SOCIETÀ TOSCANA
DI
SCIENZE NATURALI
RESIDENTE IN PISA

ATTI
DELLA
SOCIETÀ TOSCANA
DI
SCIENZE NATURALI

MEMORIE • SERIE A • VOLUME CXXIV • ANNO 2017

Edizioni ETS

UNIVERSITÀ DI PISA
MUSEO DI STORIA NATURALE
Con il contributo del Museo di Storia Naturale dell'Università di Pisa

Fondazione
Cassa di Risparmio
di Lucca
e della Fondazione Cassa di Risparmio di Lucca

INDICE - *CONTENTS*

Atti Soc. Tosc. Sci. Nat., Mem., Serie A, 124 (2017)
pagg. 83-92, fig. 9; tab. 1; *doi: 10.2424/ASTSN.M.2017.20*

Stephanie Dohner [(*)], Arthur Trembanis [(*)]

BROADKILL BEACH DELAWARE: CASE STUDY OF A BENEFICIAL USE OF DREDGED MATERIAL PROJECT

Abstract - S. Dohner, A. Trembanis, *Broadkill Beach Delaware: case study of a beneficial use of dredged material project.*

Beach nourishment (soft stabilization) has remained the dominant method of erosion control in the US over the last 30 years though increasingly it is more difficult and costly to find new and recurrent sources of beach fill sediment. Beneficial use of dredged material (BUDM) is a method of leveraging funding and sediment resources by placing dredge project spoil sediment onto adjacent beaches. In this case study, an example of a BUDM project that involved placement of fill from a channel deepening of the Delaware River onto an adjacent Delaware Bay shoreline in the wake of hurricane Sandy is highlighted. This project forms the largest beach nourishment project in Delaware Bay history and one of the largest bay shoreline nourishment projects ever conducted in the US. Through a beach survey monitoring effort utilizing both traditional GPS and unmanned aerial vehicles (UAVs) changes to this beach system and the response of the new human modified shoreline to recent storm events including hurricane Joaquin (2015) and winter storm Jonas (2016) are illustrated. While the beach system protected the community during the two extreme events, both storms caused measurable erosion to the berm and bayside dune face. Winter storm Jonas managed a shallow breach of the dune, possibly due to its record-breaking wave heights combined which were not seen during the longer, but gentler conditions created by Hurricane Joaquin.

Key words - beach nourishment, Unmanned Aerial Vehicles, drone, dredge disposal, Delaware, USA

Riassunto - S. Dohner, A. Trembanis, *Broadkill Beach Delaware: caso di studio di un progetto per un uso vantaggioso di materiale dragato.*

I ripascimenti (interventi di tipo morbido) sono rimasti le forme di intervento più utilizzate in risposta ai fenomeni di erosione costiera negli Stati Uniti durante gli ultimi 30 anni, anche se è sempre più difficile e costoso trovare nuove risorse di sedimenti da usare per alimentare artificialmente le spiagge. Un metodo che permette di usare a proprio vantaggio i fondi e le risorse di sedimenti disponibili è quello che prevede di ridistribuire sulle spiagge vicine i sedimenti di scarto provenienti da progetti di dragaggio (*beneficial use of dredge material*, BUDM). In questo manoscritto viene presentato un esempio di applicazione di tale metodo, che coinvolge la ridistribuzione di sedimenti dragati per approfondire l'alveo del Fiume Delaware lungo la costa della vicina Delaware Bay dopo il passaggio dell'uragano Sandy. Questo progetto rappresenta il maggior intervento di ripascimento di spiagge nella storia della Delaware Bay e uno dei più grandi mai realizzati negli Stati Uniti. Attraverso rilievi di monitoraggio della spiaggia effettuati per mezzo del tradizionale GPS e di veicoli aerei autonomi (*unmanned aerial vehicles*, UAV), vengono illustrati i cambiamenti del sistema spiaggia e la risposta della nuova linea di costa modificata dall'uomo a causa dei recenti eventi ad alta energia quali l'uragano Joaquin (2015) e la tempesta invernale Jonas (2016). Mentre il sistema spiaggia ha protetto la comunità durante i due eventi estremi, le tempeste hanno comunque causato un'erosione significativa e misurabile alla berma e al lato della duna rivolto verso la baia. La tempesta invernale Jonas ha prodotto la rottura della duna in alcuni punti: anche se l'incisione non è stata molto profonda, è stata probabilmente provocata dalle altezze delle onde mai registrate prima occorse durante tale evento, che non si erano viste neanche durante l'uragano Joaquin, evento più lungo ma meno violento.

Parole chiave - ripascimento, veicoli aerei autonomi (UAV), drone, dragaggio, Delaware, USA

1. Introduction

Coastal communities are seasonally bombarded with extreme events such as tropical storms and extra tropical cyclones. These storms together with relative sea-level rise processes drive shoreline retreat and attendant coastal erosion along developed shorelines. Beginning largely in the wake of the 1962 Ash Wednesday Nor'easter storm, a national program of beach nourishment (soft stabilization) has become the preferred coastal defensive strategy in the United States. Beach nourishment (soft stabilization) has many advantages over hard stabilization (e.g., seawalls and groins) in that it works with natural materials (sediment) and allows natural processes to continue with less deleterious impacts to the local environment. However, beach nourishment requires repeated application and careful selection of the source material and it is not a one-time fix. In fact, summary studies of the beach nourishment program in the US identified a total of 1,305 nourishment episodes on 382 beaches with a total estimated cost of approximately $2.5 billion USD (in 1996 dollars). Furthermore, annual expenditures consistently required upwards of $100 million USD (in 1996 dollars) in funds and sand volumes for beach nourishment have been seen to be increasing, especially on East Coast barriers (Trembanis *et al.*, 1999). Increasingly, it is difficult to find suitable beach fill material and the scarcity of the resource and environmental concerns is driving up cost and necessi-

[(*)] Coastal Sediments Hydrodynamics and Engineering Laboratory, School of Marine Science and Policy, University of Delaware (Newark DE, 19716, USA). E-mail: art@udel.edu

tating consideration of alternative sources of sediment such as the beneficial use of dredge material (Reilly & Bellis, 1983; French, 1990).

