Monitoring overwash using water-level loggers resolves frequent inundation and run-up events

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Abstract

Long-term (months to years) data on barrier-island overwash is lacking, but necessary for the proper parameterization of models addressing island response to rising sea levels, increased storminess and anthropogenic changes. Here, we present a method for recording overwash events that requires little maintenance and can endure storms. This technique uses water-level data loggers suspended in shallow wells that are anchored deeply into the ground. The loggers are placed close to the highest elevation of the barrier island along a cross-shore transect and record high-resolution (± 1 cm) and high-frequency (2 minute) water-level measurements. We developed a schema for differentiating between tidal fluctuations in groundwater, run-up overwash and inundation overwash based on the pattern of water-level changes. Interpretations were validated using field cameras aimed at the well and programmed to take a photograph every 5 minutes during daylight hours. There were some data gaps in the record caused by siltation of the logger in the well, repairing a corroded severed cable that was suspending the logger, and limited logger data storage. We constructed a year-long record of overwash frequency and magnitude from October 2012-2013 that included 43 distinct overwash events at a washover fan that initially formed in August of 2011 on Onslow Beach, NC, USA. The record revealed a shift in overwash intensity at the study site, reflecting both changing water levels and changing barrier morphology. The high number of overwash events that occurred at the washover fan 14 months after its initial formation is likely not unique to this site; however, overwash frequency needs to be measured along other shorelines using this method.

Keywords

Overwash; Washover Fan; Barrier Island Processes; Coastal hazards

1. Introduction

The morphology and evolution of barrier islands is largely driven by aeolian and hydrodynamic processes, including wind-, wave- and current-driven erosion and transport of sand along and across the shoreline. Barrier-island studies commonly use contemporaneous observations of wind, current, wave and/or water level conditions and the morphologic response of the shoreface, beach, and/or dunes to improve conceptual and numerical models of morphologic change (e.g., King, 1951; Orford and Carter, 1982; Sallenger, 2000; Anderson and Walker, 2006; Callaghan et al., 2008; Theuerkauf et al., 2014). Ocean overwash, which occurs when the water level of the ocean exceeds the height of the beach berm or dune crest resulting in the flow of water and sediment landward across a barrier island (Donnelly et al., 2006), is an important process that drives island evolution; however, it is difficult and oftentimes dangerous to collect measurements of overwash frequency, duration and height on a barrier island.

The occurrence of ocean overwash depends on ocean conditions (waves and water levels) and the morphology of the shoreline. Obtaining measurements of overwash processes from numerous morphologically distinct barrier islands would provide better constraints on overwash-threshold conditions, resulting in improved predictions of barrier-island response to rising sea level and increased anthropogenic influences. Overwash is the main process for increasing barrier-island width during transgression because it counterbalances island narrowing in response to oceanfront and back-barrier erosion by transporting sediment across the island (Leatherman, 1979; 1983; Kochel and Dolan, 1986; Timmons et al., 2010). Human development on barrier islands tends to restrict cross-shore sediment exchange, contributing to island narrowing and ultimately resulting in increased vulnerability to storms (Riggs and Ames, 2003; Nordstrom, 2014). Additionally, sand transported by overwash processes into the back-barrier lagoon or tidal

creeks can create new substrate for back-barrier environments, such as salt-marshes, grass fields, and maritime shrub and scrub (Godfrey and Godfrey, 1974), which provide essential ecosystem services like fish and bird habitat, carbon sequestration, and protection from waves (Redfield, 1972; Peterson and Turner, 1994; Pendleton et al., 2012).

