LINKING INTERNAL COASTAL FOREDUNE MOISTURE DYNAMICS TO EROSION VULNERABILITY

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Abstract: While it is recognized that moisture content plays an important role in dune-slope stability, particularly as associated with storms, there are limited quantitative measurements of internal moisture dynamics within the dune face. Here we present new data characterizing the internal horizontal, vertical, and temporal variability in dune moisture over a one-year period within a vegetated dune in Duck, North Carolina, USA. These data are related to dune stratigraphy, tides, groundwater levels, total-water levels, and precipitation to constrain the relative roles of these factors in controlling internal moisture patterns. Our results indicate that spatial and temporal patterns of internal dune moisture are driven by fluid infiltration in response to changing environmental variable(s), likely affecting the erosion potential of the dune. Complex wetting and drying patterns are also evident at the event timescale. Furthermore, there is strong seasonality in the total-moisture contents within dunes, an observation with important implications for "priming" of dunes for erosion.

Introduction

Sandy coastal foredunes (dunes) are valued for providing myriad services such as infrastructure protection, pollutant filtering, carbon sequestration, and supporting ecological niches (Barbier et al., 2011; Everard et al., 2010). The ability of dunes to provide these ecosystem services varies as dunes adjust to external forcings over time. Dune evolution is a function of complex, interconnected abiotic and biotic processes and feedbacks—not all of which are fully understood (*e.g.*, Garzon et al., 2022; Schwarz et al., 2018), and few of which are fully quantified. Our limited quantitative understanding of the physical processes controlling dune evolution in part hinders our ability to accurately predict dune change on temporal and spatial scales relevant to management needs.

Moisture-related processes are rarely included within quantitative frameworks of dune evolution, even though these same dynamics may be critically important in processes contributing to dune erosion. For example, Palmsten and Holman (2011) suggest that dune slumping is largely controlled by swash infiltration and moisture effects on dune-face stability. Swash infiltration into the dune increases the internal moisture content of the dune, and thus the weight of overburden; this can cause the destabilizing force along the failure plane to exceed the resisting strength of the sediment. However, few studies have quantified the complex temporal (*i.e.*, sub-hourly to annual) and spatial (*i.e.*, cross-shore and vertical) variations in internal dune moisture resulting from swash, groundwater, and precipitation effects (Carretero and Kruse, 2012; Palmsten and Holman, 2011). In particular, it remains unclear when, over what duration, and to what degree components of a dune are wetted, and which environmental variables most contribute to these moisture dynamics. Such knowledge can help elucidate how moisture dynamics affect dune erodibility.

The sedimentological and ecological structure of the dune will also influence spatial patterns of moisture dynamics since the infiltration of fluids into the dune is governed by substrate permeability. Substrate permeability depends on the number, geometry, and size of interconnected pores between grains and capillaries and is almost directly proportional to the porosity of the material. Permeability and porosity are functions of sediment texture such that coarse-grained, well-sorted substrates with irregular grain shapes are more permeable than fine-grained, poorly sorted substrates with uniform grain shapes (Beard and Weyl, 1973). These relationships between permeability, porosity, and sediment texture should yield differential infiltration rates through heterogeneous dune substrate, and consequently, spatiotemporal variability in internal dune moisture.

The objectives of this study are to 1) quantify variations of internal dune moisture content; 2) constrain the environmental variables responsible for those changes; and 3) assess when dunes are most susceptible to erosion as associated with internal moisture dynamics. The resulting data improve understanding of dune dynamics and help determine the capacity of internal moisture as a geomorphic agent. Importantly, these insights may enhance predictions of dune stability.

Methods

Study Site

This study relies on data collected from the foredunes of the US Army Corps of Engineers (USACE) Field Research Facility (FRF) on the northern North Carolina Outer Banks, USA (Fig. 1A, 1B). Located in a humid, subtropical climate, the Outer Banks are a wave-dominated, microtidal chain of relatively long, linear, and narrow barrier islands. This storm-modified system has long experienced sub-decadal periods of erosion and accretion (Brodie et al., 2019), including near-annual dune scarping (*e.g.*, Inman and Dolan, 1989).

