

First-Year Research in Earth Sciences: Dunes



The Impacts of Three Autumn Storms on a Lake Michigan Foredune

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ABSTRACT

Although studies have analyzed the effects of storms on sand transport and foredune development, few studies have targeted Great Lakes dunes. We investigated how autumn storms affected a foredune in Hoffmaster State Park, Michigan. Our study objectives were to analyze the nature of several autumn storms, measure erosion and deposition on the foredune, and measure effects of wave runup on the beach and foredune. We used sand traps and erosion pins to measure sand transport and surface changes. We mapped wave runup and vegetation change with GPS. Wind measurements were recorded with an on-site anemometer tower. During a two-week period, we documented three different storms with varying wind speeds and precipitation. During one storm, winds reached up to 15 m/s, causing erosion on the upper windward face of the foredune. All three storms showed wave runup onto the foredune, causing deposition in the first few rows of erosion pins. Wrack lines indicate wave runup as much as twenty meters beyond the pre-storm shoreline. Our study shows that the characteristics of autumn storms affect the amount and locations of foredune changes.

INTRODUCTION

Foredunes are essential in buffering inland dunes from wind and waves (Houser *et al.*, 2008). A recent study shows that storm strength is increasing in the Great Lakes region (Angel and Isard, 1998). The effects of storms can be observed in the many dune systems present on the west coast of Michigan. Hoffmaster State Park is an ideal location to study storm impacts because it has an extensive dune system including almost 4 km of foredune. This study looked at autumn storms to see how wind, waves, and precipitation affected a Lake Michigan foredune in Hoffmaster State Park. The objectives of the study are:

- To quantify characteristics of each autumn storm observed,
- To measure changes in the shape of the foredune, and
- To monitor wave runup onto the beach and foredune.

BACKGROUND

Dune-storm interaction is a topic that is being increasingly explored by scientists. Different studies have determined the role of storms in shaping the dune system (Houser *et al.*, 2008; Mathew *et al.*, 2010; Davidson-Arnott *et al.*, 2012) and others have shown the importance of storms and their interactions with the Great Lakes (Angel and Isard, 1998). Foredunes are especially vulnerable to storm activity because of their position relative to the beach. They take up an immediately lakeward position, acting as a buffer for wave activity and strong, coastal winds to the rest of the dune system. As a result, foredunes undergo much change due to strong influences from wind and waves from storms.

There are many variables that can affect the shape of a foredune, such as vegetation, wind speed and direction, and moisture presence. Different studies have looked at the effects of winds on sand transport occurring on the beach and foredune (Davidson-Arnott *et al.*, 2005; Davidson-Arnott *et al.*, 2010). Such studies have found that sand transport is inhibited by presence of moisture and/or vegetation, and that wind speed and direction greatly determine transport rates. If precipitation or wave runup occurs, the moisture presence dynamically influences the threshold of sediment transport based on the drying rate of the sand layer (Davidson-Arnott *et al.*, 2005). Vegetation acts as a friction element, slowing down winds near the ground. Reducing the wind velocity puts the transport rate below the threshold more often, also reducing the amount of sand transport and causing more deposition (Davidson-Arnott *et al.*, 2012). Wind direction and speed were also determined to be main factors in sand transport rates (Davidson-Arnott *et al.*, 2012)—potential sand transport rates are proportional to the cube of the wind speed.

Because of their exposed coastal position, foredunes are highly vulnerable to wave events, some of which can cause extensive damage to the foredune. Houser *et al.* (2008) found that foredunes can undergo overwash from severe storms and have their crests reduced by 2 meters in some cases. When these types of storms occur, a lot of sediment can be pulled from the shore face and into the water body, where it can be returned to the shore during fair weather times (Houser *et al.*, 2008). If the storm is severe enough, it can cause wave events that can completely obliterate the dune system. In the case of the Greenwich Dunes on Prince Edward Island, Mathew *et al.* (2010) showed that after a catastrophic storm event it took up to 70 years for the dune system to recover. Contrary to these extreme cases, waves can cause a much milder

effect on foredunes and beaches known as scarping. Scarping occurs when waves undercut a foredune or beach and create a shelf, exposing roots and potentially cutting off saltating sand from the windward face of the dune (Davidson-Arnott *et al.*, 2012).

Some studies have focused on Great Lakes storms specifically and the patterns they follow. Great Lakes storms are high energy systems that can bring heavy precipitation (sometimes sustained for several days at a time) and high winds. Since 1900, the number of strong cyclones in the annual cold season, November, and December, has been increasing (Angel and Isard, 1998). Seasonal patterns show that storm activity increases during the autumn and winter seasons (van Dijk, 2004). Because of the increased storm activity, the average wind speeds increase in the autumn and more sand movement is possible (van Dijk, 2004).