Barrier-island overwash varies in response to a suite of morphodynamic factors, producing different morphologies of the resulting deposit (washover fan). The controls on overwash and washover-fan morphology include the magnitude and duration of increased ocean-water level, wave height, wind speed and direction, berm and dune elevations, dune morphology (e.g., breaks in the dune), sediment type, resident vegetation, and accommodation space (Reading, 1996; Sallenger, 2000; Donnelly et al, 2006; Matias et al., 2008; Carruthers et al., 2013; Masselink and Van Heteren, 2014). Donnelly et al. (2006) differentiate run-up overwash from inundation overwash by the level of the ocean water relative to the elevation of the dune crest. Run-up overwash occurs when storm-surge elevation is less than dune-crest elevation but storm-surge elevation plus wave run-up exceeds dune elevation (Donnelly et al., 2006). Inundation overwash occurs when storm-surge elevation, measured independently from run-up, is greater than dune-crest elevation, resulting in water consistently flowing over the barrier. Water level measurements on a barrier island are useful for distinguishing inundation overwash from run-up overwash, in addition to determining the direction of flow across the island (Sherwood et al., 2014). The type, duration, and height of overwash defines the landward extent and morphology of the washover fan, ultimately influencing the sand budget and geomorphic evolution of the island.

Improving models that predict the occurrence of overwash should be of interest to coastal managers, as well as researchers in a variety of disciplines, including paleoclimatology, barrier-

island geology and ecology, and coastal engineering. Numerical models have been developed (e.g., Sallenger, 2000; Larson et al., 2005; Stolper et al., 2005; Tuan et al., 2007; Roelvink et al., 2009; Lorenzo-Trueba and Ashton, 2014) with the goal of pinpointing stretches of coastline vulnerable to overwash and simulating the evolution of barrier islands with respect to sea-level rise; however, there is a scarcity of field data on overwash processes for use in model parameterization and validation. Those data that do exist span short time periods (i.e. storm events) and are localized (e.g., Fisher et al., 1974; Fisher and Stauble, 1977; Leatherman and Zaremba, 1987; Guillen et al., 1994; Matias et al., 2010; Sherwood et al., 2014) because overwash events are difficult to predict, challenging to conduct field work around, and are associated with high-energy processes that can break or remove equipment. Sedimentological methods, such as analyzing the stratigraphy of washover deposits or examining washover sediment texture and grading, have been employed to understand overwash processes (Hayes, 1967; Schwartz, 1975; Kochel and Dolan, 1986; Sedgwick and Davis, 2003; Nielsen and Nielsen, 2006; Phantu Wongraj et al., 2013; Shaw et al., 2015) and those methods would be enhanced if paired with independent measurements of island inundation during sediment deposition.

A robust technique for collecting remotely-sensed measurements of overwash during a long period (years) is needed to increase the number of data-sets that can be used to improve model parameterization, validation, and applicability over a wide range of barrier-island morphologies. To address this need, we present an automated method for monitoring the frequency, duration, and height of island overwash resulting from both storm and tidal events, and a framework for interpreting those data. The method detects overwash using pressure sensors housed inside anchored shallow wells. Over the course of a year these sensors collected

high-resolution water-level data capable of detecting events ranging from run-up overwash to hurricane-induced, high-inundation overwash. This manuscript describes well design, discusses deployment on a frequently overwashing barrier island, explains the schema for interpreting overwash in the data-set, presents a year-long record of overwash, and discusses limitations and considerations for applying the technique elsewhere.

2. Materials and Methods

The method involves installing one or more anchored shallow wells with water-level loggers suspended inside on a barrier island. Overwash type, duration, and height can be determined from the water-level record and periodic measurements of the ground surface elevation adjacent to the well. To measure overwash at any cross-shore transect position along a shoreline, the well should be located at the highest elevation landward of the dune crest, or berm crest if dunes do not exist on that part of the barrier island. The well is only measuring the occurrence of overwash at that point, thus multiple wells should be installed to resolve spatial differences in overwash. For example, wells can be deployed parallel to the shoreline to resolve along-beach variation in overwash or in a line perpendicular to the shoreline to resolve cross-shore gradients in water level. Only two wells were installed in this study because the purpose was to present the well design, data-collection methodology and overwash-interpretation schema.