The Mid-Atlantic states of the U.S.A. sit in a unique location to endure tropical storms during the late summer and fall months while enjoying extra-tropical cyclones, known as nor'easters, during winter months. The seasonal events, coupled with a large-scale dredge material utilization project, provide an opportunity to monitor sediment movement and volume change at Broadkill Beach in southern Delaware Bay. This study aims to compare morphology effects of tropical and extra-tropical storms on a microtidal, fetch-limited, sandy, embayed beach with incorporation of drone monitoring techniques.

Hurricane Joaquin (October 2015) and winter storm Jonas (January 2016) provide examples of both storm types experienced in the Mid-Atlantic of the United States. It is critical to monitor the response of Broadkill Beach following storm events and long-term forcings to determine effects of the project on the surrounding wildlife and environment (Reed, 1989; Short & Trembanis, 2004; Bason, 2007; Nebel *et al.*, 2012; Nebel *et al.*, 2013). The monitoring done before and after storms Joaquin and Jonas determined sediment movement and volume change of the project during construction and after completion. This provided a unique perspective on the resiliency of the large-scale dredge material placement done by the United States Army Corps of Engineers (USACE) in conjunction with the Delaware River deepening project and following the widespread destruction of Superstorm Sandy in 2012. The project itself was aimed at reducing storm damage, reducing storm surge, reducing shoreline erosion, increasing shoreline protection, and minimizing degradation of the natural environment (USACE, 1996). Through the use of UAVs, data was collected to aid in understanding the interactions of the project and the extreme events it was designed to withstand.

2. Study Area

This case study highlights Broadkill Beach in the Sussex County, Delaware on the western shore of the Delaware Bay within the Middle Atlantic Bight on the East Coast of the United States (Fig. 1).

The study site consists of five kilometers of unincorporated partially developed shoreline with approximately 430 residents and one commercial lot containing the local convenience store. The mouth of the Delaware Bay is 11.3 kilometers south while Prime Hook National Wildlife Refuge, consisting of 8818 acres of wetland and forest, sits west of Broad-

Fig. 1 - Google Earth satellite image showing Broadkill Beach within Delaware Bay inlaid with a Google Earth geographic image of Broadkill Beach (red outline) and Prime Hook National Wildlife Refuge (light green areas). The United States with the state of Delaware highlighted in red is located in the bottom left corner of the image.

kill Beach (USACE, 1996; Stevens & Trembanis, 2012). As one of the largest estuaries in the U.S., the Delaware Bay supports 70% of the U.S. east coast oil shipping and a multi-million-dollar oyster industry (Kreeger *et al.*, 2010). Ecologically, the bay supports over 200 fish species in all life stages while the shoreline hosts the second-highest concentration of shorebirds in North America (Burger, 1983). The lower bay provides breeding habitat for the largest horseshoe crab populations and unique reef-forming worms known locally as Delaware coral (*Sabellaria vulgaris*) (Wells, 1970; Curtis, 1973; Curtis, 1975; Miller, 2002; Brown & Miller, 2012; Raineault *et al.*, 2012). These organisms' choice of breeding at Broadkill Beach makes project design, construction, and management a challenge for engineers (Botton *et al.*, 1988).

The biological, economical, and longstanding engineering history at Broadkill Beach makes for a unique case study (Hurme & Pullen, 1988; Wu & Fisher, 2002; Rutger's, 2012). It has been nourished (soft stabilization) and also hard stabilization techniques like jetties and groin have been emplaced but the beneficial use of dredged material project is the most ambitious scale-wise. Figure 2 shows Google Earth satellite imagery at Broadkill beach in 2011 (previous to Superstorm Sandy), 2015 (previous to hurricane Joaquin and winter storm Jonas) and 2017 (post-nourishment). Average beach widths are included with each year's image in Figure 2 to gauge the morphologic changes between the historic and nourished beach.

Utilization of dredge material deepened the navigation channel and extended the average beach width from 40 meters to over 120 meters. The sediments sourced from the deepening project were categorized as 90-85 percent coarse sand thus making it compatible for Broadkill Beach placement (USACE, 1996). It is interesting to note on Broadkill Beach that the subaerial sediment classification of the beach is considered non-native due to long-term anthropogenic alterations throughout history (French, 1990). Natural medium grain quartz sand sources traveled from a mobile, sandy spit at the mouth of the Delaware Bay towards the center of the beach (near Rt 16). At this point, transport diverges to the north and south, causing Rt 16 to be the sediment transport node in the area (Maurmeyer, 1978; Dalrymple, 1982). Inlets have been opened and stabilized in 1908 and 1953 but closed due to shoaling. Remnant jetties can be seen and constrain alongshore sediment transport at Broadkill Beach (Kraft & Chacko, 1978). The USACE (1996) considered the previous shoreline protection projects nonfunctional and determined the dredged material could be used to provide shoreline protection, reduce shoreline erosion, reduce storm damage, reduce inundation damage, and protect against future sea level rise estimates of 2-4 centimeters locally, all while minimally impacting the surrounding natural environment (Kreeger *et al.*, 2010).

Fig. 2 - Google Earth satellite imagery is shown in chronological order from 2011, 2015, and 2017. The average beach width was calculated from ten cross-sectional measurements. Standard deviations of beach widths were 18 meters in 2011, 3 meters in 2015, and 5 meters in 2017.

