Washover Fan Evolution, Assateague Island National Seashore, MD (2012-2019)

by

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ABSTRACT

Washover fans are coastal geomorphological features found on barrier islands. These features often help aid with barrier island landward migration. Within the scientific community, research is often based around pre- and post- storm data. However, in this study we analyze fan data between 2012-2019. The 2012-2017 LiDAR data was downloaded from NOAA Data Access Viewer, while the most recent 2019 data was collected by East Carolina University's research team using a Phantom 4 Pro drone. The imagery collected by the UAV were processed in Agisoft Metashape Pro and ArcMap Desktop. Both sites were observed for evolutionary traits within themselves and between one another. Similarities in topographic raising and lowering were found, as well as sediment build up at the fan's lateral extents, wedge-like fan, rectangular and v-shaped channels, and a flattening of the overall surface. The human impacted 75 fan from the berm construction project also followed similar patterns as the 85 natural fan. The information gained by this study can help inform the NPS staff how fast and large the fan is growing with time. This thesis research helped identify evolutionary traits of washover fans through time and should be compared to other fans located in distant locations for further analysis.

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A Thesis

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M. S. Geography

by

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CHAPTER 1: INTRODUCTION

Introduction

Washover fans are essential geomorphological features in barrier island dynamics. Sediment transport to and from these features aids in a barrier island roll over and produces habitat that increases the biodiversity on barrier islands (salt marshes, maritime shrubs) (VanDusen et al., 2016). Washover fans tend to form during elevated sea levels from coastal storms such as: Nor' Easters, hurricanes, and frontal storms. Sea level rise when combined with larger and more frequent localized storms fueled by climate change, may increase the frequency and magnitude of overwash and washover fan dynamics in coastal communities, which places coastal homes and infrastructure at a greater risk of a variety of impacts. There is a need in the scientific community to understand how extreme events, such as coastal storms, impact the resilience of buffering landforms such as barrier islands (Naylor et al., 2016). Advancing our understanding of washover fan evolution will lead to an enhanced understanding of geomorphic changes within barrier islands and the impact on human activities, thus allowing for an ability to reduce any possible risks to society due to coastal overwash (Naylor et al., 2016).

Research Purpose

Here, I examine washover fan evolution through a series of observations between 2012-2019. My goal is to provide details on geomorphic changes of washover fans located on Assateague Island National Seashore, MD. The research will also investigate whether human induced washover fans behave similarly to a natural washover fan. The anticipated findings will allow managers and policy makers to reduce any possible risks to society due to coastal storm overwash such as: beach encroachment to buildings and homes and buried roads (Naylor et al., 2016), and provide insight in berm notch program success.

There is a current lack of knowledge in the scientific community to understand how these buffering landforms i.e. barrier islands, work to resist and recover from extreme coastal events (Naylor et al., 2016). Understanding the evolution of washover fans on barrier islands is one way to resolve this issue, as washover fans are an adaptation of barrier islands ability to resist and recover from sea level change. Several research questions are addressed in the current study that are designed with unraveling evolution of washover fans with the Assateague Island National Seashore, MD. The questions are as follows:

1. What are the topographic and morphological changes that take place within a washover fan and the throat feeding the fan over a seven-year period?
2. Are the patterns of topographic and morphological change similar in two washover fan systems within close proximity to one another over a seven-year period?
3. How do the findings from this research inform scientists and managers within the Assateague Island National Seashore about the short-term evolution of washover fans and the potential for future human induce modification to enhance coastal morphodynamics?

Washover Evolution and Modeling in Literature

Washover Fan Overview*:* Barrier islands represent prominent coastal features along much of the eastern United States. They are relatively recent and highly dynamic coastal landforms (Tillmann and Wunderlich, 2013) that provide protection for the coastal mainland and surrounding bays and salt marshes (Leatherman, 1988). Barrier islands dissipate wave energy associated with coastal storms but are often unstable due to sea level rise and extreme storms, which cause the islands to migrate landward (Leatherman, 1988). Barrier island migration is often linked with the creation of tidal inlets and overwash processes that transfer sediment across the island. Washover fans, a morphological feature associated with overwash on barrier islands, are the focus of this proposed study. Washover fans re-arrange sediment across the surface and represent a tentative, but significant sink for sediment on barrier islands (Matias et al., 2008; Matias et al., 2010).

Washover fans evolve as sediment is transported by overwash flow through low points in the dune crest. Overwash results from super elevation of water levels during storms and extreme runup associated with high storm waves. As the water levels rise, the crest of the dune is overtopped causing incision followed by lateral undercutting to the dune (Matias et al., 2010; Leatherman, 1998). Typically, overwash feeds on weakened areas of the dune crest to begin incision (Leatherman, 1998). The incision deepens causing a higher velocity of flow, with the highest velocity observed at the berm crest (Holland et al., 1991) and an increased amount of erosion in the channel feeding the fan. Overwash flow decreases in velocity as it moves laterally across the backside of the barrier island, depositing sediment in a fan-like feature (Matias et al., 2010). As overwash travels through the throat, lobes of sediment continue to grow until a new throat forms. Once a new throat forms, the previous water supply is removed which in turn creates a new entry path for overwash. New throats can also be formed when a topographic barrier impinges their growth (Lazarus and Armstrong, 2015). Coastal storms such as hurricanes, Nor' Easters, and frontal storms are the leading causes of washover fan formation; however, non-storms such as spring and neap tides can also produce overwash events (Matias et al., 2017). On a shorter time-scale, such as days to months, washover fans can cause obstruction to "built" environments as they can bury roads and parts of buildings, but on the larger scale of hundreds of years, overwash has constantly reshaped barrier islands as they move landward (Leatherman, 1988).

Washover fan morphology*:* Washover fans often contain a low-lying central area that is surrounded by higher relief areas found on the distal parts of the fan (Feagin and Williams, 2008; Williams, 2015; Yovichin and Mattheus, 2018). All fans roughly resemble a conic shape; however, washover fans can be broken down into two main groups: channelized and non-channelized fans. Non-channelized fans can be further separated into three main categories: lobate, consisting of multiple lobes of sediment, dissipative, fan width decreasing in the landward direction, and apron-sourced, continuous groups of sediment in a lateral direction (Hudock et al., 2014). Washover fan shape can also be modified by other characteristics within the fan, such as: an increase of fan area due to an increased fan length and/or an increased fan throat width which increases fan area (Hudock et al., 2014). The prominence of channelized or non-channelized fans is often a result of back beach elevations, where uniform beach elevations induce non-channelized fans and non-uniform back beach elevations induce channelized fans (Morton and Sallenger, 2003). Fan thickness often depends on the underlying topography, where lower relief areas create high relief spots on the fan and antecedent high relief areas create lower relief areas (Williams, 2015). Overall, washover fans have a wedge-like shape due to the decrease in flow velocity as sediment and water is transported landward (Matias et al., 2010).

Washover Fan Sedimentology*:* The aforementioned variations in washover fan morphology often exhibit varied 3D sedimentary architecture. Most fans are composed of medium to coarse grained sediment (Tillmann and Wunderlich, 2013; Feagin and Williams, 2008; Matias et al. 2009; Yovichin and Mattheus, 2018), but also can be composed of shells (Tillmann and Wunderlich, 2013) and heavy minerals (Kochel and Wamplfer, 1989; Feagin and Williams, 2008). Sedimentary units in washover fans tend to be poorly sorted (Matias et al., 2009; Tillmann and Wunderlich, 2013; Matias et al., 2017). Washover fan deposits with greater depths often exhibit poorer sorting, indicating that early deposition on the fan is often poor and non-laminar (Feagin and Williams, 2008; Shaw et al., 2015). Overall, washover fans are laminated, plane bedded features that tend to dip in the landward direction (Shaw et al., 2015; Kochel and Wampfler, 1989; Tillmann and Wunderlich, 2013). A pattern tends to develop as sediment is deposited. Coarser grained sediment tends to be deposited in the central parts of the fan, whereas finer grained sediment is deposited towards the lateral parts of the fan (Tillmann and Wunderlich, 2013) resulting from a decrease in flow velocity near the center of the fan (Matias et al., 2010).