STUDY AREA

Our research site was located in P.J. Hoffmaster State Park in Norton Shores, Michigan (Figure 1). We focused our measurements on a portion of the foredune and subaerial beach. Immediately east (landward) of the foredune is an active saucer blowout on the dune ridge. At our study site, an anemometer tower had been previously set up on the foredune for another study (van Dijk, 2004, 2014). The study area received very little foot traffic, as it is in the far south section of the park, far from parking areas in the state park.

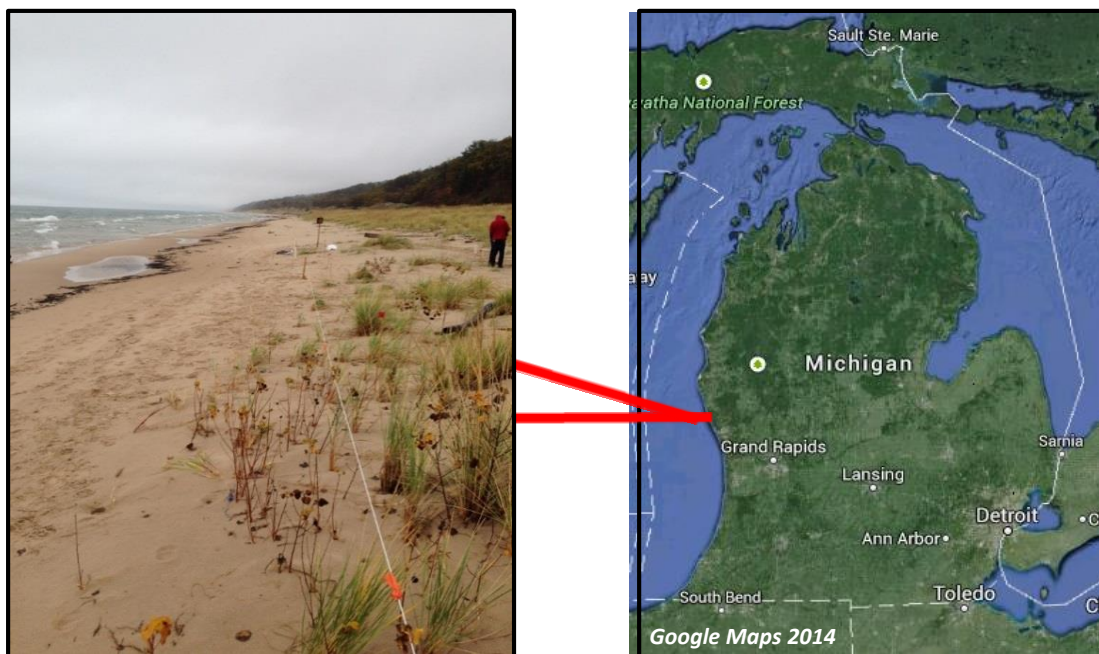


Figure 1: Photograph of study area and its location on the coast of Lake Michigan.

METHODS

Our site measurements took place over two weeks, from October 24 to November 6, 2013. A number of methods were used to quantify characteristics of each storm, measure change in the shape of the foredune, and monitor wave runup onto the beach and foredune. In order to identify each storm, we examined wind data and used a wind speed of 7 m/s as the threshold for storm classification.

An anemometer and wind vane tower was used to measure wind conditions during the course of the study. The tower was comprised of cup anemometers at 4.55m, 2m, 1m, and 0.5m heights with a single wind vane at 4.55m. Measurements were taken every half hour, recording an average wind speed, wind vector, maximum, and minimum for the period of time. For this study, any wind data reported will be data collected by the 4.55m anemometer and wind vane. We also collected data from regional sources on storm characteristics such as wave heights, amount of precipitation, and atmospheric pressure (Table 1).

Erosion pins were used to monitor changes in dune shape due to erosion and deposition. The pins were placed in a 5m x 5m grid extending across the windward face of the foredune to the crest. Pin heights were measured weekly to determine the amount of sand that had been displaced by aeolian or wave activity. We compared this data with wind speeds during storms to identify if there was a relationship between strong storm winds and higher sand transport.

GPS units were used to map wracklines from wave runup. We looked for wracklines by identifying lines of debris in the sand. In order to take the proper measurement, the GPS user walked the path of the wrackline whilst recording the data. The data was then downloaded, post-processed, and brought into Esri ArcGIS 10 where it was superimposed upon a basemap. We calculated the distance of each wrackline from the average shoreline position during the study.

Storm Data	Measurement	Characteristics	Source
Wave height	Daily average (in meters)	Buoy in Lake Michigan near Norton Shores, MI	National Oceanic and Atmospheric Administration (2013)
Precipitation	Daily total (in mm)	National Weather Service station at Muskegon Airport, Muskegon, MI	Weather Underground (2013)
Air pressure	Daily average (in hPa)	National Weather Service station at Muskegon Airport, Muskegon, MI	Weather Underground (2013)

Table 1: Characteristics of storm data collected from regional sources.