This led to an artificial dune and widened berm design with dimensions described in Figure 3. Personal photos (by the author) of the beach and the photo locations with respect to the study site are shown in Figure 4. The nourishment project was complete at the time of the photos in Figure 3 and project dimensions can be seen in photos A and B. The final photo (D) shows the un-nourished beach at the southern end of the study site. Photo D is representative of the previous morphology of Broadkill Beach before the sediment placement. The dune system of photo D is typically

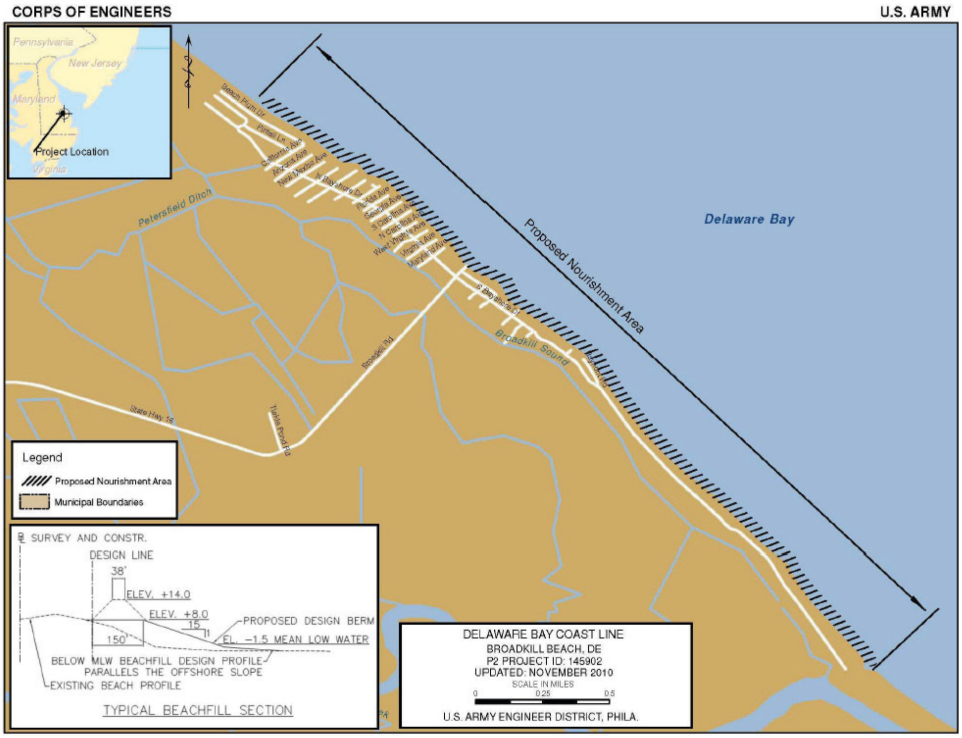

Fig. 3 - Drawing of Broadkill Beach dredge material utilization project. Project extents (miles), dimensions (feet), volumes (cubic meters), and costs (USD) are presented above (USACE, 1996; USACE, 2016).

covered year round with grasses and shrubs with periodic vegetation on the berm when vehicle traffic is minimal, thereby allowing natural seed germination (Kelly, 2014). Dune damage in photo C is typical for this area where storm surge allows wave energy to reach the dune toes and enables scarping (Morton *et al.*, 1994).

3. Storm Characteristics

Delaware (and Broadkill Beach) are located in the Mid-Atlantic states of the U.S. and subject to two extreme storm types with differing characteristics and associated damage depending on the storm origin. These storms come in the form of nor'easters (extra-tropical cyclones) from the internal U.S. and tropical storms moving from east to west across the Atlantic Ocean. Historically, nor'easters are the more frequent event in the Mid-Atlantic but average lower intensity than tropical storms (Blake *et al.*, 2013; Berg, 2016). Typically, tropical storms (hurricane) have stronger sustained winds and higher waves however; extra-tropical storms (nor' easter) create higher storm surge combined with longer storm duration (Dolan & Davis, 1992). Longer duration and higher storm surge typically cause more erosion for the Mid-Atlantic region of the United States rather than the quick input of energy from tropical storms (Zhang, 2001). The Storm Power Index (SPI) developed by Dolan and Davis (1992) relates the offshore significant waves heights and storm duration to the intensity of nor' easters. This index has been shown to favor tropical storms (Zhang, 2001), therefore the Erosion Risk Index (ERI) developed in Kriebel & Dalrymple (1995) weights the duration based on the number of tidal cycles and incorporates storm surge height, which results in more erosion risk associated with storm surge, duration, and wave height rather than wave height being the major factor. Two storms were used in this case study for monitoring the study site response. Winter storm Jonas was a nor'easter in mid-January of 2016 and hurricane Joaquin was an indirect hit of a tropical storm. Storm characteristics are presented in Table 1 with data derived from NOAA offshore buoy (44009) records and Delaware tidal station (8557380) located in Lewes, DE. Station 44009 is located 48.2 kilometers southeast of Cape May, New Jersey in a water depth of 30.5 meters.

While hurricane Joaquin created extended wave action on the eastern shore of the U.S., winter storm Jonas broke storm surge and tide height records (2.82 meters) at the mouth of Delaware Bay (WIS Hindcast Data). Figure 5 plots the significant wave heights (meters) during both storms from buoy 44009 against time in hours. The dotted red line denotes the two-meter point when the event is deemed "significant" in terms of waves.

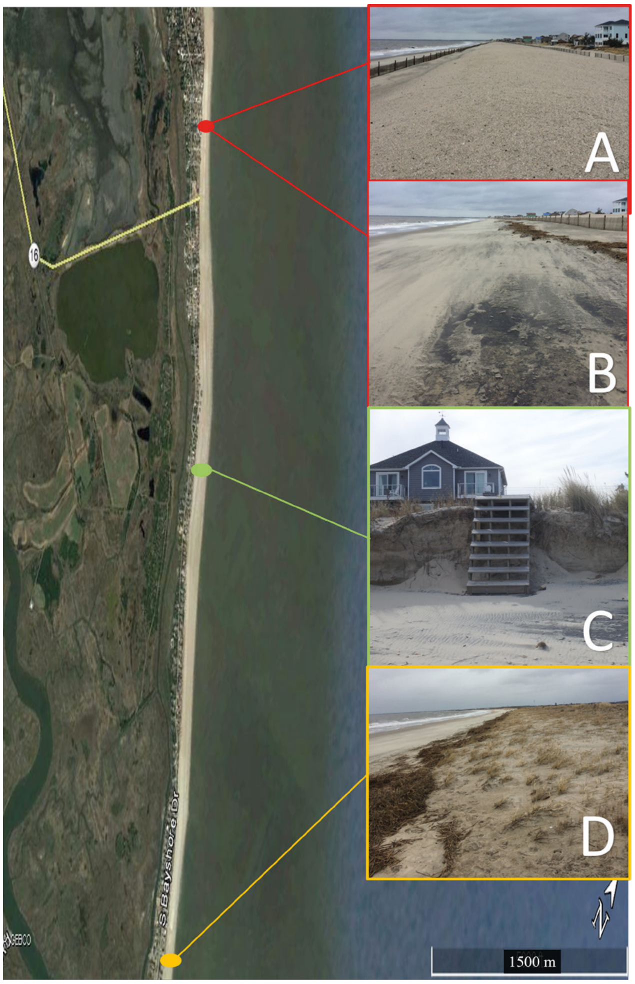

Fig. 4 - Google Earth image of Broadkill Beach with Route 16 (main road) highlighted in yellow. Photos A and B are from the northern end of the study site (red dot) showing the dimensions of the dune and berm extension. Placer depositions and a vegetation rack line can be seen in photo B following hurricane Joaquin. Photo C shows dune scarping following hurricane Joaquin in the middle portion (green dot) of the site. Photo D details the un-nourished beach at the southern (orange) end of the site which represents typical beach morphology of the area.