The vegetated dune system at the FRF backs an intermediate beach that is ~55 m wide (local island width is ~660 m). The typical foreshore beach slope is 0.1 m/m (Cohn et al., 2021). Tides are semi-diurnal, with a range of ~1 m (Birkemeier et al., 1985), and wave conditions are moderate (significant wave height = 1 m) (Cohn et al., 2021). Beach sediment textures are highly spatially and temporally variable, although in general the lower foreshore is a mix of medium sand and small pebbles and the upper beach is characterized by fine sand (Cohn et al., 2021). At the time of sensor deployment (Summer 2021), the dune crest height

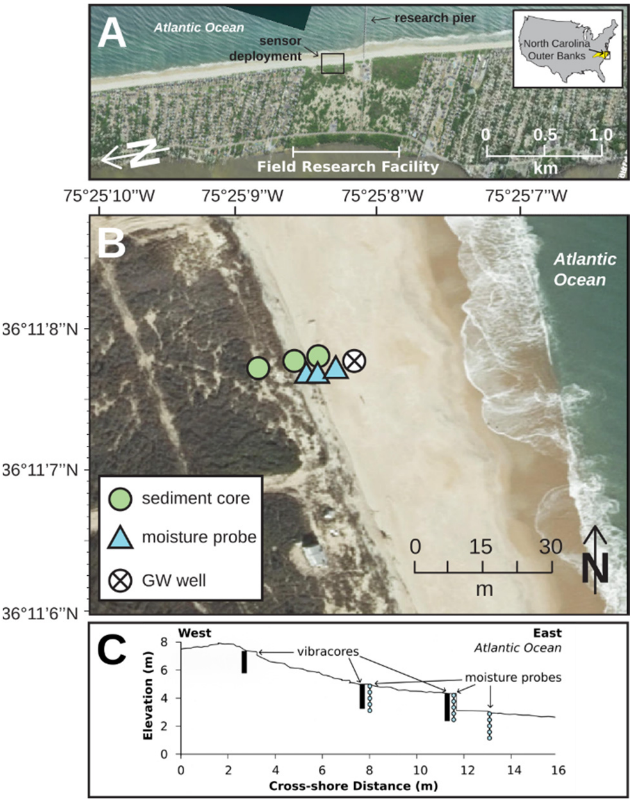

Figure 1. Aerial imagery of the study area (NAIP, 2020) (A); study site depicting relative locations of sediment cores, moisture probes, and groundwater (GW) monitoring well (B); and topographic cross-section of annotated topographic profile showing locations of sensor deployments (C).

was 7.92 m NAVD88, the dune toe height was 2.80 m NAVD88, and the stoss slope was vertically scarped from 2.92–4.30 m NAVD88 (Fig. 1C). Henceforth, all vertical references are relative to the NAVD88 datum.

Environmental and Physical Forcings

Sedimentologic/stratigraphic, groundwater, tide, wave runup, and precipitation data provide necessary context to relate dune moisture content with controlling environmental variables. Dune sedimentology and stratigraphy were characterized from three vibracores (each penetrating to 1.42–1.89 m below the ground surface [bgs]) that were collected at the crest, slope, and scarp of the monitored dune (Fig. 1C). Sediment cores were split, photographed, described for sedimentary structures, texture (as compared to standards), mineralogy, and color (Munsell, 2012), and sampled at a minimum of 10 cm intervals for analysis of grain size and shape. Sediment size and shape were analyzed from oven-dried samples using a CAMSIZER® X2. Grain-size statistics were calculated using the Graphic Method (Folk, 1980). Sediment bed thicknesses were determined based on changes in sediment texture, composition, and color.

Local tide data were compiled from the National Oceanic and Atmospheric Administration National Buoy Data Center from Station ID 8651370 (Duck, North Carolina), located off the FRF research pier, to generate a time series of still-water levels (SWL). Water-level elevations (m) were measured at 6-minute intervals over a 12-month period from 30 August 2021 to 31 August 2022 (*i.e.,* the study period) using NAVD88 as the tidal datum.

One groundwater-monitoring well was installed on the backshore. Groundwater well pressure measurements were collected at 15-minute intervals using ONSET® HOBO® Water Level Data Loggers for a subset of the study period. Atmospheric pressure data from a sensor located at the FRF were used to convert the groundwater well pressure sensor data into elevations (https://chlthredds.erdc.dren.mil/thredds/catalog/frf/catalog.html).