RESULTS

During the study, three storms were observed (Figure 2). Each storm lasted approximately two days, with a 2-3 day interstorm period between each storm. During the interstorm periods, wind and wave activity were much milder in nature. Table 2 shows the details for each storm.

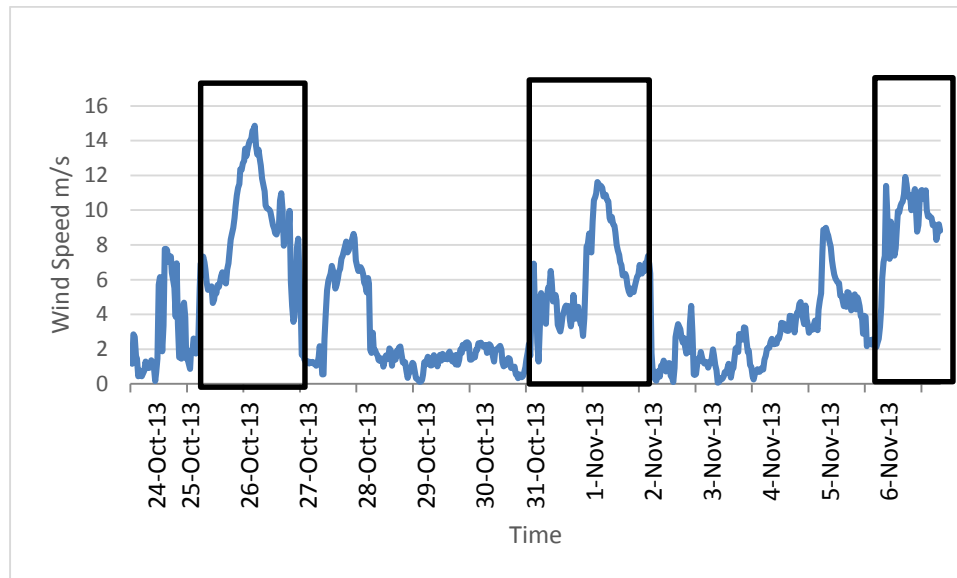


Figure 2: Wind speeds (in m/s) during the study period. Storms are identified by the boxes. Site visits occurred on October 24, October 31 and November 7.

	Storm 1		Storm 2		Storm 3	
	10/25	10/26	10/31	11/1	11/5	11/6
Average Wave Height (m)	2.8	2.75	1.8	1.7	1.5	1.6
Average Wind Speed (m/s)	6.6	9.7	4.6	8.1	4.9	9.7
Maximum Wind Speed (m/s)	13.5	14.85	8.65	11.62	11.9	11.3
Precipitation Amount (mm)	0.25	T	27.18	6.35	T	19.30
Average Pressure (hPa)	1023	1011	997	999	1023	1012

Table 2: Weather and wave details for the three storms. (T indicates trace amounts of precipitation.)

Storm Characteristics

Storm 1 lasted from October 25-26 for a total of 20.5 hours. During the event, the anemometer recorded average wind speeds of 11.1 m/s. The maximum recorded wind speed was 14.9 m/s. Winds prevailed from the SW, but shifted NW towards the end of the storm (Figure 3). The highest wind speeds came from the SW. During this storm, very little precipitation occurred.