Variables Contributed to Overwash Development*:* The area in which washover fans form is difficult to predict. There have been copious amounts of research undertaken to understand the variables leading to the washover fan formation. A major contributor to washover fan formation and thickness is antecedent topography (Williams, 2015). Pre-existing dune structures also contribute to the onset of washover fans, as overwash most commonly originates in weak areas of the dune crest (Kochel and Dolan, 1986; Leatherman, 1988). Areas with low foredunes (Matias et al., 2008) as well as depressions in stable foredunes and back dunes, and a steep slope on the backside of the dune favor overwash formation (Kochel and Dolan, 1986). Back beach elevations (Morton and Asbury, 2003), nearshore bathymetry (Houser, 2012), orientation of the coast (Fletcher et al., 1955; Leatherman, 1988; Vandusen, 2016), coastal bedrock (Yovichin and Mattheus, 2018), near shore bars (Matias et al., 2014), low tidal regime (Hudock, 2014; Kochel and Dolan, 1986; Leatherman, 1988), other hydrodynamic variables such as wave height and period (Yovichin and Mattheus, 2018), and areas of high storm frequency (Leatherman, 1988) have influenced the onset of washover fans. Washover fan morphometry and size also depend on the accommodation space available. This space is often influenced by structural erosion, developed dunes and inlets, and man-made development, with the most influential factor being dune development (Vandusen et al., 2016; Matias et al., 2008). The accommodation space also affects the fan's ability to spread across the back barrier, thus influencing the fan length (Lazarus and Armstrong, 2015).

Past Methodological Approaches in Capturing Washover Fan Data*:* One of the most prevalent approaches in capturing washover fan data is the use of sedimentological data. Vibracores have been used to collect data from overwash and have been interpreted to find sedimentological patterns within washover fans (Tillmann and Wunderlich, 2013). Fan stratigraphy has also been used to analyze the evolution of a fan over a span of time (Shaw et al., 2015). Research requiring sedimentological data is often dependent on point measurements, leading to interpolation throughout the remaining parts of the fan. The use of surface and subsurface hydrology has also been attempted to explore episodes of overwash, for example, water loggers have been used to capture overwash intervals over a given time (Vandusen et al. 2016). While water loggers provide a unique approach in understanding overwash dynamics, the information gathered relies on a point measure. Washover fans are small features and, when using point measures, essential data may be lost when analyzing overwash dynamics especially when there is not a high density of point measures taken. To combat this issue, physical models have been explored to capture the evolution of washover fans during simulated storm events (Lazarus and Armstrong, 2015). Out of the approaches provided, the physical model appears to be the best example, providing that the entire overwash fan can be modeled and analyzed. However, modeling storm-like characteristics can be challenging and ultimately, field data is missing. Other types of equipment used in the field to capture data include: flow meters, cameras, and pressure transducers (Matias et al., 2010; Andriolo and Matias, 2015). Principal findings regarding overwash evolution from these approaches are discussed in the previous sections. While these approaches have produced significant information on understanding overwash dynamics, estimation and interpolation are often required when analyzing the data. These lead to data uncertainty, which is often not measured in the current literature.

Use of UAV Data Collection and Photogrammetry*:* Structure from Motion (SfM) provides an optimal workflow for producing repeat surveys in the field, can be collected with a few people team (Nagle-McNaughton and Cox, 2019), and can be collected either on the ground or aerially (Anderson, Westoby, and James, 2019). Imagery may be collected at higher altitudes to cover a greater spatial area but may result in lower resolution; however, it may not necessarily affect the quality of the data (Sturdivant et al., 2017). Lower altitude UAV image capturing flights are typically used for SfM data collection and can produce quality and accuracy comparable to GNSS and TLS data (Mancini et al., 2013). However, data collected using SfM requires accurate technical influences, such as the flight configuration, and is more sensitive to various environments such as different surface types (Lin et al., 2019). Another issue associated with SfM data is the possibility of occlusions and shadowing resulting mostly from fewer viewpoints (Smith et al., 2015). Lastly, increased error may be associated with smooth surfaces as the processing may have issues matching images (Mancini et al., 2013).

The use of ground control points is essential for obtaining the most accurate results in the SfM workflow and analysis (Cardenal et al., 2019; Sturdivant et al., 2017). Ground control points control the overall accuracy of the SfM workflow (Smith et al., 2015) and must be taken into consideration when planning their position to ensure a good image geometry network.

Various software has been used to analyze SfM data including: CloudCompare (for analysis), Agisoft (for point cloud creation) (Nagle-McNaughton and Cox, 2019), Pix 4D, and Drone Mapper (which are UAV focused) (Anderson, Westoby, and James, 2019). CloudCompare can be used to calculate the volumetric change in coastal areas overtime in a quick process (Nagle-McNaughton and Cox, 2019). One downside from using CloudCompare for analysis is the inability to save in-between steps (Nagle-McNaughton and Cox, 2019).

SfM has been proven to be an acceptable approach in collecting data in various coastal settings such as: coastal boulder deposits (Nagle-McNaughton and Cox, 2019), and sandy shorelines and dunes (Sturdivant et al., 2017). The use of repeat surveys associated with SfM can analyze changes spatially and temporally in coastal areas and how these changes may relate to coastal processes (Sturdivant et al., 2017). Structure from motion allows change to be captured in large-scale coastal areas, with high resolution, and minimal training, allowing people of all skill levels to perform the task (Nagle- McNaughton and Cox, 2019). Similar to the information obtained from airborne LiDAR, SfM approaches can also be used to determine areas of land and ocean (wet-dry lines) in coastal areas (Sturdivant et al., 2017).

Risk analysis of coastal areas can be done in almost real-time due to the ease and quickness of using SfM approaches, therefore lowering the risk of harm to people and structures (Cardenal et al., 2019). The use of SfM in landslide prone areas proves that this method can be used in other areas involving hazard risk analysis and mitigation. The high accuracy associated with SfM workflows make it a powerful approach that can be used in disaster management (Mancini et al., 2013). SfM can be used in areas that have a high frequency of disasters but have minimal resources or in areas that need reoccurring terrain models (Ratner et al., 2019). The use of “crowd sourcing” can be a beneficial approach in collecting imagery during a crisis or after a major event to rapidly gain data (Ratner et al., 2019). Although, the data captured by various resources may have varying image resolution and quality, the overall point cloud produced from the SfM workflow is accurate enough for analysis (Ratner et al., 2019).

The thesis research uses a combination of methods that includes data gathered from UAV photogrammetry and legacy lidar data sets from sites along the Assateague Island National Seashore, MD. The UAV field surveys are conducted onsite. Agisoft Metashape software is used to process photos and produce digital elevation models. Legacy lidar data from the same locations is gathered from the NOAA Data Access Viewer along with associated aerial photography. These aerial photographs are also enhanced with additional aerial photography from the Google Earth. These data will provide observations from 2012 to 2019, with the most recent data coming from the UAV data. The data provide an opportunity to investigate the topographic and morphological changes of two washover fan systems. The second chapter is designed as a peer-reviewed article that explores the morphodynamics of the fan system that expands our scientific understanding of these critical features in barrier island evolution and provides insights to management of coastal settings.