Wave and precipitation data are collected by the USACE FRF and made publicly available on the CHL THREDDS data server. Wave data are recorded at 30-minute intervals by the FRF 17 m and 26 m (water depth) Datawell Waverider Buoys located ~3.2 km and ~16.1 km, respectively, offshore of Duck. These data were used to calculate wave runup ($R_{2\%}$ [*i.e.,* the elevation exceeded by only 2% of swash waves]) following the approach of Stockdon et al. (2006) and using the py-wave-runup package (Leaman et al., 2020) in Python. Total-water levels (TWLs) were calculated as the combination of the tide gauge-measured water levels and the empirically estimated wave runup. Precipitation measurements were collected in the main compound of the FRF using a digital collection of tipping-bucket rain gauges. Precipitation data are reported as cumulative precipitation totals (mm) in 10-minute intervals derived from multiple sensors.

Internal Dune Moisture

We studied internal dune moisture content within the upper 2 m of the vadose zone (region intermittently saturated between the groundwater table and ground surface) of the vegetated FRF dunes. Data from in-situ moisture probes installed along a cross-shore transect are used to characterize spatial and temporal variations in internal dune moisture over the study period. Moisture probes were deployed at the dune slope, scarp, and toe (Fig. 1C). Each was configured with five METER® moisture sensors situated at 0.4 m vertical intervals, with the shallowest sensor at 0.4 m below the ground surface. Moisture measurements were collected at 5-minute intervals throughout the entire 12-month period.

Results

Environmental and Physical Forcings

Sedimentology and stratigraphy

Textural and stratigraphic analysis of the dune shows both cross-shore and vertical variations in sediment texture (Fig. 2) and sedimentary structure. On average, the dune is composed of well-sorted (0.32 Φ), round (mean aspect ratio = 0.74; mean sphericity = 0.88), coarse-grained (D_{50} = 0.55 mm), quartz sand with a near-symmetrical (0.02), mesokurtic (1.04) distribution. Roots, plant debris, whole and disarticulated shells, and shell fragments were observed within the sediment cores. Sediments generally coarsen seaward, with average median grain size (D_{50}) at the dune crest, slope, and scarp equal to 0.33 ± 0.09 mm, 0.52 ± 0.44 mm, and 0.71 ± 0.79 mm, respectively. Average median grain sizes range from 0.24–0.62 mm at the dune crest, 0.24–1.8 mm at the slope, and 0.23–4.14 mm at the scarp. Sediments at all dune positions are generally very well sorted within the first 100 cm bgs. In contrast, sediment sorting at depths between 100 and 180 cm bgs is variable, fluctuating between very well sorted and poorly sorted. Sediment sorting is most variable at the dune scarp (0.18–1.02 Φ) and least variable at the dune crest (0.17–0.44 Φ).

Dune sediment cores reveal complex internal stratigraphy, with variable bed thicknesses. The average bed thickness of sediment at the dune crest, slope, and scarp are 10.9 ± 9.3 cm, 11.5 ± 8.5 cm, and 7.9 ± 7.9 cm respectively.

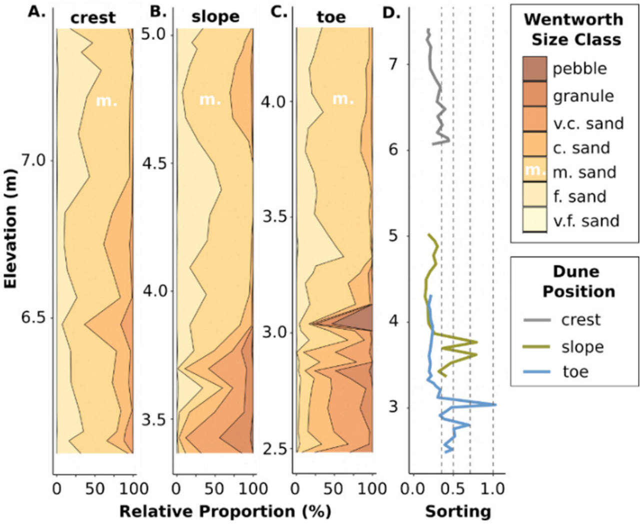

Figure 2. Cross-shore and vertical variations in grain size distribution (A—C); and sorting (D).