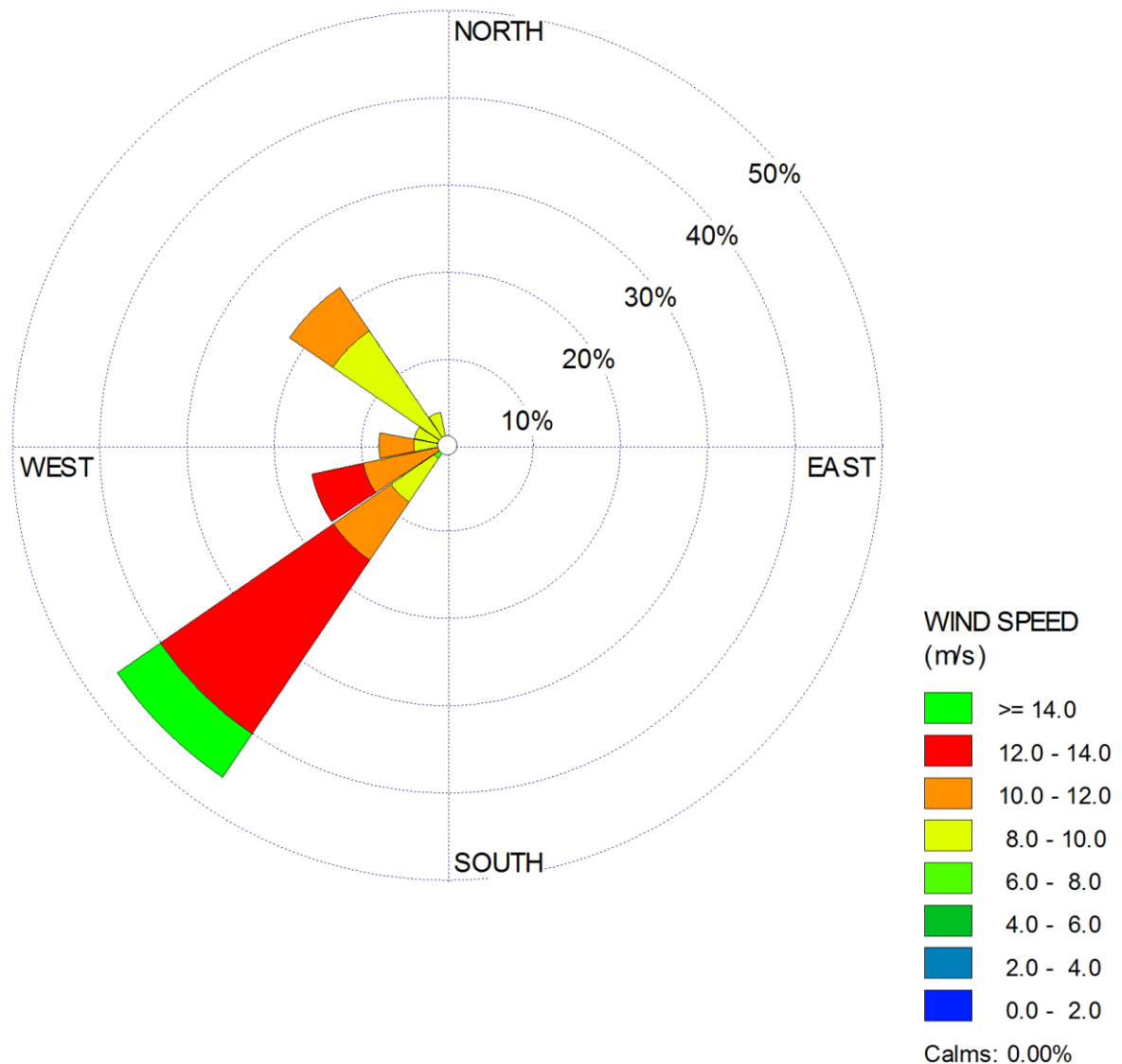


Figure 3: Wind rose (showing frequency of wind speeds from different directions) for Storm 1.

Storm 2 lasted from October 31-November 1, totaling 26.5 hours. During this storm event, anemometer records showed wind speeds averaging 9.5 m/s. The maximum recorded wind speed was 11.6 m/s. A majority of winds came from the W, but there was activity from the NW, WNW, WSW, and SW (Figure 4). Again, the strongest winds came out of the SW. This storm had precipitation throughout the entire event.