2.1. Well construction

Our well design consisted of a slotted polyvinyl chloride (PVC) well screen (2 m long, 5 cm internal diameter and 0.25 mm slotted screen), capped at the bottom with a conical PVC well point and at the top with a PVC test plug (Fig. 1). The well screen was buried vertically, leaving

the top 50-90 cm exposed above ground to provide easy access to the well and allow for changes in surface elevation around the well due to erosion or deposition, which would otherwise expose the water-level logger or bury the top of the well, respectively. The base of the well was about 50 cm below the water table and the above-ground portion of the screen was wrapped with plastic to prevent wind-blown sand from filling the well. To prevent horizontal and vertical movement of the wells after installation, we used a fence post driver to set a 3 m length of 1.5 cm diameter steel rebar in the ground to the point of refusal and attached the well to the rebar using two metal worm-gear hose clamps. Inside each well we suspended an Onset HOBO® U20 water-level logger from the PVC test plug using a plastic-coated, 0.635 cm-diameter stainless steel cable. Initially, the water-level logger was positioned below the water table, approximately 10-20 cm above the bottom of the well. The offset between the depth of the sensor on the logger and the top of the well was measured to the nearest mm. The depth of the water-level logger in the well had to be periodically adjusted during the observation period to account for sediment accumulating in the bottom of the well and corrosion of the cable. The new offset was recorded so that water levels could be referenced to the same position. Around 85% of the time the water-level logger was submerged and was always below the ground surface; a position that must be maintained for the entire observation period in order to obtain a complete record.

2.2. Data collection and processing

We set the water-level logger to a 2-minute recording interval, which, given memory constraints, required data to be downloaded once each month. During initial deployment and when data were downloaded from the logger, we collected elevation measurements on the ground surface about 1 m away from the well and at the top of the well using a Trimble RTK-

GPS (± 0.5 cm horizontal and ± 2.0 cm vertical). In addition, we determined a reference water level by measuring the distance from the top of the well to the water surface. We used these measurements to: 1) convert observed water levels to the North American Vertical Datum of 1988 (NAVD88) by referencing the well top; 2) evaluate the vertical stability of the well (our wells moved up and down an average of 4.4 ± 2.3 cm (SD) during month-long observation periods); 3) estimate overwash duration and height based on the recorded water level and the elevation of the ground surface next to the well; and 4) account for drift in the sensor using the reference water level.

Water-level logger data were processed using HOBOWare Pro software. Water-level measurements from the sensor were corrected for variations in barometric pressure, which were measured simultaneously by an above-ground pressure sensor located 500 m southwest of the wells at an elevation that would always be sub-aerially exposed. In addition, if the water level in the well was above the sensor at the time of data download, then we provided the software with a reference water level (i.e. distance from the sensor to the water surface measured manually, Fig. 1).

2.3. Field testing

We tested our well design at an active washover fan on Onslow Beach, North Carolina, USA (Fig. 2) from October 2012 to October 2013. Onslow Beach is a barrier island located on Marine Corps Base Camp Lejeune with mean and spring tidal ranges of 1.3 and 2 m, respectively. The washover fan is located in the southwestern part of the island, where dune elevations are low (< 1 m), beach width is narrow (< 50 m), and the shoreline has been consistently eroding across annual and decadal time-scales (Theuerkauf and Rodriguez, 2014).

The fan formed initially during Hurricane Irene in August 2011 and has continued to evolve in response to frequent overwash, typically 1-3 times per month during spring tides as well as during storm events (based on daily observations by Camp Lejeune base personnel and our own observations). The southwest portion of Onslow Beach is undeveloped; thus, during overwash, water can flow unimpeded by infrastructure from the ocean across the width of the barrier, onto the back-barrier salt marsh and into associated tidal channels.

We visited the site 13 times during the testing period (every month) to collect data (Fig. 3). In February, 2013 we used a Riegl three-dimensional LMSZ210ii terrestrial laser scanner to map the topography of the washover fan (Fig. 2). The surface elevation of the fan gradually decreases landward from the berm crest at 1.0 m NAVD88 to the back-barrier marsh at 0.25 m NAVD88 (mean high water = 0.36 m NAVD88). During the three months prior to sensor deployment, field observations at the washover fan by Camp Lejeune environmental management personnel, revealed spatial differences in geomorphology and overwash frequency and extent; some portions of the fan experienced overwash while others did not. The geomorphology of the washover fan also varied temporally and we observed changes in berm elevation, dune shape, breaks in the dune topography, and back-barrier slope and elevation during the 2012-2013 period. In order to capture some of the spatial variability in overwash, we installed two wells, one on each side of the washover fan (Fig.2). The wells were initially installed in shallow channels (5-10 cm deep). Wells A and B were located ~25 and 50 m landward of the berm crest, respectively. Well B was positioned at a lower average ground surface elevation (~0.7 m NAVD88) than Well A (~0.9 m NAVD88).