4. Mapping Methods and Results

The study site sampled pre and post hurricane Joaquin and winter storm Jonas (occurrence year can be found in Table 1). Topographic data was collected using a Topcon GR-5 Real Time Kinematics (RTK) GPS system with a receiver on a surveying backpack. Error from this system was recorded at 12 millimeters horizontally and 18 millimeters vertically, including factory error of five millimeters horizontally and 10 millimeters vertically. Error values depended upon the number of satellites in range, satellite locations, and meteorological conditions. RTK corrections were received via a wireless cell phone system (DiCarlo Network) with a permanent base station housed at the University of Delaware's Sharp Campus in Lewes, DE. Transects were completed with points every two meters and line spacings of ten meters. RTK GPS surveys were conducted within two hours of the predicted low tide window following storm events defined as periods with significant wave heights greater than two meters for three hours. This methodology is consistent with RTK GPS surveying methods around the world (Harley *et al.*, 2011). Aerial images of the study site were taken using a DJI Phantom 3 Advanced quadcopter, known as an unmanned aerial vehicle (UAV) or drone. Images were taken every 5 seconds at an altitude of 40 meters with the camera facing downward (nadir) on an electric gimbal mount for stability. Flights at 40 meters altitude average 1.8 cm per pixel while 80 meter altitude averaged 3.5 centimeters per pixel. Image overlap was 80% and ground control points (GCPs) were seeded within the survey area and measured using the RTK GPS to constrain error in image post-processing. Images were stitched using Agisoft Photoscan photogrammetry techniques to create digital elevation models (DEMs) and orthomosaics of the study area (Fig. 4). The software initially stitches individual UAV images together by matching points within overlapping images. Structure-from-Motion (SfM) algorithms enable

Table 1. Storm characteristics for hurricane Joaquin and winter storm Jonas derived from offshore buoy 44009 and tidal station 8557380.

	Joaquin (October 2015)	Jonas (January 2016)
Max H_s (m)	6.11	8.41
Max T_p (s)	13.79	13.79
Mean Wave Direction (deg)	107	145
Max Wind Speed (m/s)	21.8	26.3
Mean Wind Direction (deg)	141	208
Storm Surge[a] (m)	1.22	1.58
Storm Tide[b] (m)	1.51	2.82
Duration (hr)	114	42
Storm Power Index (m^2/hr)	4256	2971
Risk Index (m^2/hr)	7.5	23.7

a: storm surge is water height above normal astronomical tide level.
b: storm tide is water height above the North American Vertical Datum of 1988 (NAVD88).

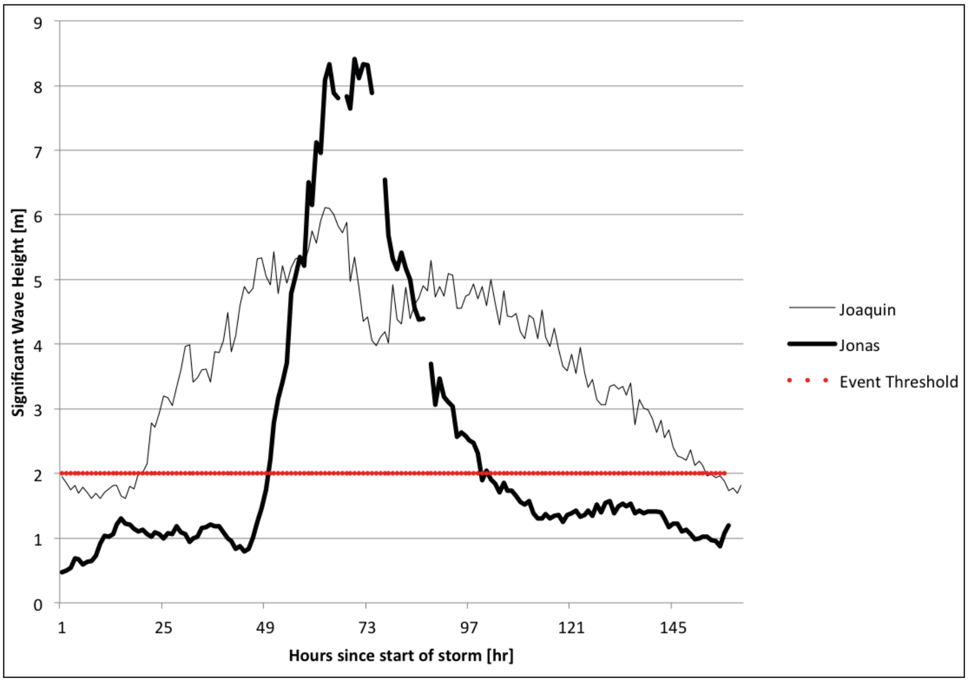

Fig. 5 - Significant wave heights (meters) versus hours since the start of the storm from buoy 44009, offshore of Delaware. The red line indicates the two meter significance threshold for storm waves.