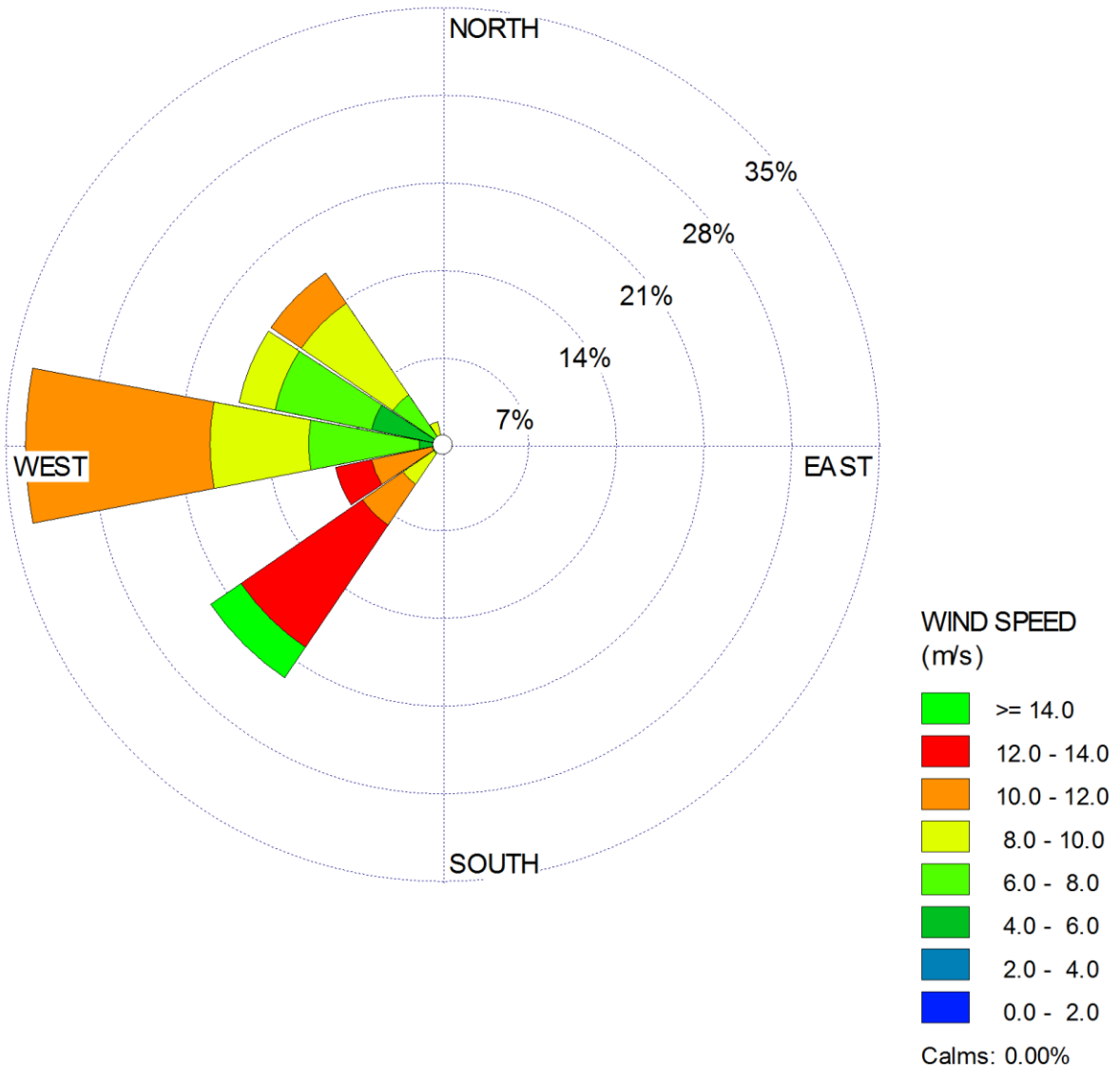


Figure 4: Wind rose (showing frequency of wind speeds from different directions) for Storm 2.

Storm 3 lasted from November 6-7, lasting for 35 hours total. During this storm, the anemometer recorded average wind speeds of 9.6 m/s. The maximum for the storm was recorded at 11.9 m/s. The majority of winds for this storm came from the NW, but there was activity along every vector from NW to SSE (Figure 5). Again, the strongest winds came from the SW. This storm also had precipitation occur, but only on the second day. The storm event was still in progress when the study ended.