Water level commonly reached <5 cm above the ground surface, making it difficult to distinguish between inundation and run-up overwash. To validate our interpretation of overwash

type from the water-level-logger data using visual data, we deployed three Reconyx Hyperfire HC500 trail cameras on the washover fan from April 2013 to October 2013. Cameras were distributed and aimed to provide maximum spatial coverage to document the origin(s) of water on the fan and in the wells (e.g., overwash, rain, water rising from the back side of the island). Camera batteries were changed, lenses were cleaned, and memory cards were replaced contemporaneously with the water-level-logger data download (Fig. 3). Camera 1 recorded the western part of the fan, camera 2 included Well B in its field of view, and camera 3 captured the eastern part of the fan near Well A (Fig. 2). Each camera was programmed to take a picture every 5 minutes during daylight hours. In addition to documenting overwash, the cameras also provided important information on precipitation, which commonly raised the water level above the ground surface. Precipitation data from the New River Air Station, located 22 km north of the study area (Fig. 2), were used to help identify rain events prior to installation of the cameras; however, that station likely missed isolated rain events that occurred at Onslow Beach. Significant wave heights were measured during the observation period at station 41109, located 6.5 km offshore of the washover fan in 13.2 m water, and those data (values every 30 minutes) are served by the National Oceanic and Atmospheric Administration's National Data Buoy Center (Figs. 2, 3).

3. Results

Mean significant wave heights > 1.87 m impacted Onslow Beach during 2% of the observation year (Fig. 3). The highest two wave-height events occurred on December 21 (3.17 m) and June 7 (3.11 m) during a winter extra-tropical storm and Tropical Storm Andrea, respectively. There were 9 winter storms that produced waves > 1.87 m and the largest produced

waves above that level for 16 hours. Shortly after we deployed the wells, Hurricane Sandy passed offshore of Onslow Beach as a Category 1 hurricane on October 27 and 28 and produced waves >1.87 m for 33 hours on October 27 and 28, 2012. Hurricane Sandy was the longest duration wave event of the year. After the cameras were deployed on April 10, we captured 7 wave events > 1.87 m, including Tropical Storm Andrea, which was a 16-hour event.

There were some gaps in the water-level record due to the logger memory becoming full before we could download data and sediment accumulation in the well to a level above the logger. All of the events with a mean significant wave height > 1.87 m produced water-level peaks at wells A and B. The highest water-level event at the wells occurred during Hurricane Sandy, when the water rose to 0.9 and 0.7 m above the sensor at Wells A and B, respectively. From April to September there was at least one water-level peak each month and those peaks reached similar heights above the sensor in each well. The ground surface elevations at Wells A and B were never below the water-level loggers during the observation period, and the year-long ground-surface elevation range was 45 and 43 cm, respectively (Fig. 3). Changes in the ground-surface elevation during the year were similar at both wells, showing the highest variability (45 cm) between October, 2012 and March 2013 and < 11 cm variability between April and October 2013. The ground-surface elevation at Well A was the same at the beginning and end of the observation period. At Well B, the ground-surface elevation was 25 cm lower at the end of the observation period than it was at the beginning.