Tides, groundwater, total water levels, and precipitation

Tide, groundwater, TWL, and precipitation variations between 30 August 2021 and 31 August 2022 are presented in Fig. 3.

Tides are semi-diurnal with a great diurnal range of 1.73 m. The average SWL over the study period is -0.01 m. Monthly average SWLs were highest in October (SWL_{avg} = 0.18 m) and lowest in February (SWL_{avg} = -0.16 m). Groundwater data were collected from 30 August 2021 to 31 October 2021. Average groundwater levels at the backshore are approximately 0.6 m. These oscillate with the daily tidal cycle, though there is a temporal lag between tides and observed groundwater response. Additionally, there is a smaller range of water levels measured at the groundwater well on the backshore (-0.12–1.72 m) as compared with the total tidal range measured from the offshore tide gauge. Total water levels exceeded the dune toe 1.4% of the study period. The average TWL over the study period is 0.91 m. Monthly average TWLs were highest in January (TWL_{avg} = 1.3 m) and lowest in March (TWL_{avg} = 0.63 m).

Precipitation was nonuniform over the study period (Fig. 3). January and July 2022 were the wettest months, with a cumulative precipitation total of 170.4 mm and 179.5 mm and an average of 0.038 and 0.04 mm of precipitation falling over a 10-minute interval, respectively. September 2021 was the driest month (total precipitation = 0.018 m; average precipitation = 0.004 m [10-minute interval]).

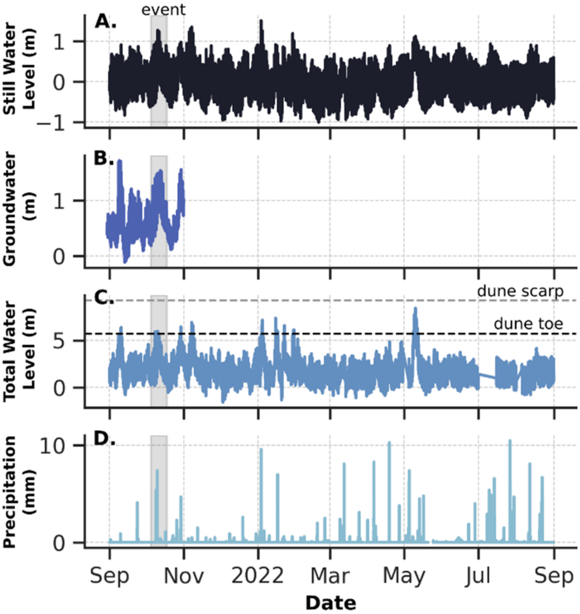

Figure 3. Variations in still water level elevation (A), groundwater (B), total water levels (C), and precipitation (D) over the study period (30 August 2021 – 31 August 2022).

Internal Moisture Variations within the Dune

Internal dune moisture content varied spatially between sampling locations and with depth, revealing clear patterns of moisture gradients (Fig. 4). Moisture levels generally increased seaward, with average moisture content for the dune slope, scarp, and toe equal to 4.2%, 5.9%, and 14.5%, respectively. Probes in the dune slope and toe indicate the dune moisture content initially decreases with depth and then begins to rebound at ~1.2 m and ~0.8 m bgs, respectively. In contrast, moisture content at the dune scarp generally increases with depth, except at the lowest sensor position (*i.e.*, 2 m bgs).

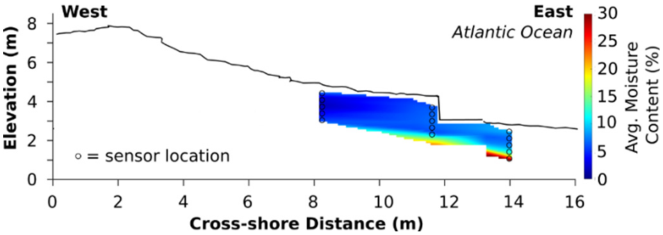

Figure 4. Average internal moisture content within the dune, 30 August 2021 to 31 August 2022.

The dune was predominantly unsaturated (*i.e.*, moisture content less than 30%) throughout the study period. Only the dune toe measurement location ever reached saturation, and even here only for 6.2% of the study period and predominantly at the deepest sensors. At sampling depths above 0.9 m, the dune toe was saturated less than 2% of the study period.