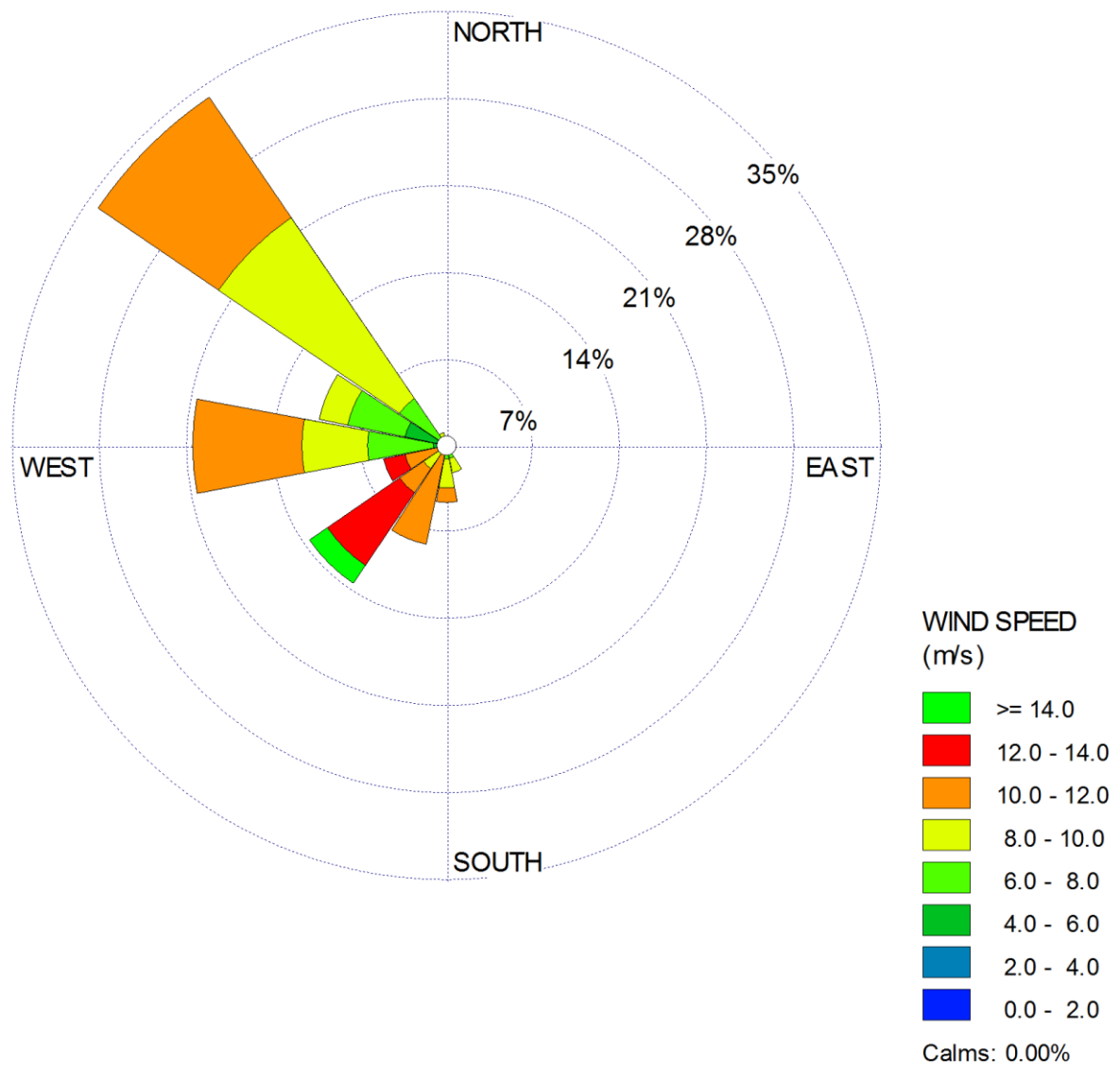


Figure 5: Wind rose (showing frequency of wind speeds from different directions) for Storm 3.

Sediment Movement and Foredune Change

Surface change occurred mainly as deposition on the lakeward portion of the foredune (Figures 6-7). Very little erosion and/or deposition occurred on the vegetated portion of the foredune. On the lakeward portion of the foredune, most of the surface change that occurred was deposition; however, the first lakeward row of pins experienced mostly erosion. The only exception was pin G1, and this pin had a medium-sized pile of sand with vegetation close to it.

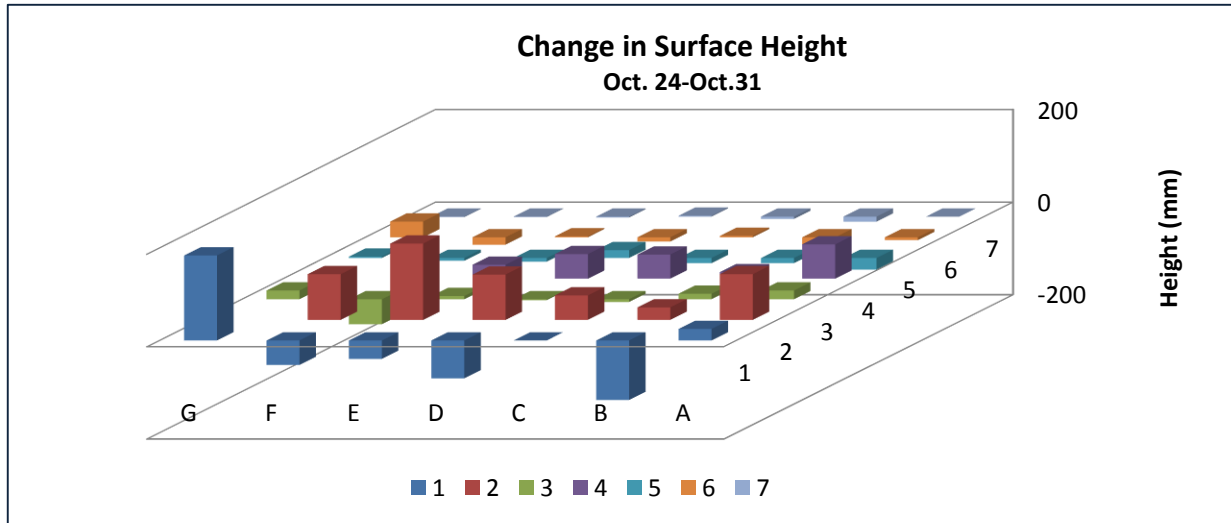


Figure 6: Erosion and deposition that occurred during the first week of the study. The horizontal axis shows the erosion pin letter and number. Row 1 was closest to the shoreline.