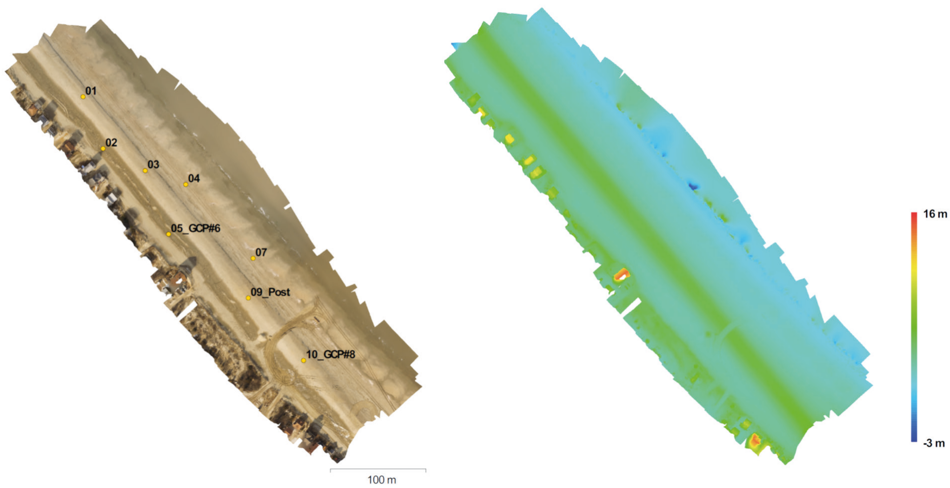

Fig. 6 - An orthomosaic with seeded GCPs (left, 1.64 cm/pixel) and DEM (right, 6.54 cm/pixel) of Broadkill Beach by Route 16 following winter storm Jonas. Both images were created using aerial imagery and photogrammetric processing.

ties between matching points of different images (Rovere *et al.*, 2014; Casella *et al.*, 2016). Embedded GPS metadata allows the software to group geographically close images first, rather than comparing one image to every other image in the dataset. Mosaics are reduced to dense point clouds with elevation values calculated from the stitched images. RTK GPS points in the form of ground control points (GCPs) are used to constrain horizontal and vertical errors in the points cloud and subsequent data products. A dense point cloud is created from the initial sparse point cloud and all later data products (i.e., DEM, mesh) are created from the dense points cloud and export in multiple file formats. Figure 4 on the left is the orthomosaic created from stitching individual images together while Figure 4 (right) is the resulting DEM from the stitched images. The pre and post survey DEMs were then differenced to determine volume change related to each storm. Figure 5 displays the results of the surface differencing as accretion and erosion plots for the study area.

Visually, results show hurricane Joaquin and winter storm Jonas eroding the dune toe, berm, and foreshore of the nourishment area. Some accretion was seen at the base of the dune following Jonas, which may be attributed to slope settlement before and after the storm (Jackson & Cooper, 1999). The total volume change

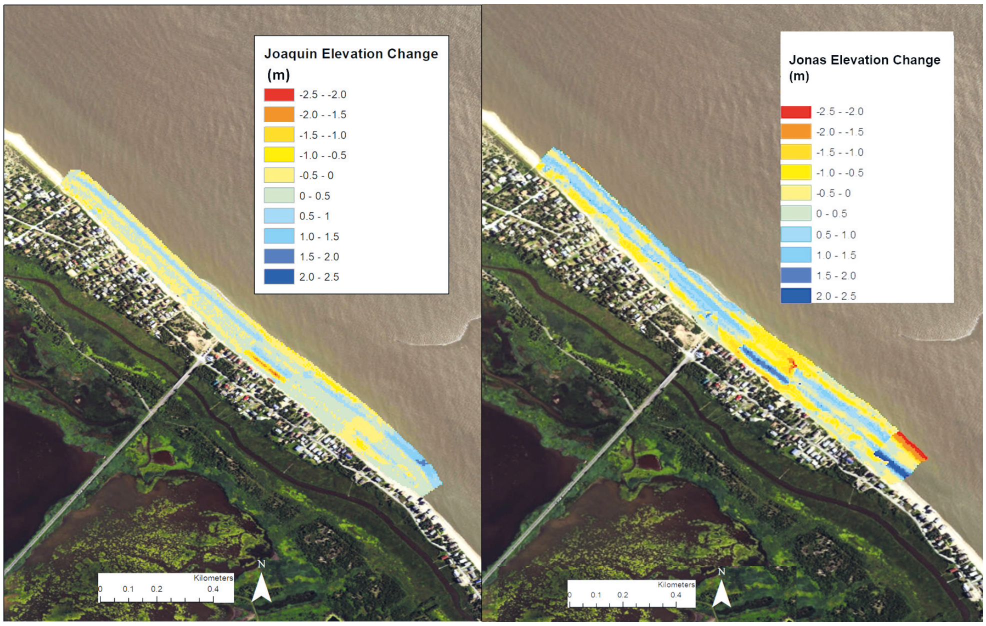

Fig. 7 - Elevation change following hurricane Joaquin (left) and winter storm Jonas (right) in meters. Increasing elevation (accretion) is shown in blue while decreasing elevation (erosion) is shown in red. These calculations were done over a smaller portion of the original study site due to data availability. The road seen intersecting the elevation change maps is Rt. 16 from Figure 1.