CHAPTER 2: FIELD DATA COLLECTION AND ANALYSIS

Introduction

Washover fans are important features that give barrier islands the ability to roll over and migrate landward. They also serve as critical habitat in turn increasing biodiversity in coastal settings (VanDusen et al., 2016). Washover fans are often formed from coastal storms such as hurricanes or Nor' Easters, but certain spring or neap tides can also provide enough elevated water levels to induce overwash (Matias et al., 2017). Overwash begins to carve out channels through weak points in the dune line, creating a passageway for water and sediment to be distributed to the back barrier (Matias et al., 2010; Leatherman, 1998) (Figure 2.1). Washover fans tend to have low-lying centers and higher outer edges (Feagin and Williams, 2008; Williams, 2015; Yovichin and Mattheus, 2018). These fans can be described as either channelized or non-channelized and tend to increase in surface area as fan length increases or fan throat

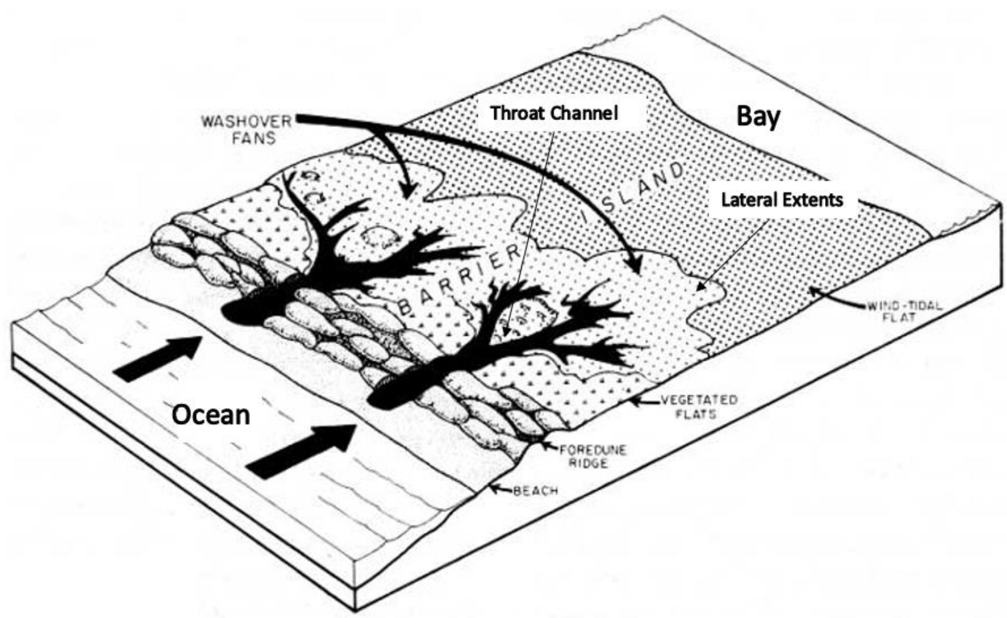


Figure 2.1: Washover fan diagram (U.S. Department of the Interior)

width increases (Hudock et al., 2014). Fan morphology tends to be wedge-like in shape due to the decrease in flow velocity as sediment and water are transported to the back barrier (Matias et al., 2010).

Overwash fans are typically medium to coarse grained (Tilmann and Wunderlich, 2013; Feagin and Williams, 2008; Matias et al., 2009) and are commonly poorly sorted (Matias et al., 2009, Tilmann and Wunderlich, 2013; Matias et al., 2017). The coarser sediment is usually deposited in the central parts of the fan, while the fine sediment travels to the lateral extents of the fan through overwash transportation (Tilmannn and Wunderlich, 2013). Current knowledge on washover fans has stemmed from pre- and post- storm data or physical models to gain an understanding of geomorphological changes of these features during these coastal storms. However, these observations, while providing important information on these features, lack an overall understanding of the evolution of these features over longer time scales. There is a current need in the scientific community to understand how coastal storms effect the resilience of barrier islands and washover fans (Naylor et al., 2016). Here, the focus is on how two washover fans located on Assateague Island, MD evolve between 2012-2019. Similarities and differences between the two sites are examined for evolutionary patterns that can be found through the investigation of the geomorphological changes. These years were chosen given they had the highest quality and reliable data available on the NOAA Data Access Viewer. The 2019 data was collected with an UAV by the current researcher.

Figure 2.2: A: 7.5 Fan located on Assateague Island, MD. B: 8.5 Fan located on Assateague Island, MD

Study Area

Assateague Island is a microtidal transgressive barrier island located on the east coast of Maryland (Figure 2.2). Assateague is composed of low discontinuous dunes, vegetated back barrier, and a narrow marshland surrounding the bayside of the island (Schupp et al., 2013). This island, once connected to the northern island, Fenwick, was created by a hurricane in 1933, carving an inlet in between the two islands. In order to reduce boat traffic time, a jetty was placed at this inlet, and is still there today. While this jetty has proven to be useful for transportation and recreational use, it has caused a disruption in longshore sediment transport, thus starving the northern end of Assateague Island from sediment. This starvation has caused the northern end of Assateague to shift landward at an exceeding rate and the number of washover fans to increase (Assateague Island National Seashore North End Restoration Project Introduction). The two washover fans studied in this research are located at: 85 Fan, 18S 488522.89m E 4233924.74m N, which has become vegetated in the past three-four years, connects to the bay, and was formed before Hurricane Sandy (Figure 2.2B) and the 75 Fan, 18S 488872.13m E, 4234734.05m N, which has constrained flow and was formed at the southern end of constructed berm project (Figure 2.2A).

Two washover fans were selected along the northern shore of Assateague Island (Figure 2.2). The washover fan selection was based on sampling one site impacted by an experimental research project (Schupp et al., 2013) that had incised channels in the barrier island to increase overwash (Figure 2.2B) and another not impacted by this action (Figure 2.2A). These sites were also selected for the close proximity to reduce any other local variability in the shoreline that might lead to differing response in the washover fan evolution. These fans were named based on the NPS mile markers. Fan 85 occurs near mile marker 8.5 and fan 75 occurs near mile marker 7.5 (Figure 2.3).