4. Interpreting water-level data

Recorded peaks in water level can result from several different processes, which at times co-occur, including: inundation overwash, run-up overwash, groundwater fluctuations caused by

tides and rain, and flooding caused by heavy rain. It was not possible to differentiate between these processes that raise the water level above the ground surface by simply clipping observations below the measured ground-surface elevation from the data set. Processing the data set with the ground surface as the overwash threshold and analyzing results for run-up and inundation overwash initially provided a number of false-positives, as determined by inspection of the camera record, by including heavy rainfall events that caused flooding, but were not coincident with overwash. In some instances, the filter also failed to identify overwash events that were recognized in the photos. This likely occurred because of both changes in sediment-surface elevation between site visits and the uncertainty associated with surface-elevation measurements (~2 cm RTK-GPS error). False positives were only a problem when the water-level height was close to the ground-surface elevation. Large inundation overwash events (>10 cm), like the one associated with Hurricane Sandy, were easily recognized in the water level record. Consequently, in order to develop an interpretation schema we used the photos to identify smaller overwash events, extracted the water-level time series for those events, and identified water-level patterns indicative of low inundation overwash (< 10 cm water depth above the ground surface) and run-up overwash. Identifying diagnostic patterns for the different types of overwash and flooding from rain allowed us to interpret the water-level record when camera data were not available. Furthermore, we confirmed that all camera-documented overwash events were also recorded by a water-level logger.

4.1. Inundation overwash

Hurricane Sandy produced the highest recorded water levels of the year, and although it impacted the site before cameras were installed, based on the elevation of the ground surface and

the water level record, the storm unquestionably caused multiple inundation events around the wells (Fig. 4). When the sensors were deployed before the storm, the ground-surface elevation at Well A was 0.7 m NAVD88. Preceding the first high tide on October 27, around 04:00, the water level rose at the well to a depth of 11 cm, and covered the ground surface for about 2 hours. Later that day, the water level inundated the area to a maximum depth of 16 cm around Well A for ~13-18 hours. Both of those events are inundation overwash because the elevation of the water cover recorded by the sensors far exceeded all washover-fan elevations, indicating water extended continuously from the ocean, across the island and to the back-barrier tidal channels. Large storm events, like Hurricane Sandy, that cause long-duration (>5 hours) inundation and are associated with high winds, waves and precipitation, produce water-level fluctuations > 10 cm above the ground surface and are easily recognized as inundation overwash in the data set. Low (< 10 cm) inundation overwash events are more difficult to recognize and require interpretation (e.g., those shown the day after Hurricane Sandy and July 21-24; Figs. 4, 5).

The two water-level peaks that occurred during the first high tides of October 29 and 30 are interpreted to have exceeded the ground surface elevation at Well A (Fig. 4). At the end of the observation period that included Hurricane Sandy, the elevation of the ground surface around Well A had increased to ~0.9 m NAVD88. This 0.2 m vertical accretion could have taken place any time between October 11 and November 10, but most likely occurred during the Hurricane Sandy overwash event; which is analogous to overwash deposition examined during Hurricane Ike by Shaw et al. (2015) on the Matagorda Peninsula, Texas. After the storm, when the washover fan experienced inundation overwash during the first high tides of October 29 and 30 (higher high water), the water level fell rapidly from the maximum height to ~0.9 m NAVD88,

and below that, the decrease in water level decelerates (Fig. 4). That decrease in rate of water-level fall is interpreted as the transition from floodwater to groundwater influence and can likely be used as an indicator of the ground-surface elevation. The low-amplitude fluctuations in water level above 0.9 m NAVD88, when the area around Well A was inundated by ~5 cm (29 Oct, 07:00-09:00) and ~8 cm (30 Oct, 07:00-10:15), respectively, are from waves passing through the area during both inundation overwash events (Fig.4).

Camera photos of overwash that occurred after April validate the interpretation of low-inundation overwash events. The short-duration water-level high recorded at both wells on the evening of July 23 was captured as low-inundation overwash by cameras 2 and 3, which imaged a sheet of water flowing constantly over the beach crest to the back-barrier tidal channels and salt marsh (Fig. 5). Three low-inundation overwash events recorded at Well A and one low-inundation overwash event recorded at Well B during July 21-24, occurred around a spring tide (full moon on July 22) and show a rapid increase in water level as the area around the well is flooded to a height above the ground surface for a period > 10 minutes. Water level is continuously above the ground surface at a nearly constant elevation, as indicated by a high density of water-level observations, at the inundation maximum (Fig. 5). On July 22 and 24, the second high tide did not produce overwash at Well B's cross-shore location on the washover fan; rather, the water-level record shows tidally-influenced fluctuations in groundwater levels as a rapid increase in water level to a maximum followed by a gradual water-level decline. The general low-inundation overwash pattern of a rapid increase in water level that plateaus at a maximum is different than the skewed parabolic tidally-influenced fluctuations in groundwater, and was used to recognize low-inundation overwash throughout the year (Fig. 5).