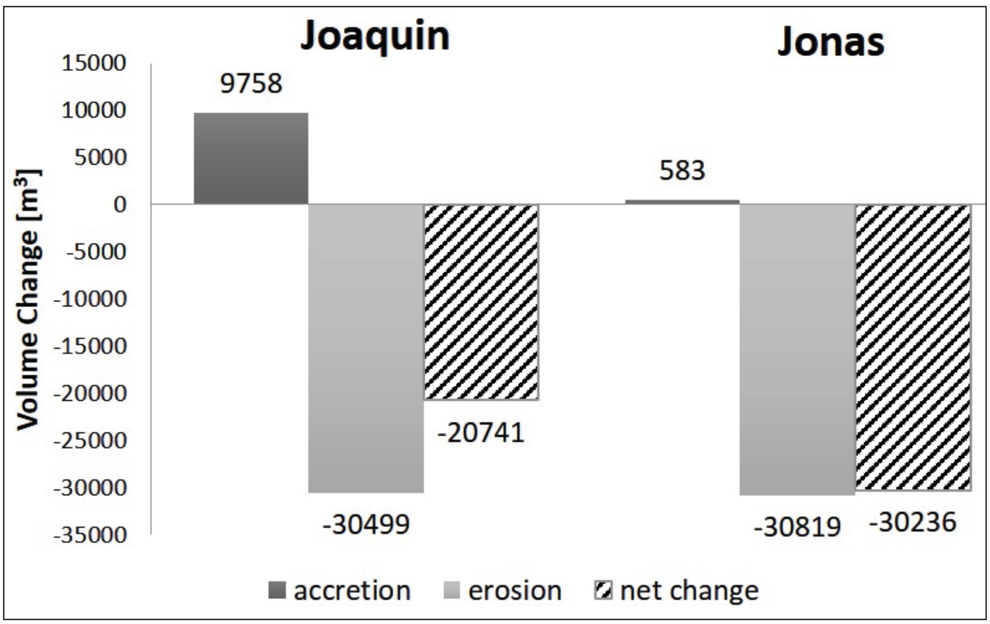

Fig. 8 - Accretion, erosion, and net volume change (accretion + erosion) in cubic meters for the hurricane Joaquin and winter storm Jonas at Broadkill Beach, DE. All volume changes are in reference to MLW (NAVD88) and values in cubic meters are labeled above the corresponding column with errors of +/- 120 cubic meters.

presented in Figure 8 shows winter storm Jonas eroding more sand volume than hurricane Joaquin.

More widespread erosion occurred during winter storm Jonas than hurricane Joaquin, particularly on the berm and beach-facing side of the dune. These are interesting results as hurricane Joaquin had a longer duration (4.8 days) but lower intensity (hydrodynamically) than winter storm Jonas (1.8 days). The longer duration coupled with lower wave energy may account for the mild accretion seen on the berm of the beach while the landward dune face and dune top eroded under strong winds and rain (Davis & Dolan, 1991; Davis & Dolan, 1993). When looking at the Erosion Potential Index in Table 1, the results are less surprising as winter storm Jonas had a higher EPI than hurricane Joaquin even though Joaquin greatly out ranks Jonas on the SPI scale. The greater storm surge during Jonas allowed wave energy to move further inland without dissipation, thereby enabling erosion of the frontal dune and berm.

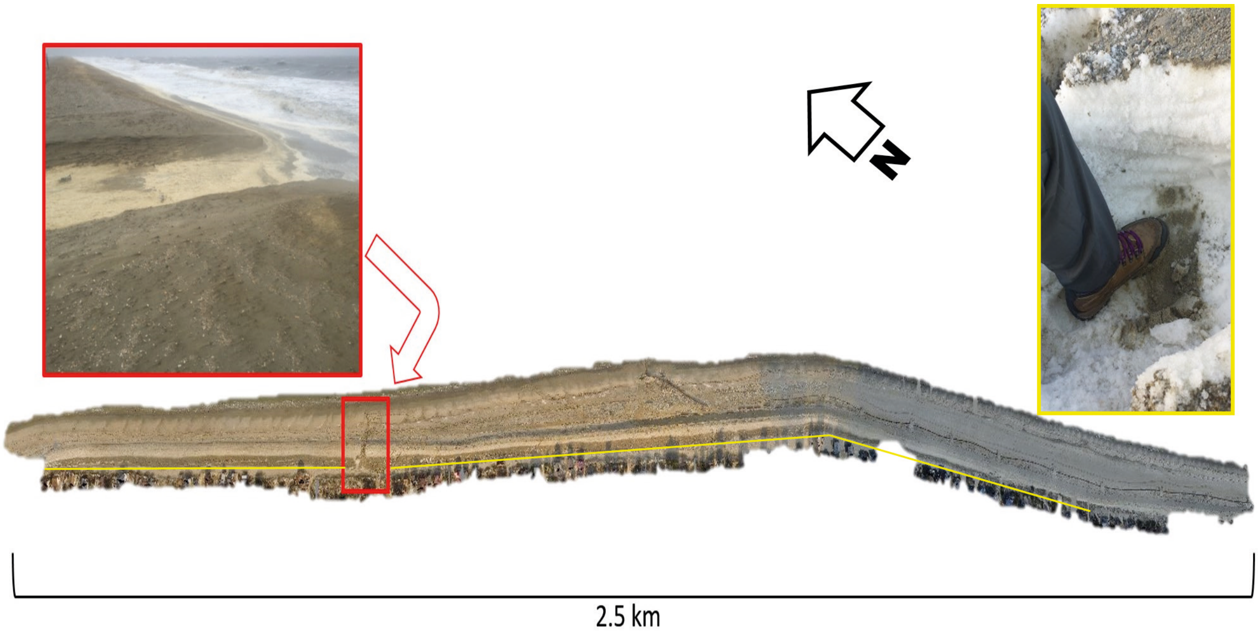

Fig. 9 - Orthomosaic of Broadkill Beach following winter storm Jonas. This mosaic was created from aerial images stitched using photogrammetry post-processing. The shallow dune breach is outlined in red on the orthomosaic and a personal photo taken by a resident outlined in red above the mosaic (left). A personal photo by the authors shows a snow bank covered by sediment on the landward side of the dune (right). The position length of the snow bank is highlighted by the yellow line above.

5. Storm Impacts and Lessons Learned

While results showed erosion of the nourishment project at Broadkill Beach during both storm events, winter storm Jonas took a bigger bite from the shore with its more intense waves and storm surge than hurricane Joaquin. It is important to note the duration of hurricane Joaquin was three days longer than winter storm Jonas, but Jonas provided a direct hit with more extreme conditions than the glancing blow of Joaquin. Winter storm Jonas caused several intriguing formations on the nourishment dune, including a shallow breach of the dune top, near Route 16 and snow bank on the leeward side of the nourishment dune. Figure 9 shows the breach (red rectangle) via an orthomosaic of the entire study area with an inlaid personal photo of the breach provided by a local resident. In the mosaic, there is a noticeable sediment color difference between north and south Broadkill Beach. This was due to differing light levels on the two days of aerial survey, thus exposure levels resulted in sediment color changes within the images.