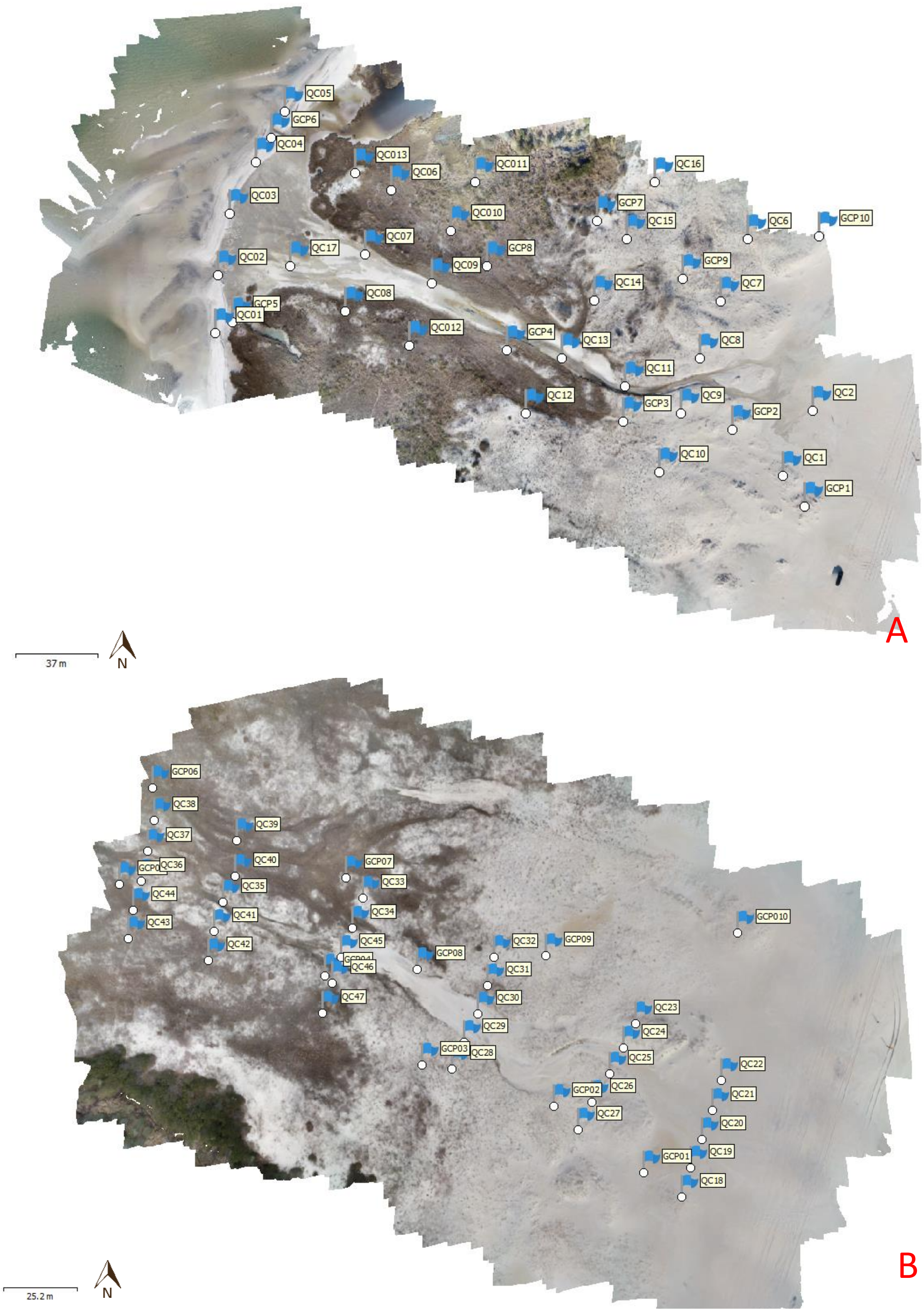


Figure 2.3: A: GCP and QC layout for fan 85. B: GCP and QC layout for fan 75.

Methods

The research uses a combination of field data and historical data to assess the short-term evolution of washover fans from 2012 to 2019 within the northern section of Assateague Island National Seashore, MD. UAV data collection, combined with GNSSrtk ground and quality control points, provide the most recent data. Older data are obtained from legacy lidar data sets gathered from NOAA's Data Access Viewer. These data are processed to the same spatial resolution to perform analyses of topographic change and a variety of profile measurements aimed to assess the morphological variability of the features.

Field Data Collection

RTK-GNSS Survey***:*** Ten red and black iron cross targets were used as ground control points (GCP) and placed randomly around the area of study to help connect images when processing the data (James et al., 2017b) (Figure 2.4 A). Survey precision increases as more GCPs are implemented into the field and the placement of these GCPs are critical as they georeference points for the images obtained from the UAV (James et al., 2017a). Thirty 4x4 orange and white iron cross quality control points (QCP) were nailed into the ground in a systematic box-like pattern throughout the fan area (Figure 2.3 A and B). The quality control points were used to aid in the stitching together of photos for the creation of one overall model of the area.

Figure 2.4: A: Example of GCP target. B: Example of QCP target

A real-time kinematic global navigation satellite system (GNSSrtk), Trimble Spectra Precision SP80, was used to further enhance the accuracy of the placement of the GCPs and QCPs. The GNSSrtk was placed over the center of each GCP for a total of 180 epochs to enhance the accuracy of the measurement, while 90 epochs were used for the quality control points given the quantity of points to be measured. Since the area of study is relatively small, a higher accuracy and precision of data is needed to quantify geomorphic change data during the overwash process. A text file was created of the northing, easting, and elevation of each GCP and QCP for subsequent analytical use.

The base station was set up on a point located near the 85 washover fan. The base remained over the same point for four hours, which was in line with past surveying practices used by scientists at the National Park Service (NPS). The base station recorded the location and elevation every second for four hours. The SfM-MVS data were projected to the Maryland State Plane coordinate system in Trimble Business Center (TBC) using the 12B Geoid. Northing, Easting, and Elevation were used as the coordinates and meters as the unit of measure. To ensure high quality results, the following acceptance criteria were used:

Horizontal Precision	**Vertical Precision**
Flag: 0.020m + 1.0ppm	Flag: 0.050m + 1.0ppm
Fail: 0.050 m + 1.00ppm	Fail: 0.100m + 1.0ppm

Ground properties were included in the point spreadsheet and the maximum PDOP values were used in the vector spreadsheet. The results from TBC are used as part of the National Oceanic Atmospheric Administration’s (NOAA) Online Positioning User Service (OPUS) solution (https://geodesy.noaa.gov).

The data were processed with OPUS to determine the most accurate Northing, Easting, and Elevation (Orthometric Height). These parameters are as follows: Northing: 66707.962m, Easting: 563675.332m, and Elevation: 3.321m. These results were uploaded into the data controller and collection of the GCP and QCP began.

UAV Survey*:* A Phantom 4 Pro UAV was used to collect imagery at the two locations. DJI's Ground Station Pro app was used to design the layout of all flights auto-piloted flights. Flights were flown 33 m above the surface and the hover and capture mode was used to capture all photos. Half of the total flights were flown in one direction while the remaining flights were flown in a cross-path to the initial flights. The camera was set to a 70-degree angle and each flight had 80% horizontal and vertical overlap.

The photogrammetry and Structure-From-Motion Multi-View Stereo (SfM-MVS) methods have been used with success in various physical environments such as soil changes (Eltner et al., 2017), ice-margins (Mallalieu et al., 2017), and coastal regions (Holland et al., 1991). The success of the SfM-MVS approach in a variety of geomorphic settings dictates a similar approach can be used in the current study. These data are combined with legacy lidar data to produce digital elevation models (DEM) to investigate morphometric and topographic changes to the washover fan systems from 2012-2019.

Historical Data Collection

NOAA Data Access Viewer: NOAA Data Access Viewer was used to obtain LiDAR from the following years: 2012, 2014, 2016, 2017. These years were chosen because they were the most high-resolution LiDAR data when compared with earlier years with coarser resolution that would have made detection of small washover fan features difficult to resolve. The years 2013 and 2015 were not used because there was no elevation data set in NOAA Data Access Viewer. The following LiDAR were downloaded for both sites:

2012 USACE Post-Sandy Lidar: MD & VA

2014 NOAA NGS Topobathy Lidar: Post-Sandy (SC to NY)

2016 USGS Lidar Post- Hurricane Hermine: Assateague Island, Maryland and Virginia

2017 USACE NCMP Topobathy Lidar: East Coast (NY, NJ, DE, MD, VA, NC, SC, GA)

Data Processing

Agisoft Metashape Pro*:* All images of the 75 and 85 fan were separately uploaded into Agisoft Metashape Pro. Processing followed the Agisoft Metashape Pro workflow (Figure 2.5). Data were collected using Geoid 12B, therefore the Geoid 12B was downloaded from: https://www.agisoft.com/downloads/geoids/ to ensure proper vertical datum use in the model building. Once all of the targets and quality control points were added to the photos, Agisoft assesses the error of the GCP and QCPs. The errors associated with the 85 fan were as follows: GCP were 0.025197m, QCP were 0.055243m and the error associated with the 75 fan were as follows: GCP were 0.026568m and QCP were 0.045561m. The dense clouds were exported as an .asc file and uploaded into ArcMap.