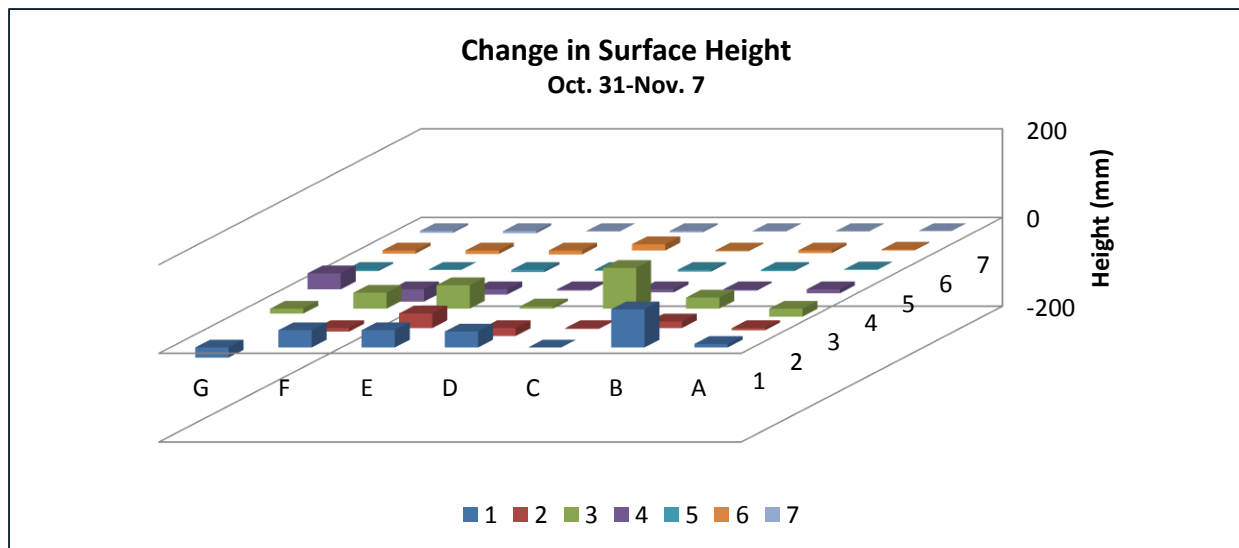


Figure 7: Erosion and deposition measured at erosion pins during the second week of the study. The horizontal axis shows the erosion pin letter and number. Row 1 was closest to the shoreline.

In week one, there was more total surface change measured at erosion pins compared with week 2. In week 1 deposition totaled 18 cm in some areas (Figure 6). Erosion occurred mainly in the first row of pins. In rows 2-4, deposition occurred almost exclusively. Rows 4 through 7, where the vegetated section of the foredune begins, showed no significant sediment erosion or deposition.

In week two, there was less surface change measured at erosion pins, and the distribution varied slightly. Maximum deposition was around 8 cm (Figure 7). This time, deposition occurred in the first row of pins as well as in rows 2-4. There was no significant sediment erosion or deposition on the vegetated portion of the foredune, rows 4-7.

Wave Runup

The wracklines we observed were mostly sticks and washed up plant debris (Figure 8). Some wracklines were located over 20 meters inland from the shoreline at the time of measurement. The most inland wrackline observed was during Storm 3 (Figure 9). During the second site visit on October 31, two wracklines were observed at different distances. Actual measurements between the wracklines and the beach are indicated in Table 3.

During the first site visit, sand traps had been placed along the beach to measure sand transport. During the second week, we found that a large log had been washed onshore and had destroyed these traps. It took five people to move this log out of the way.



Figure 8: A wrackline comprised of mostly sticks and dead plant matter is visible in this photo of our study area.