Internal dune moisture content varied temporally on monthly and event (*i.e.*, hours to days) timescales (Figs. 5A, 5B, 5C), revealing both intra-annual trends and wetting and drying patterns. For example, average monthly internal moisture values were highest in January 2021 at all probe locations. The driest months varied between moisture probe locations: the dune slope, scarp, and toe were driest in December 2021, September 2021, and August 2021, respectively.

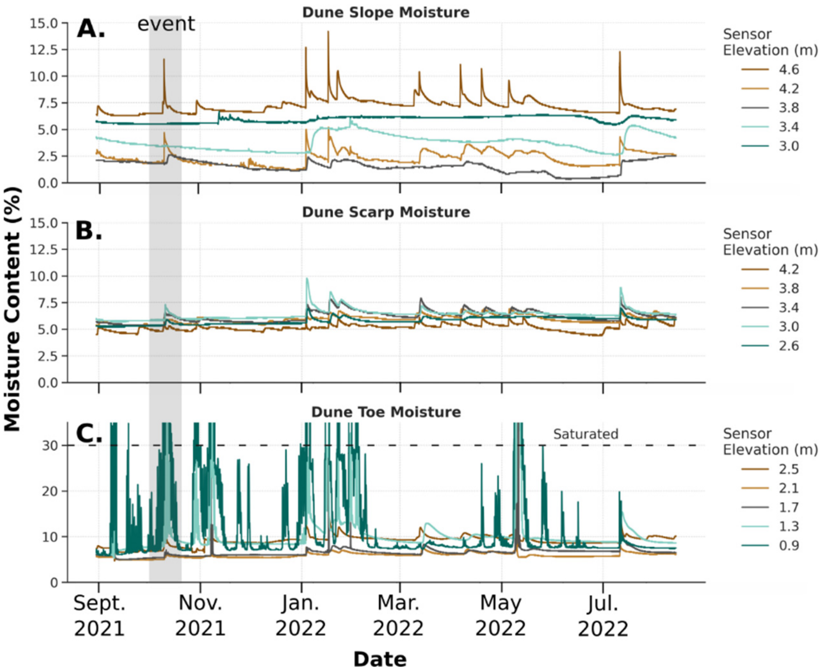

Figure 5. Variations in internal dune moisture at the dune slope (A), scarp (B), and toe (C) from 30 August 2021 to 31 August 2022.

At the event timescale, internal dune moisture content varies temporally and spatially, both in the cross-shore and with sensor elevation. This spatiotemporal variability is exemplified during 5–18 October 2021 (Fig. 6) when a large, unnamed low-pressure system impacted the Outer Banks. Over this period, moisture content at the 4.6 m sensor on the dune slope increased from 7.4% to 11.3% within 30 minutes (0.02 days) and peaked at 11.6% within 100 minutes (0.07 days). This portion of the dune slope took 1.3 days to return to its previous, drier state. Elevated moisture levels during this event were detected at all sensor elevations of the dune toe, but not the dune slope and scarp. Furthermore, the heightened moisture levels detected at the dune toe lasted for a longer period of time and were of a greater magnitude: dune toe moisture values were elevated above average levels for 11 days (4.3 days before elevated levels were detected at the dune slope). Portions of the dune toe (those with elevations ≤ 1.3 m) were consistently saturated for a period of 2.38 days. These spatiotemporal variations in internal dune moisture are likely attributable to environmental variables.