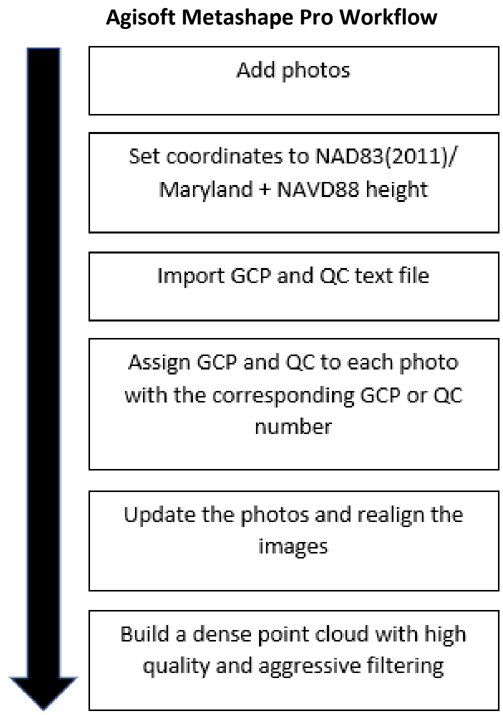


Figure 2.5: Agisoft Metashape Pro workflow for washover fan data.

ArcMap Desktop

ArcMap was used to create profiles and investigate volumetric changes of the fans over time. A series of steps were needed to ensure all data was in the same

ArcMap Processing Flow Chart

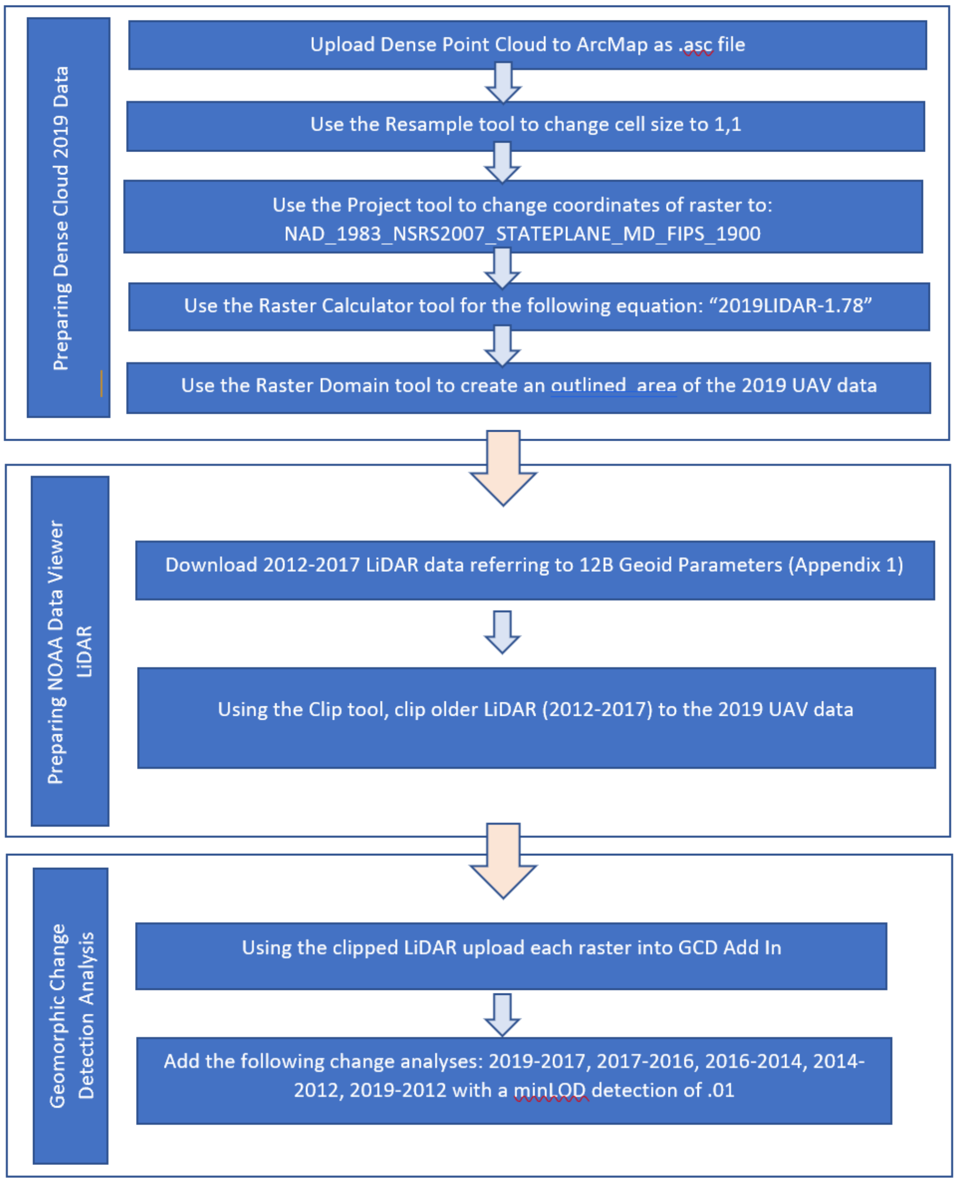


Figure 2.6: ArcMap Desktop methodological workflow for washover fan data.

coordinate system and the same cell size (Figure 2.6). The use of a minimum level detection of 0.05 was chosen same cell size (Figure 2.6). The use of a minimum level detection of 0.05 was chosen as the best approach given that the error volume was smaller in comparison to propagated error, probability approach or the fuzzy inference.

Data Analysis

Descriptive Statistics*:* The descriptive statistics including: mean, standard deviation, kurtosis, and skewness were calculated using Excel's Data Analysis tool add-in. These four variables were focused on for this study, as they could provide insight into the throat and fan elevational change, revealing patterns that may be missed by the profile. The use of descriptive statistics also provides a quantitative analysis of the profiles.

Profiles*:* Eleven polylines were created in ArcCatalog to represent the following cross-sections on the washover fan: radial 25, 50, and 75, transverse 25, 50, 75, longitudinal of throat, and lower, middle, and upper of the throat channel (Figure 2.7). The end of the throat was measured at the point where sediment began moving laterally as it exited the dunes, and the radials began at the center of the washover fan apex where radial profile 0 and 100 represent the lateral extents of the fan. All polylines were created based off of polygons that were created using imagery from Google Earth Pro. These polygons were separated by areas of the fan itself and the throat, where the throat was defined by the channel starting at the oceanside of the dune line and ending at the bayside of the dune line. The largest area of washover fan and throat were used as the base to create