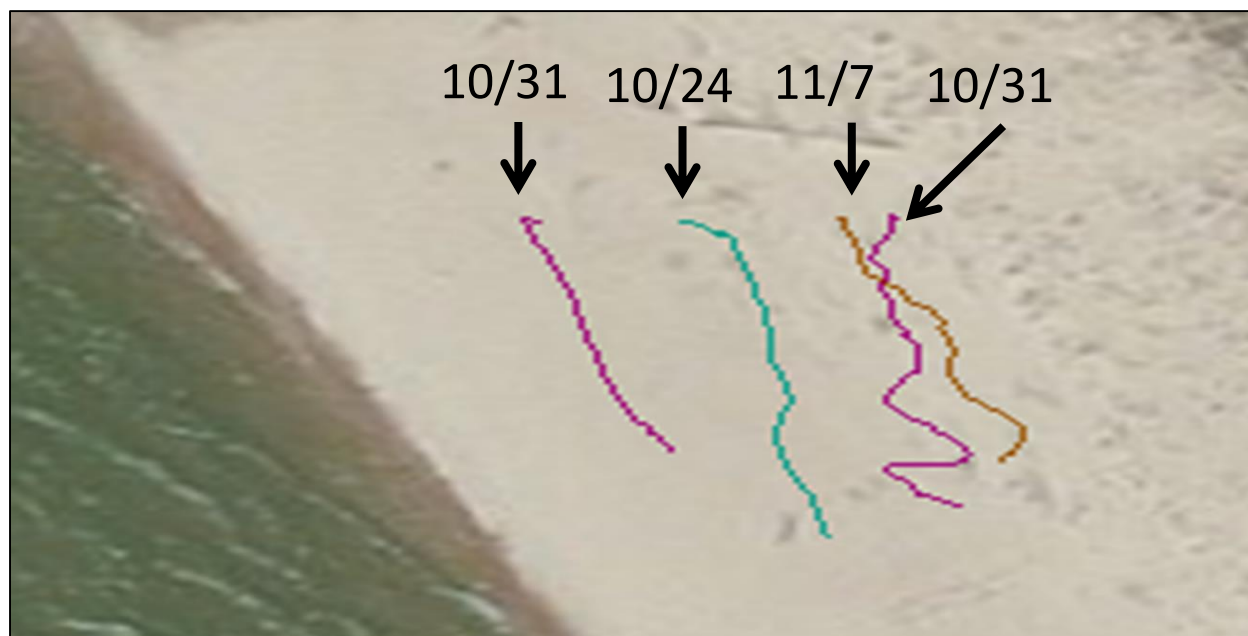


Figure 9: Mapped wracklines from GPS measurements on October 24, October 31 and November 7. The date of the base photo is unknown, but it is unlikely to be from the same time as our study.

	Site Visit 1 (Oct 24)	Site Visit 2 (Oct 31)	Site Visit 3 (Nov 7)
Wrackline Distance from Shoreline (m)	6.2	3.0, 20.0	24.0

Table 3. Distance from the shoreline to the mapped wrackline(s) during site visits.

DISCUSSION

The three storms had different characteristics. Storms 1 and 3 were similar in wind speeds, wave heights, and pressures; however, storm 1 was slightly stronger in all three aspects. The main difference between these two storms is the amount of precipitation that fell. Storm 3 had 19.30 mm of rainfall, whereas storm 1 had only 0.25 mm of rain. Storm 2 had very different characteristics than the other two storms. Storm 2 was a lower pressure event with much lower wind speeds and wave heights, and also significantly more precipitation. Precipitation during the entire storm event totaled 33.53 mm.

Erosion and deposition occurred on the sparsely vegetated lakeward portion of the foredune and not as much on the vegetated foredune. The erosion in the first row of pins and deposition farther inland is the effective growth of the foredune. Foredunes do not advance

landward like other coastal dunes; rather they grow wider and upward (van Dijk, 2014). This is because vegetation roots the slipface in position and prevents the foredune from moving inland. Deposition from aeolian and wave transport occurs where the wind or waves encounter vegetation on the foredune's windward slope. The synergistic effects of these actions cause a net vertical growth of the foredune as opposed to a horizontal movement.

Most of the measured surface change is presumed to be from wave runup and not aeolian activity. The wrackline data show that wave runup covered most of the non-vegetated portions of the beach and foredune during the storms. In Storm 2, the wracklines extend into the third row of erosion pins, and the waves went even further landward in Storm 3. Prior studies have shown that wet sand undergoes less transport from wind because of the effects of water and the added weight to the sand grains (Davidson-Arnott *et al.*, 2005). With most of the beach sand wet from wave runup during the storms, it is unlikely that most of the sand transported to foredune deposition sites was moved by the wind.

Furthermore, waves covering the beach reduced the amount of available fetch length for sand transport. Because the wrackline moved so far inland, the amount of sand exposed to the wind, or fetch, was reduced and therefore the wind could not move as much sand. Although the first and third storms had diagonal vectors, which is optimal for maximizing fetch, the wave runup diminished the fetch to a minimal amount, making high transport rates unlikely.

The wrackline data shows that waves were active on beach sediments and some foredune sediments. Prior studies have shown that waves, when strong enough, can have effects on a dune system ranging from scarping to complete destruction of the dune system (Mathew *et al.*, 2010). We did not observe such damaging effects, but there was clear evidence of waves strong enough to noticeably change the foredune shape. The log that moved inland during Storm 2 is an example of the wave energy that is available to move materials during storm events. Because it took five people to move the log, we can estimate the weight of the log at 400-500 pounds.

We had four observed wracklines; however, only three of them were from storms during our study period. The wrackline observed on October 24 was from a storm event that took place before our study began. We interpret the two wracklines observed on October 31 to be from Storms 1 and 2. Because Storm 2 was in progress during our measurements, we interpreted the wrackline closer to the shoreline to be a Storm 2 wrackline and the wrackline furthest from the shoreline to be from Storm 1. We also interpreted the wrackline mapped on November 6 to be

from Storm 2—from the latter part of the storm event. At the time of our observations, it appeared that Storm 3's wave runup was still pushing inland and the storm's wrackline had not yet been created by the water level receding.

CONCLUSIONS

This 2-week study in autumn 2013 observed and recorded the effects of three storms on a foredune in Hoffmaster State Park. During this time, storm events brought with them high winds, precipitation, and increased wave activity. Erosion occurred on the immediate lakeward portion of the foredune, and deposition occurred in the portion immediately east. Vegetated portions of the foredune had little sediment transport. Wave runup moved far landward during storm events, marked by wracklines over 20 meters landward from the pre-storm line. Finally, storms affected shape of the foredune by either enhancing or restricting sand transport depending on storm characteristics such as wave runup, wind speeds, wind directions, and precipitation.

ACKNOWLEDGEMENTS

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