014). The primary cause of the low trapping rates on 02 November and 25 December was the low average wind speeds. In order to achieve sufficient sediment entrainment, sustained high-speed winds are required (Bagnold, 1941; Butterfield, 1993).

The 02 November and 25 December events both have sufficient fetch lengths (Table 4.4). A potential constraint on 25 December is the elevated moisture contents (Table 4.4). Moisture increases the amount of shear stress required to dislodge particles (Davidson-Arnott et al., 2008). Although there is moisture present during the 25 December trapping event, the primary constraint to transport for the 02 November and 25 December events was the low winds (Table 4.1).

5.3 Sediment Characteristics

Historically, the beach in Bay Head is comprised of coarse and medium sand that is primarily composed of quartz with pebble and shell lag (McMaster, 1954). Based on the sediment that was collected in Bay Head in 2014 the sediment characteristics remain consistent with these earlier findings. Throughout the sampling, the surface sediment diameter was medium to very coarse sand. This implies that over the last half-century the sediment characteristics have not changed and there is no new source of sediment.

The coarse sediment in Bay Head will require a greater amount of force to become dislodged and entrained. Stronger winds are required to create a sufficient saltation cloud and significant transport. For all of the trapping events the trapped sediment was medium sand. The shear velocity of the wind was not strong enough to exceed the threshold for the all of the surface sediment, but only the finer particles.

The upwind surface sediment had larger mean grain sizes than the trapped sediment which will alter the respective thresholds. Based on Bagnold's (1941) equation there is a direct relationship between large grain diameter and shear threshold required for transport. Selective entrainment is created by the difference in thresholds for the surface and trapped sediment.

The large grain size increases threshold of entrainment for the bulk sediment and is a constraint to transport at the study site.. South of Bay Head in Avalon mean size of surface sediment was as low as 0.16 mm and had a transport rate of 12.50 $kg\ \ m^{-1}\ hr^{-1}$ during average wind speeds of 6.3 $m\ s^{-1}$ (Nordstrom, Jackson and Korotky, 2011). The finer grain sizes at that beach allowed saltation to occur at a relatively low wind speed. Based on the calculated threshold at the site in Bay Head, an average wind speed 6.3 $m\ s^{-1}$ would not exceed the threshold of entrainment for the bulk or trapped sediment. Due to the large grain sizes and elevated threshold at Bay Head, stronger winds are required in order for saltation equilibrium to occur. The large grain size and lag may also reduce transport by increasing the critical fetch length that is required for saltation (Lynch et al., 2008). The sediment supply at this site can strongly affect the transport rates at this beach (Williams and Lee, 1995).

CHAPTER 6

CONCLUSIONS

The results of this study indicate the impact surrounding development has on the wind direction and velocity on a developed beach within an enclave. Westerly offshore winds are reduced by residential homes adjacent to the site. The house reduces wind velocity and promotes gustiness downwind during northerly alongshore winds. The house and also deflects winds and creates an overspeed around the edges. The conclusions that can be drawn as a result of this study are:

1. During winds near the shear threshold velocity selective entrainment of fine grain sediment can occur. Finer sediment with a lower threshold will be entrained leaving the coarse sediment as a lag. This results in sediment-flux during relatively low winds.
2. This site is constrained by both transport and source limits. The winds are not competent enough to entrain all sediment resulting in a transport-limited system. An enclave with reduced fetch, reduced wind speeds, large grain sizes and lag result in source-limiting conditions.
3. Sediment flux is reduced within the enclave due to reduced wind velocities. During alongshore winds, wind velocities within the enclave are intermittent and lower than at the Berm Crest due to the house to the north of the site. At the corners of the house the wind is deflected and creates an overspeed. Also, entrained particles are deflected around the sand-trapping fence located seaward of the house. The deflection of winds and entrained sediment results in a trapping rate at the Berm Crest up to two orders of magnitude greater.

The findings of this study have great implications for beach management methods in developed areas with enclaves. The reduced wind speeds are not able to deliver sediment to the foredune at an appreciable rate. As a result these beaches may not be

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