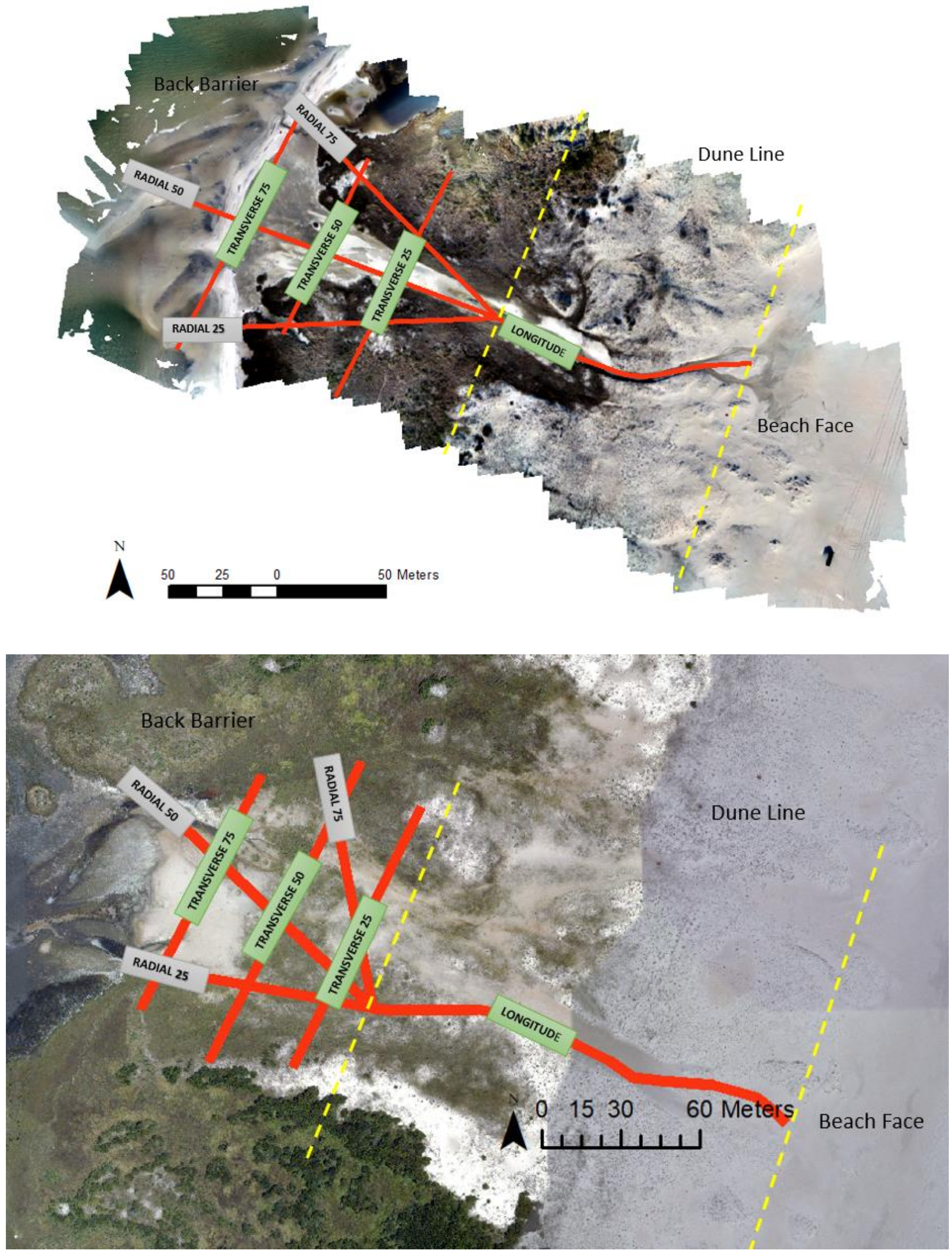


Figure 2.7: A: Locations of profiles on 85 Fan B: Locations of profiles on 75 Fan

polylines ensuring all data were included for each area between 2012-2019. The stack profile tool, which allows profiles from multiple layers in the same geographic locale, was made for three transverse, three radial, one longitudinal, and three throat transverse lines of each fan. Profiles were exported into Excel as a text file to create the profile using a scatter plot. The profiles and GCD outputs were further analyzed to understand the fans progression through time.

Geomorphic Change Detection*:* The GCD add-in for ArcGIS examines the changes over time to the topography of the two fans and follows a similar workflow to Wheaton et al. (2010) using a probabilistic approach to assess the minimum level of detection. Surface lowering and raising (sediment transport) will be investigated using a series of thresholding approaches: minimum level of detection (Brasington et al., 2000; Lane et al., 2003), propagated errors (Brasington et al., 2000, 2003; Lane et al., 2003), and probabilistic errors (Lane et al., 2003). Measurement of erosion, deposition, and no change are quantified while reducing measurement uncertainty, which enhances the findings of sediment transport within and between the washover fans and in turn, produce a greater understanding of washover evolution.

Each LiDAR data set for the years under investigation were uploaded into the Inputs section of the GCD Project Explorer. Once all years were added, change detection analyses were performed between the two consecutive years (2014-2012, 2016-2014, 2017-2016, and 2019-2017). An overall change detection of 2019-2012 was also performed to place individual time changes into a broader context. The outputs from GCD were reviewed to understand patterns of topographic raising and lowering and movement of sediment within the washover fan between 2012-2019.

Results

Definition of Terms*:* The term “channel” refers to low spots within the throat and fan’s surface, therefore, increasing the amount of velocity and overwash through certain

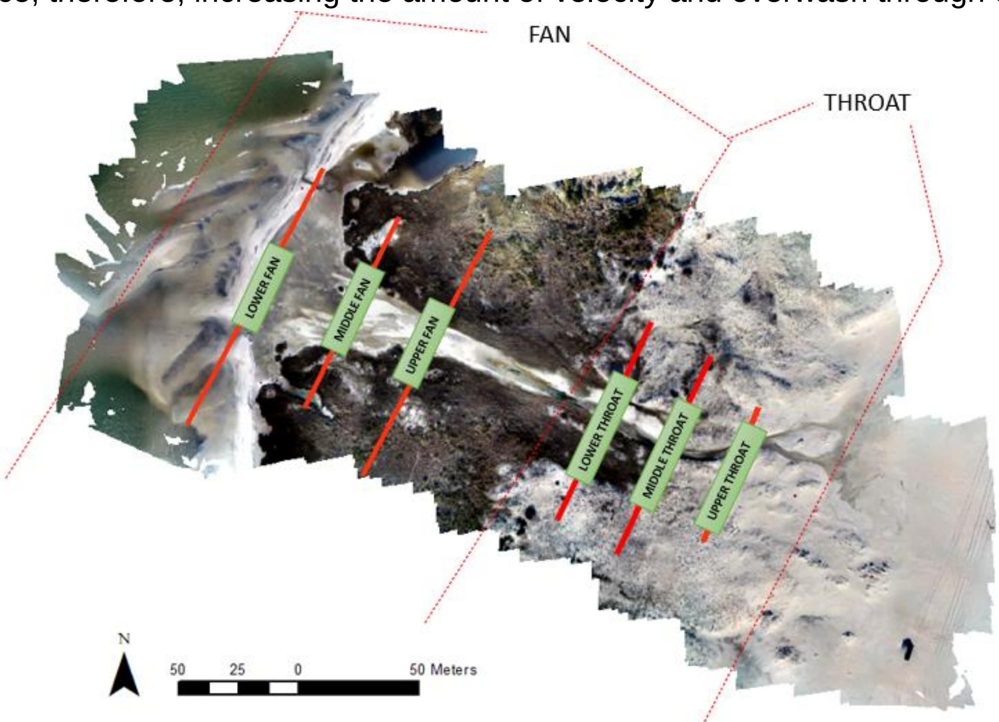
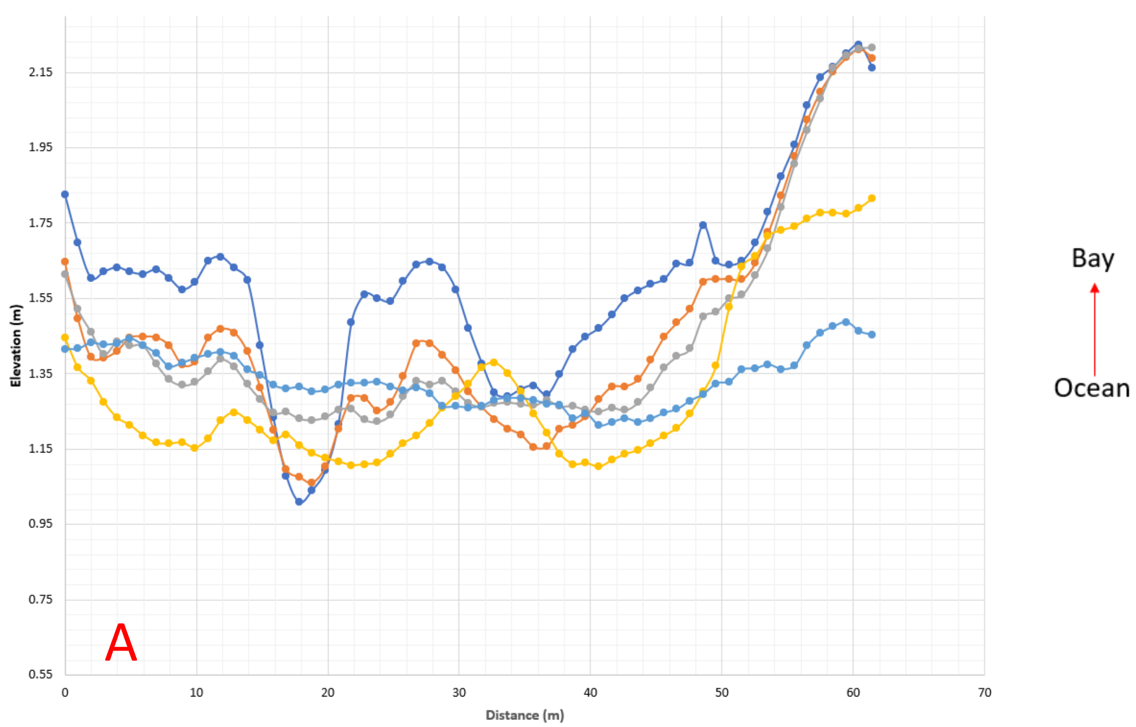