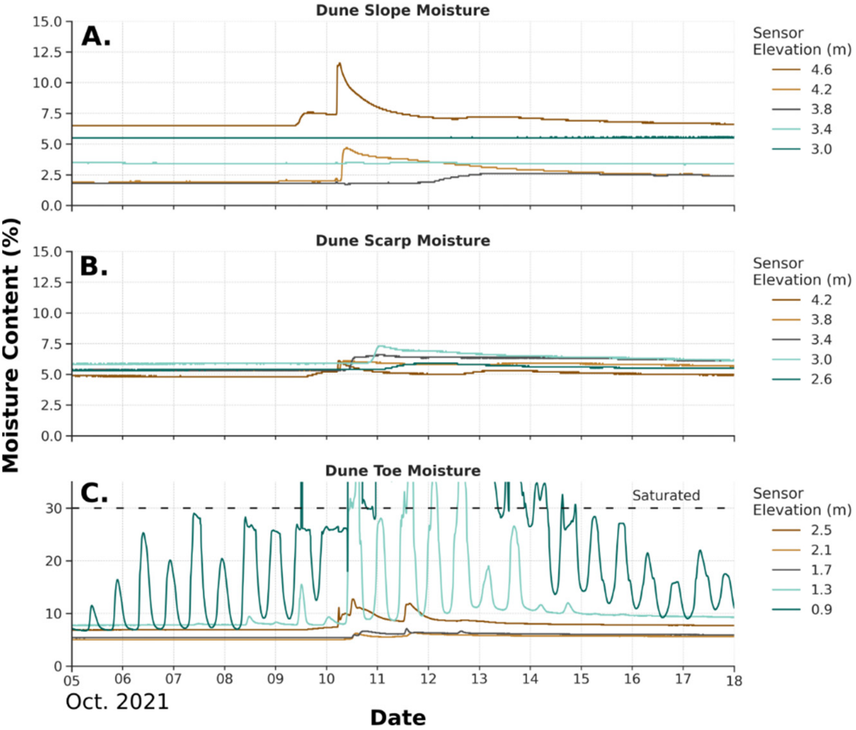

Figure 6. Variations in internal dune moisture during the October 2021 storm event at the dune slope (A), scarp (B), and toe (C).

Event-Scale Processes

Exploring internal dune moisture dynamics during a single event provides insight into wetting and drying patterns associated with precipitation, TWLs, groundwater, and tides. Comprehensive environmental forcing data is available for the same aforementioned storm event from 5-18 October 2021 for which moisture trends are described.

Over the event duration, a total of 65.3 mm of precipitation fell at the FRF. Precipitation began on 9 October and was concentrated on three days: 9 (16.5 mm), 10 (34.4 mm), and 12 (8.5 mm) October. Daily SWLs were also higher than average during 5–18 October 2021, peaking at 1.3 m on 10 October. Groundwater response consistently lags behind SWLs recorded at the tide gauge. This lag time is longer for intermediate high tides (*e.g.,* 1.9 hours between tide and groundwater peaks on 5 October) and shorter for more extreme high tides (*e.g.,* 0.6 hours between peaks on 10 October). TWLs exceeded the dune toe only 0.76% of the event duration, including at least one daily exceedance on 8 October and 10 October. TWLs peaked on 10 October at 2.9 m and consistently exceeded the dune toe for 1.5 hours (longest consecutive duration of TWLs above the dune toe); however, TWLs never exceeded the elevation of the crest of the dune scarp crest.

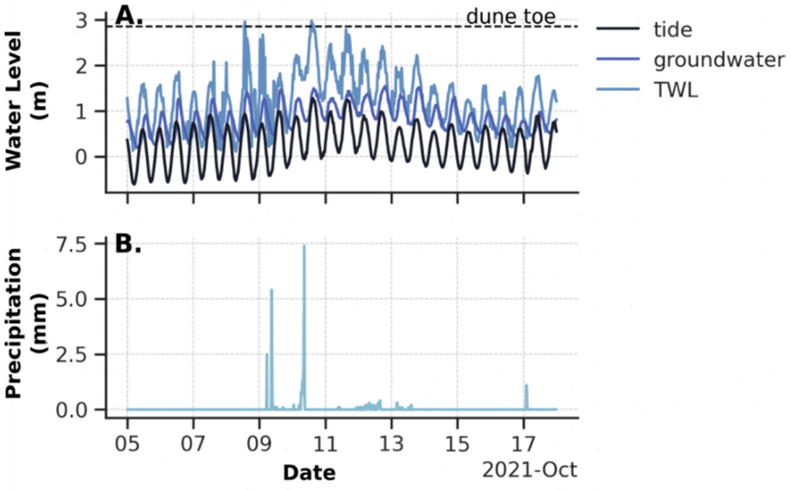

Figure 7. Variations in still water level, groundwater, and total water levels (A) and precipitation (B) from 5–18 October 2021.