Figure 9 also shows a dark line of sand (directly above yellow line) between the dune and houses at Broadkill Beach. This was found to be a layer of snow, approximately 0.5 meters deep, covered with a few centimeters of sand. It seems reasonable that snow was deposited during winter storm Jonas and then covered with sediment when the dune was breached. When the area and depth of the snow bank is considered in volume calculations, the snow bank accounts for 13,500 cubic meters of misidentified volume within the digital elevation model. This correlated to increased erosion calculations following winter storm Jonas, essentially net sediment change was greater following Jonas than Joaquin. Initially, this result was unexpected but resulted in an important lesson learned: aerial RGB (red, green, blue) imagery measures only the surface information, potentially resulting in misleading results unless ground truthing is incorporated at the study site.

A perhaps more widely applicable key lessons of this study points to the importance of three-dimensionality in coastal morphology. Cross-sectional profiles are the staple of coastal data collection, whether following storm events or as part of standard monitoring practices but are lacking in completely describing a three dimensional surface when study sites are spatially varied with dune extent, berm width, and vegetation coverage. Alquini *et al.* (2016) comments on the need for “low-cost, integrated engineering devices to collect extensive, real-time datasets” as a way to improve and modernize monitoring systems so that longshore, drainage basin, and fluvial inputs are incorporated into datasets for decision making and monitoring. The findings of this study suggest considering UAVs for rapid, accurate coastal monitoring, particularly for complete study site coverage when areas may be unsafe or inaccessible such as the dune scarping and collapse seen by Alquini *et al.* (2016) in Migliarino – San Rossore – Massaciuccoli Regional Park (Tuscany, Italy). Ease-of-use with UAVs and the post-processing software make a strong case for incorporation by scientific, engineering, management, and policy groups for a holistic approach to coastal field sites where high-resolution, three-dimensional data can provide insight into the multi-dimensional factors that contribute to coastal morphology change.

6. Conclusions

An ambitious dredge material utilization project was designed and completed at Broadkill Beach, Delaware (USA) by the United States Army Corps of Engineers in March of 2016. So far since initial construction, the project has already weathered hurricane Joaquin and winter storm Jonas in a span of three months. Utilizing the rapid response capabilities of a quadcopter UAV, the volume change of the project was monitored before and after these two events to see how the project faired. It was unsurprising to see both events were, in general, erosive to the study site, but unique features were created by winter storm Jonas' record-breaking waves and ferocity. The shallow dune break was captured with the high-resolution capabilities of structure-from-motion algorithms to stitch aerial images into one mosaic and create high-resolution elevation surfaces with less than two centimeters per pixel.
Monitoring the response of the nearly one million cubic meters of dredged sediment placed at Broadkill Beach using UAVs enable accurate representation of the volume changes in a short period of time before and after two extreme storm events. There was an important lesson learned using the UAVs in that it will image exactly what is on the surface. If that surface is sand covering snow bank, the UAV will not dig beneath the surface layer. This provided high-resolution data to determine sediment volume changes due to individual storm events but intelligent post-processing and site knowledge is still needed by humans to reach accurate conclusions from the data. Thus far, Broadkill Beach's dredge material nourishment project has withstood challenging conditions. Continual monitoring of its response to future extreme events and long-term processes will provide insight into the interactions of large-scale nourishment projects, the conditions that shape them, and their effects on the surrounding environment.

Acknowledgements

The authors gratefully acknowledge NOAA Sea Grant (NOAA SG 2016 x 18 RRCE x 8 TREMBANIS) for project support in this study. The concept and techniques behind this effort were first worked out during a sabbatical by Trembanis at the University of Ferrara. Countless graduate and undergraduate students have volunteered to assist in the field survey effort and we are extremely thankful for their time and talents, with special gratitude to Tim Pilegard, Carter DuVal, Ken Haulsee, Danielle Ferraro, Justin Walker, and Hannah Rusch. This manuscript belongs to a series of papers originally submitted to the 3rd International Forum of the Sea and the Coast held on October 13th-15th, 2016 in Forte dei Marmi (Tuscany, Italy).

REFERENCES

Alquini F., Bertoni D., Sarti G., 2016. Extreme Erosion of a Dune Crest Within a Short Timespan (January-September 2016): The Recent Case in the Migliarino – San Rossore – Massaciuccoli Regional Park (Tuscany, Italy). *Atti Società Toscana Scienze Naturali, Memorie, Serie A* 123: 5-16.

Bason C., Jacobs A., Howard, Tymes M., 2007. White Paper on the Status of Sudden Wetland Dieback in Saltmarshes of the Delaware Inland Bays. Delaware Department of Natural Resources & Environmental Control. 8 pp.

Berg R., 2016. National Hurricane Center Tropical cyclone Report Hurricane Joaquin. Report AL112015.

Blake E.S., Kimberlain T.B., Berg R.J., Cangialosi J.P., Beven II J.L., 2013. Tropical Cyclone Report Hurricane Sandy. National Hurricane Center Report.

Botton M.L., Loveland R.E., Jacobsen T.R., 1988. Beach erosion and geochemical factors: Influence on spawning success of horseshoe crabs (Limulus polyphemus) in Delaware Bay. *Marine Biology* 99(3): 325-332.

Brown J.R., Miller D.C., 2011. Persistence and distribution of temperate intertidal worm reefs in Delaware Bay: a comparisonof biological and physical factors. *Estuaries and Coasts* 34: 583-596.

Burger J., 1983. Survey of Shorebird Utilization of Delaware and Raritan Bays in Relation to Energy Activities. Prepared for the Endangered and Nongame Species Program, New Jersey Division of Fish, Game, and Wildlife. Trenton, NJ.

Casella E., Rovere A., Pedroncini A., Stark C.P., Casella M., Ferrari M., Firpo M., 2016. Drones as tools for monitoring beach topography changes in the Ligurian Sea (NW Mediterranean). *Geo-Marine Letters* 26 January 2016. DOI: 10.1007/s00267-016-0435-9

Curtis L.A., 1973. Aspects of the life cycle of Sabellaria vulgaris Verrill (Polychaeta: Sabellariidae) in Delaware Bay. Ph.D. Dissertation, Department of Biological Sciences, University of Delaware, Newark.

Curtis L.A., 1975. Distribution of Sabellaria vulgaris Verrill (Polychaeta: Sabellariidae) on a sandflat in Delaware Bay. *Chesapeake Science* 16: 14-19.

Dalrymple R.A., 1982. An Assessment of an Erosion Problem. University of Delaware Ocean Engineering Program. Resource Report CE-82-22.