Figure 2.8: Location of description of throat and fan areas

points of the throat/fan. The term “throat” will be defined by the large passageway cut through a dune feature, providing an opening for overwash to cross from the ocean to the back barrier.

The terms “upper”, “middle”, and “lower” are used to describe different portions of the washover fan for a more in-depth analysis of the throat and fan features. The upper portion of the feature is located closest to the ocean, while the lower portion is closest to the bay (Figure 2.7). The length of each the fan and throat were measured into thirds to decide the sections. The radials were measured in 45-degree angles from the dune line (0 degrees).

Throat - Within Fan Variability (85 fan*):* Topographic raising and lowering are spatially discontinuous across the upper throat between 2014-2019. Two concave features form around 10-20 meters and 30-40 meters distance resulting from channel formation and scouring of the surface caused by one or multiple overwash flow(s) (Figure 2.9). The middle throat exhibits similar channel development in the years following 2012. Two channels began to develop, 2-17 meters (one) and 25-35 meters (two) distance in 2014 and were separated by sediment deposits reaching roughly 1.3 meters in height (Figure 2.9). This trend continues until 2017, where channel one began to incise further, while channel two began to fill in as more overwash is captured in channel one. The lower throat only experiences the development of one channel during this same timeframe. A longitudinal profile of the throat tended to resemble step-like features when active overwash was present. In 2016, these morphological features formed on the oceanside of the fan between 0-60 meters distance (Figure 2.11). In addition to the increased sediment deposition along the



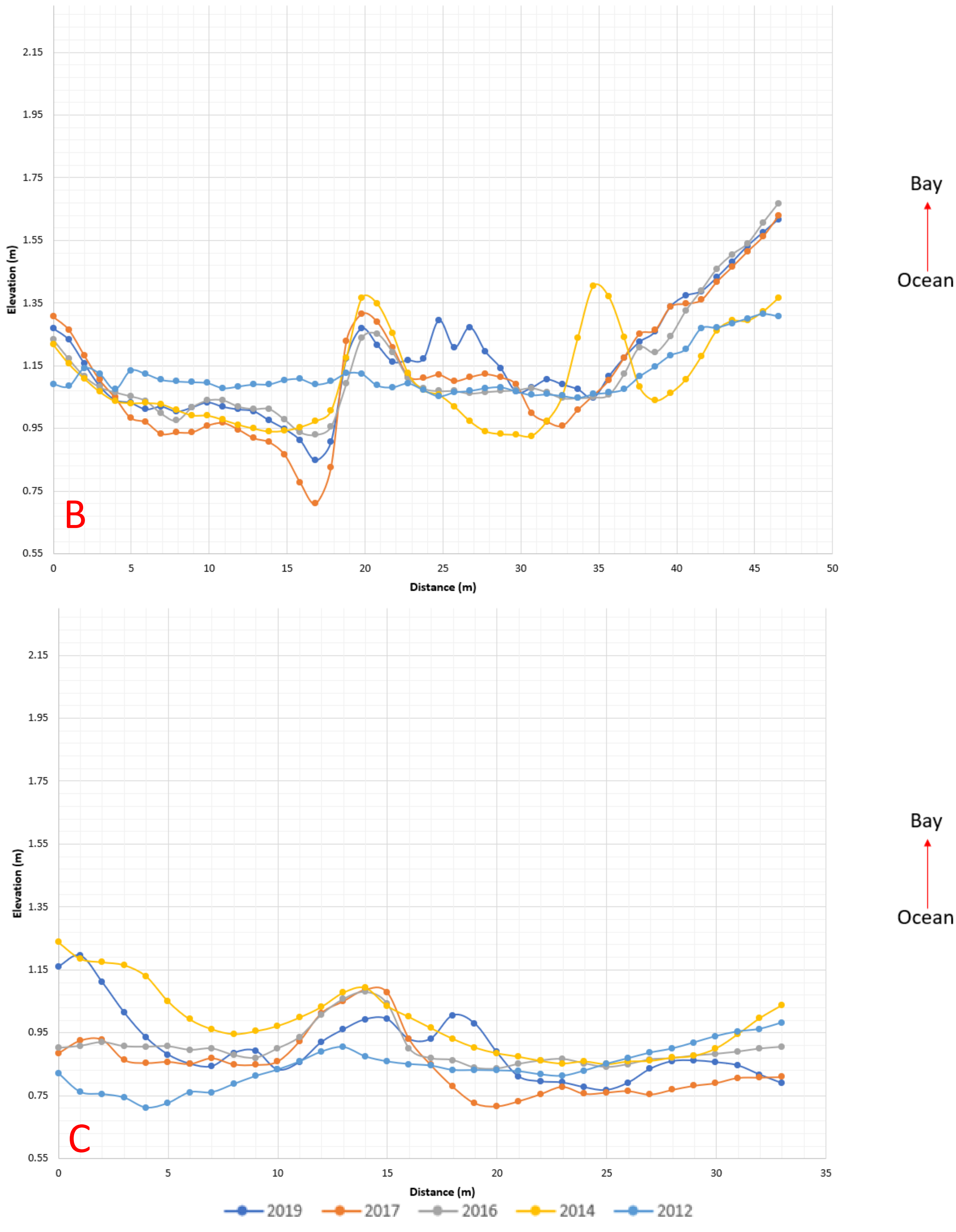
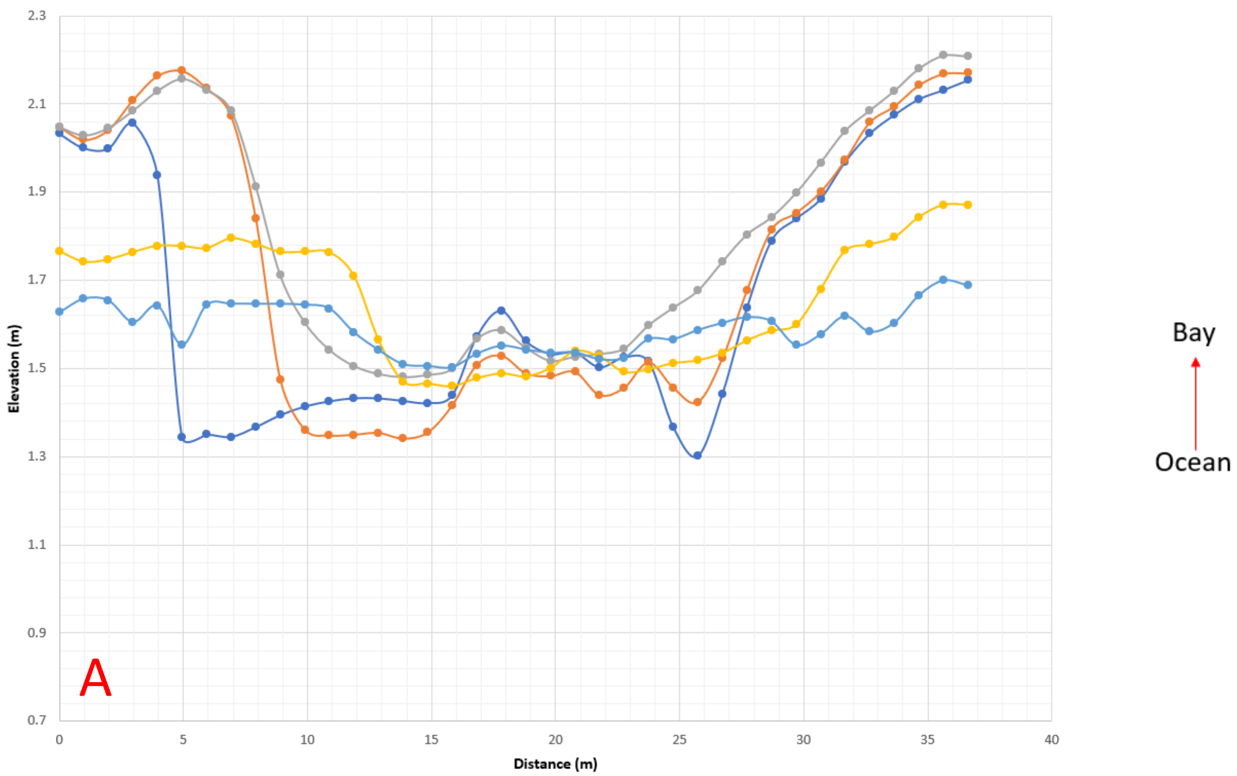