4.2. Run-up overwash and rain events

On July 21, the day before a spring tide, camera 2 imaged run-up overwash at Well B; waves impacted the ground surface at Well B but water did not flow across the entire island into the back-barrier tidal channels and salt marsh (Fig. 5). Water-level loggers recorded a rapid (12 minute) increase to peak water level during inundation of the well to the ground surface, which was immediately followed by a prolonged (>10 hr) decrease in water level, largely driven by the falling tide (Fig. 5). That distinct pattern of the water level rising rapidly to a short-duration peak differs from low-inundation overwash and tidally-influenced fluctuations in groundwater and was used to identify run-up overwash events in the year-long record of water levels. Another example of this pattern can be seen in the record immediately following Hurricane Sandy during the second high tides of October 28 and 29 (lower high water; Fig. 4). Again, run-up overwash is easily distinguished from inundation overwash in the water-level logger record by its rapid increase to a peak level, as indicated by the absence of sustained water level observations at the inundation maximum. During run-up overwash, the high frequency of swash and backwash and the short duration of the events, relative to our water-level logger sampling interval of 2 minutes, prevents resolving individual surges of water crossing the barrier and impacting the wells.

On July 12-13, heavy rain led to a series of short-duration water-level spikes, with several instances of flooding around the wells (Fig. 5). This event was imaged with the cameras and recorded at both wells, though Well B experienced water-level spikes hours before the rain event registered in Well A because Well B was lower in elevation and more prone to experiencing surface flooding. The pattern of flooding from rain shows multiple short-duration spikes in water level, which in all cases were associated with heavy rainfall events documented with our

cameras and/or nearby weather stations. Whereas rain often presents multiple peaks in water level within a tidal cycle and can occur at any time, overwash events generally present a single peak that coincides with high tide (Figs. 4, 5), except during inundation associated with high-magnitude events like hurricanes. Thus, knowledge of local tidal stage timing is important for differentiating flooding from rain and run-up overwash.

4.3. Spatial variations in overwash

The differences in water level observed between our closely-spaced wells indicate the high spatial variability in overwash that can occur along a barrier island, especially during low-inundation and run-up overwash. The elevation of the ground at Well B was approximately 10 cm below Well A between July 21 and 23; however, the sensor in Well A recorded inundation overwash 3 times, while the sensor in Well B only recorded inundation overwash once (Fig.5). During that time period, NOAA Buoy 41036, located in Onslow Bay 50 km directly offshore of Onslow Beach, recorded the average wind speed as 8.3 ± 1.5 m/sec and significant wave height at station 41109 was 1.5 ± 0.2 m (± 1 SD), both out of the south-southwest. Those are not storm conditions for the area (Theuerkauf et al., 2014) and explain why the depth of inundation overwash recorded at the washover fan was low (< 5 cm; Fig.5). During the first and second water-level peaks of July 22-23, the water-level logger in Well B recorded run-up overwash conditions and an increase in the level of the groundwater, respectively, while inundation overwash was recorded in Well A during both water-level peaks. Although the ground surface at Well B was lower in elevation than Well A, we observed on July 18 that the area around Well B was less susceptible to overwash because it was situated behind a berm that was higher in elevation than the area in front of Well A. The berm likely deflected the water away from Well

B, towards the northeast area of the washover fan and Well A. During low-magnitude overwash events, small variations in topography, which can be induced by along-shore variability in berm and dune elevations or beach cusps, strongly influence the water-level records, thus multiple wells should be deployed at a given site.