Davis R.E., Dolan R., 1991. The 'All Hallows' Eve Storm-October 1991. *Journal of Coastal Research* 8: 978-983.

DAVIS R.E., DOLAN R., 1993. Nor'easters. *American Science* 81: 428-439.

DOLAN R., DEAN R.E., 1992. An Intensity Scale for Atlantic Coast Northeast Storms. *Journal of Coastal Research* 8(4): 840-853.

FRENCH G.T., 1990. Historical Shoreline Changes in Response to Environmental Conditions in West Delaware Bay. University of Maryland.

HARLEY M.D., TURNER I.L., SHORT A.D., RANASINGHE R., 2011. Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. *Coastal Engineering* 58: 194-205.

HURME A.K., PULLEN E.J., 1988. Biological Effects of Marine Sand Mining and Fill Placement for Beach Replenishment: Lessons for Other Uses. *Marine Mining* 7: 123-136.

JACKSON C., 1999. Beach fetch distance and aeolian sediment transport. *Sedimentology* 46: 517-522.

KELLY J., 2014. Effects of human activities (raking, scraping, off-road vehicles) and natural resource protections on the spatial distribution of beach vegetation and related shoreline features in New Jersey. *Journal of Coastal Conservation* 18(4): 383-398.

KRAFT J.C., JOHN C.J., 1978. Paleogeographic analysis of coastal archaeological settings in Delaware. *Archaeology of Eastern North America* 6: 41-60.

KREEGER D., ADKINS J., COLE P., NAJAR R., VELINSKY D., CONOLLY P., KRAEUTER J., 2010. Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning. Partnership for the Delaware Estuary, PDE Report No. 10-01. 1-117 pp.

KRIEBEL D.L., DALRYMPLE R.A., 1995. A northeaster risk index. R & D Coastal Engineering, Newark, Delaware, 33 pp.

MAURMEYER E.M., 1978. Geomorphology and evolution of transgressive estuarine washover barriers along the western shore of Delaware Bay. PhD thesis, University of Delaware.

MORTON R.A., PAINE J.G., GILBEAUT J.G., 1994. Stages and durations of post-storm beach recovery, southeastern Texas coast, USA. *Journal of Coastal Research* 10(4): 884-908.

MILLER D.C., 2002. Pre-construction Sabellaria vulgaris Baseline Monitoring at Broadkill Beach Sand Placement Site, Sussex County, Delaware. Final Report for U.S. Army Corps of Engineers Contract Number DACW61-01-P-0291. 35 pp. + CD.

NEBEL S.H., TREMBANIS A.C., BARBER D.C., 2012. Shoreline analysis and barrier island dynamics: Decadal scale patterns from Cedar Island, Virginia. *Journal of Coastal Research* 28(2): 332-341.

NEBEL S.H., TREMBANIS A.C., BARBER D.C., 2013. Storm frequency and barrier island erosion rates, Cedar Island, Virginia. *Journal of Coastal Research* 29(1): 133-144.

RAINEAULT N.A., TREMBANIS A.C., MILLER D., 2012. Mapping benthic habitats in Delaware Bay and the coastal Atlantic: acoustic techniques provide greater coverage and high resolution in complex shallow water environments. *Estuaries and Coasts* 35 (2): 682-699.

REED D.J., 1989. Patterns of Sediment Deposition to Subsiding Coastal Salt Marshes, Terrebonne Bay, Louisiana: The role of winter storms. *Estuaries* 12: 222-227.

REILLY F.J. JR., BELLIS V.J., 1983. The Ecological Impact of Beach Nourishment with Dredged Materials on the Intertidal Zone at Bogue Banks, North Carolina. U.S. Army Corps of Engineers Coastal Engineering Research Center.

ROVERE A., CASELLA E., VACCHI M., MUCERINO L., PEDRONCINI A., FERRARI M., FIRPO M., 2014. Monitoring Beach Evolution Using Low-Altitude Aerial Photogrammetry and UAV Drones. *EGU General Assembly Conference Abstracts* (Vol. 16).

Rutger's University Haskin Shellfish Research Laboratory, Partnership for the Delaware Estuary, 2012. Delaware Living Shoreline Possibilities: Final Report. Submitted to Delaware Coastal Zone Program. 86 pp.

SHORT A.D., TREMBANIS A.C., 2004. Decadal Scale Patterns In Beach Oscillation and Rotation Narrabeen Beach, Australia-Time Series, PCA And Wavelet Analysis. *Journal of Coastal Research* 20 (2): 523-532.

STEVENS H., TREMBANIS A.C., 2012. Case Study of Fowlers and Prime Hook Beaches, Delaware. In J.A.G. Cooper and O.H. Pilkey (eds.), Pitfalls of Shoreline Stabilization: Selected Case Studies, Coastal Research Library 3. DOI: 10.1007/978-94-007-4123-2_16

TREMBANIS A.C., PILKEY O.H., VALVERDE H.R., 1994. Comparison of Beach Nourishment Along the US Atlantic, Great Lakes, Gulf of Mexico, and New England Shorelines. *Coastal Management* 27(4): 329-340.

United States Army Corps of Engineers, 1996. Broadkill Beach, DE Final Feasibility Report and Environmental Impact Statement. 250 pp.

United States Army Corps of Engineers, 2016. Wave Information Systems Hindcast Data, ERDC, Vicksburg, Mississippi. Accessed on 15 May 2016.

WELLS H.W., 1970. Sabellaria reef masses in Delaware Bay. *Chesapeake Science* 11: 258-260.

WU S., YARNAL B., FISHER A., 2002. Vulnerability of Coastal Communities to Sea-Level Rise: A Case Study of Cape May County, New Jersey, USA. *Climate Research* 22: 255-270.

ZHANG K., DOUGLAS B.C., LEATHERMAN S.P., 2001. Beach Erosion Potential for Severe Nor'easters. *Journal of Coastal Research* 17(2): 309-321.

(ms. pres. 15 settembre 2016; ult. bozze 17 ottobre 2017)

Edizioni ETS
Piazza Carrara, 16-19, I-56126 Pisa
info@edizioniets.com - www.edizioniets.com
Finito di stampare nel mese di dicembre 2017