Discussion

Controls on Internal Dune Moisture

As wave runup infrequently exceeded the dune toe, the observed variability in moisture content during our study period was likely in response to changes in precipitation, evaporation/evapotranspiration, groundwater level, and tides. Differences in sediment texture within the dune may also contribute to the observed spatial patterns of moisture content (*e.g.*, Agnew, 1988; Dincer et al., 1974) since permeability typically increases with grain size and sorting (Beard and Weyl, 1973). For example, sediment at the moisture sensor positioned at 3.4 m on the dune slope is distinctly coarser (average median grain size [D_{50}] increases from 0.51 to 1.87 mm) and better sorted (from moderately sorted to well sorted) than that at 3.8 m. This textural change yields an increase in permeability from $7.02e^{-11}$ m^2 to $1.75e^{-9}$ m^2, as calculated using the Krumbein and Monk (1943) equation. Thus, the associated increase in permeability, in conjunction with greater groundwater influence, may account for the consistently higher moisture values recorded at the 3.4 m sensor elevation as compared to that at 3.8 m. Textural variability within the dune impacts not only spatial susceptibility to infiltration (and therefore moisture content), but—by extension—erosion potential. These dynamics may be particularly important at the dune scarp, where sediment layers on the stoss slope are vertically exposed and already vulnerable to erosion when swash impacts the dune (Hesp, 1988; Davidson et al., 2020).

The environmental variables contributing to internal dune moisture vary temporally and spatially, particularly in the vertical domain. At all dune positions, infiltration from precipitation likely accounts for elevated moisture contents at the shallowest depths (*e.g.,* Farrell et al., 2021; Gardner and McLaren, 1999). In contrast, moisture levels at the greatest depths below the ground surface are associated with groundwater (Bakker, 1990) and tidal influence. These spatial variations are particularly evident at the event timescale: during the 5–18 October 2021 event, the lowest dune-toe sensor (0.9 m) began to exhibit tidal influence and fluctuate above background moisture levels 4.1 days before any other sensor responded to the event (Fig. 7). Tidal and groundwater influence was detectable at the dune toe (0.9 m sensor) for 11 days. During this same event, precipitation increased the moisture content within upper portions of the dune toe and slope. However, these elevated moisture levels persisted only for 1.3 days. These results indicate that there is a "ramping up" and "ramping down" period for tidal and groundwater influence on internal dune moisture content, whereas the contribution of precipitation to moisture content is temporally constrained.

Seasonal trends in dune moisture content are also apparent (Fig. 2). Similar to infiltration from swash, elevated moisture levels from precipitation increase the weight of overburden (*e.g.*, Zhang and Liu, 2009) within the dune. This indicates that seasonal patterns of precipitation may independently influence the erosion potential of the dune. Specifically, dunes may be more susceptible to slump in mid-winter when precipitation and moisture levels are high. This seasonal susceptibility is exacerbated by the occurrence of nor'easters, which often have elevated TWLs for multiple days at a time and therefore can contribute to substantial dune erosion when TWLs are in the collision regime (*e.g*., Cohn et al., 2021; Ruggiero et al., 2001).

Implications: spatial and temporal erosion "priming"

Taken together, our results indicate that dunes may be spatially and temporally "primed" for erosion based on internal moisture dynamics. For example, the extended temporal tidal and groundwater influence on internal dune moisture dynamics during the "ramping down" period after a storm may partially explain the heightened vulnerability of the dune to erosion in response to sequential storm impacts (*e.g*., Splinter et al., 2014). This temporal erosion vulnerability may be further compounded by spatial patterns in moisture dynamics: based on their close proximity to the shoreline, low elevation, seaward sections of the dune—consistently the wettest portions—are most likely to be impacted by high total water levels that can facilitate dune erosion.

Conclusion

This study demonstrates internal dune moisture dynamics have high spatio-temporal variability, likely affecting the erosion potential of the dune. Spatial variability in internal dune moisture content is influenced by local environmental forcings. These spatial patterns in moisture content are further influenced by variable sediment characteristics within the dune that affect permeability, and thus water infiltration. Temporal variations in moisture content reveal both strong seasonality and complex wetting and drying patterns at the event timescale. These spatiotemporal variations in the total moisture content within dunes have important implications for "priming" dunes for erosion.

Acknowledgments

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