5. Discussion

5.1. Overwash Record

The ultimate objective of this method was to provide a continuous, long-term (>1 yr) record of overwash frequency, duration, and depth that could be used for assessing coastal hazards and parameterizing process-response models of barrier island geomorphologic change. We define overwash duration as the amount of time water was continuously recorded above the ground surface and overwash depth as the maximum depth of water above the ground surface. In most cases, obtaining these measurements from the record is straightforward; however, accretion and erosion around a well that takes place between well surveys adds uncertainty in the measurement of duration and depth of overwash (Fig. 4). To account for those uncertainties, we first identified each overwash event by type (run-up or inundation), and then binned inundation overwash events into low- and high-inundation overwash based on the duration and maximum height of water above the presumed ground surface. During low-inundation overwash events, the water level was above the ground surface for 5 hours or less and the maximum water depth was less than or equal to 10 cm. Major events (e.g., Hurricane Sandy), defined as high-inundation overwash, occurred when the duration of inundation overwash exceeded 5 hours and maximum water depth was greater than 10 cm.

Using water-level data from Well A, we constructed a year-long record of overwash events (Fig. 6). We identify two periods of increased overwash frequency and magnitude associated with storms (Fig. 6): October 2012 (Hurricane Sandy), and February - March 2013 (two Nor'easters). Following the numerous inundation overwash events of March 2013, run-up overwash, which commonly occurred during spring tides, was the most frequent type of overwash. This change in overwash type that started in April was due both to changes in barrier morphology around the wells, which increased elevation and decreased susceptibility to inundation overwash, and the quiescent spring and summer months (April to September 2013). Consequently, year-long records of overwash can reflect both changing water levels and changing barrier morphology.

The washover fan initially formed in August 2011 during Hurricane Irene and 14 months later, when we started this monitoring effort, the washover fan continued to overwash. We recognized 2 high-inundation, 22 low-inundation and 19 run-up overwash events during a one-year period. Washover fans are commonly attributed to a single storm-induced overwash event such as Hurricane Ike on Matagorda Peninsula, Texas (Shaw et al., 2015) or a few overwash events, such as on the barrier spit Skallingen, Denmark that was interpreted by Nielsen and Nielsen (2006) to have overwashed an average of 3 times/year. The method we describe here allowed us to identify 43 overwash events during a year on Onslow Beach, and that high frequency of overwash is unprecedented but likely not unique to this site.

5.2. Method Limitations and Considerations

The method provides high-resolution long-term measurements of barrier-island overwash; however, there are a few limitations. When the water level is close to the ground-

surface elevation, interpretation of overwash from the water-level record is not always clear, making the inclusion of additional data-sets (e.g. camera traps and meteorological data) helpful for corroborating results. The wells cannot be deployed and left unattended for year-long periods; rather, they should be visited at least monthly to ensure the cable is still suspending the logger, the logger is not silted in, and to measure ground surface elevations around the site. They should also be inspected after extreme storm events to verify that they are still upright and functioning.

Barrier morphology is spatially dynamic, making any overwash record from a single well only indicative of local conditions around that well, especially for small-magnitude overwash events. Deploying multiple wells along and across a barrier will increase resolution of overwash magnitude and spatial variability. Spacing wells along a barrier island at different elevations, and frequently measuring changes in barrier morphology during the study period, will provide the highest spatial resolution. While well placement and number will depend upon a particular study's objectives, it is always important to constrain changes in the geomorphology of a study area. Ephemeral and migrating topographic features, such as berms, dunes, beach cusps, and runnels will directly affect water movement across the barrier and interpretation of the water-level record. Multiple wells spaced across a barrier can provide information on the landward extent of run-up overwash, improve differentiation between run-up overwash and inundation overwash, and determine whether overwash initiated from the estuary or ocean (this was not demonstrated in our study). If only the highest-magnitude events are of interest, when the entire island is inundated during a major storm, then fewer wells can be installed.

6. Conclusions

Deploying a water-level logger inside an anchored shallow well to monitor overwash provides a means of collecting a continuous water-level record, capable of resolving overwash frequency and magnitude over time intervals of a year or more. This method frees researchers from having to anticipate individual overwash events, which can be difficult to predict because of changing beach morphology and hydrodynamic conditions, and from making observations during potentially perilous conditions. Our year-long record contains many overwash events that occurred during periods when there were no large storms as well as during several severe storms. The geomorphology of low-elevation barrier islands can be influenced by overwash processes in the absence of storms, and we show run-up overwash associated with every spring tide in the spring and summer of 2013. Generally, interpretation of the well record was straightforward and could be accomplished by simply examining the water level patterns; however, there were some occasions where accurate interpretation of the record required the use of additional sources of information (e.g. geomorphology, meteorology). Confidence in interpreting the water level record is enhanced when wells are deployed simultaneously with cameras that can verify overwash events. Increasing the spatial resolution of overwash by increasing the number of wells deployed along and across an island will provide additional information on the gradient of the water surface and interactions between island morphology and overwash distribution, type, height and frequency. The long temporal coverage provided by the data logger combined with the minimal time and effort required for managing equipment and interpreting the data make the well method a practical and efficient way to monitor overwash.

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Figure Captions

Figure 1. Photograph and schematic showing a well and water-level logger deployed on the barrier island.

Figure 2. The test site was an active washover fan on Onslow Beach, NC, USA. Imagery collected in April 2013 and provided by Marine Corps Base Camp Lejeune (A). Digital elevation model created from terrestrial laser scanning data collected Feb. 6, 2013 showing the morphology of the beach and washover fan (B). Contour interval is 0.15 m. Camera symbol arrows denote camera direction.

Figure 3. Significant Wave Height measured 6.5 km offshore of the site (top) and water level at wells A (middle) and B (bottom) during the observation period. Significant wave height exceeded 1.87 m during 2% of the period (gray line). Water level is plotted relative to the initial sensor depth and data gaps are indicated. Negative values were clipped and exist because the sensor depth was adjusted throughout the year when the cable was replaced. Ground surface elevation is also plotted relative to the initial sensor depth and was measured about 1 m away from the wells when data were downloaded from the sensor (December ground-surface elevation at Well B is missing due to poor satellite reception).

Figure 4. A 5-day well record showing water levels before, during, and after Hurricane Sandy. Solid horizontal green (gray) line represents pre-hurricane ground surface elevation (measured Oct 11, 2012) and the dashed horizontal green (gray) line represents approximate ground surface

elevation after the hurricane (measured Nov 21, 2012). Vertical blue (gray) lines mark the timing of high tides. Solid red (black) squares denote inundation overwash; hollow red (black) squares denote run-up overwash. Inundation overwash during Hurricane Sandy lasted for 13-18 hrs. The reader is referred to the web version of this article for references to color.

Figure 5. Water-level record from wells A and B and corresponding photos of the washover fan during a rain event (W), dry weather (X), and two discrete overwash events (Y & Z). Horizontal green (black) lines show measured ground-surface elevation at each of the wells on July 3, 2013; vertical blue (gray) lines mark the time of high tides. Solid red (black) squares denote inundation overwash; hollow red (black) square denotes run-up overwash. Photos were taken by Camera 2, which was positioned near the back-beach and pointed landward across the fan (see Fig. 2). Well B is located within the yellow (black) oval on each photo. Note that Photo X, was taken on July 17, 2013 and does not correspond with the graph. The reader is referred to the web version of this article for references to color.

Figure 6. Year-long record of overwash recorded by Well A (Oct 2012 - Sept 2013). Each bar represents a single overwash event; bar length indicates event duration (hrs). Black bars denote run-up overwash; blue (gray) bars denote low inundation overwash with maximum water depth above the ground ≤ 10 cm; red (white) bars denote high inundation overwash with water depth above the ground > 10 cm. Hollow gray boxes show time periods covered in Figs. 4, 5. The reader is referred to the web version of this article for references to color.

Figure 1

Figure 2

Figure 3

Figure 4 (Color)

Figure 5 (Color)

Figure 6 (Color)

Figure 1 (Greyscale)

Figure 2 (Greyscale)

Figure 3 (Greyscale)

Figure 4 (Greyscale)

Figure 5 (Greyscale)

Figure 6 (Greyscale)