Figure 2.9: Cross-section profiles of the 85 fan throat at A: Lower throat B: Middle throat C: Upper throat

lower throat (Figure 2.11). The step-like features began to level out as sediment is deposited at the interface of the throat and upper fan (Figure 2.11).

Throat - Within Variability (75 fan): Convex sediment mounds were deposited throughout the throat's surface and this coincided with the formation of a channel near the throat-fan interface that was rectangular in shape (Figure 2.10). Eventually, erosion occurred on the left side of the throat, causing widening of the channel, over five meters in width within a two-year time frame (2017-2019) (Figure 2.10). Rectangular channel forms were also found at the middle portion of the throat. However, it was not until 2016, that a channel could be identified. Depositional features also occurred on the 75 fan throat, though they mostly appeared in the middle of the profile (Figure 2.10). The upper throat resembles the same patterns as the middle of the throat, though a distinct channel does not form until 2016. The channel continues to incise in 2017, deepening approximately 0.3 meters and ultimately transforms into a rectangular shape (Figure 2.10). The longitudinal profile of the upper throat erodes, as deposits of sediment migrate across the middle and lower fan. In 2014, approximately ten centimeters of sediment were eroded on the upper throat; however, a mound of sediment developed between 65- 80 meters distance of throat indicating a transfer of sediment through the throat feature (Figure 2.11).



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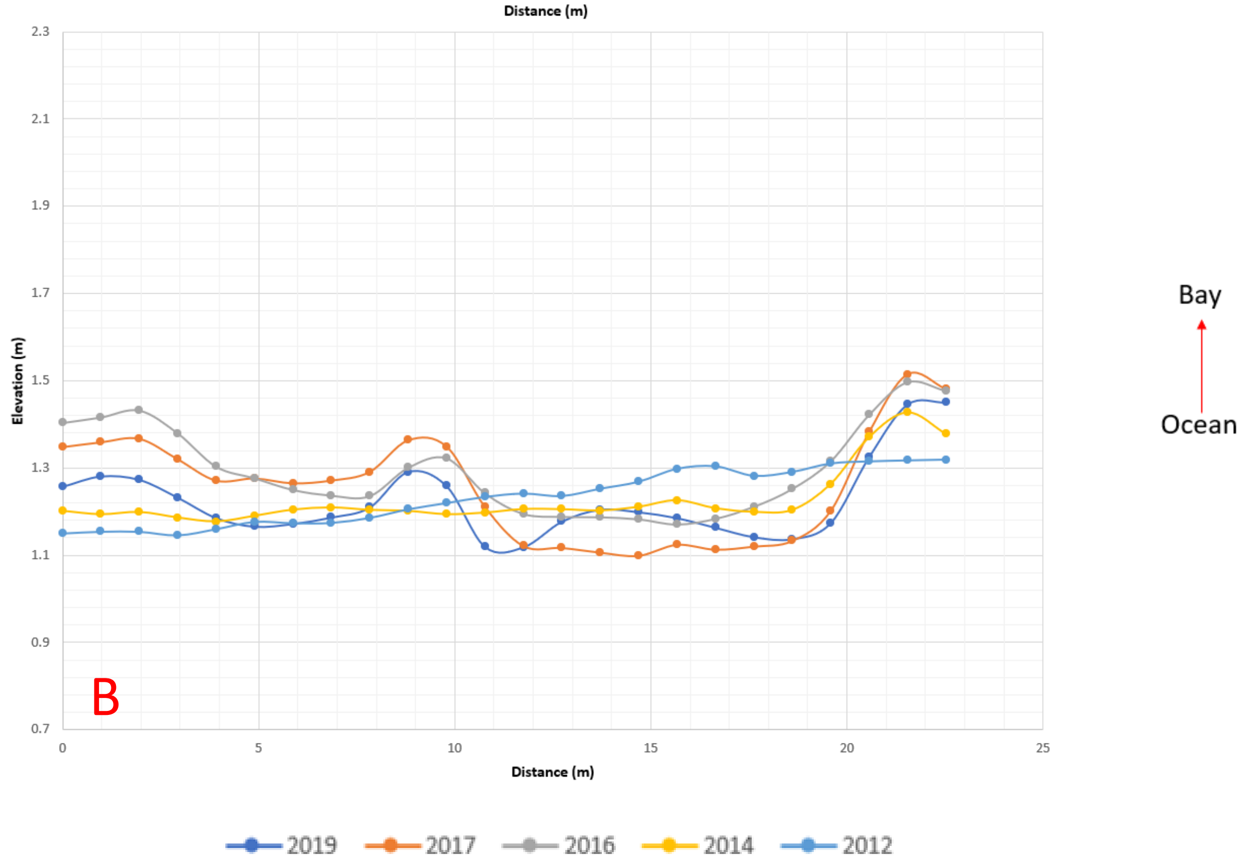

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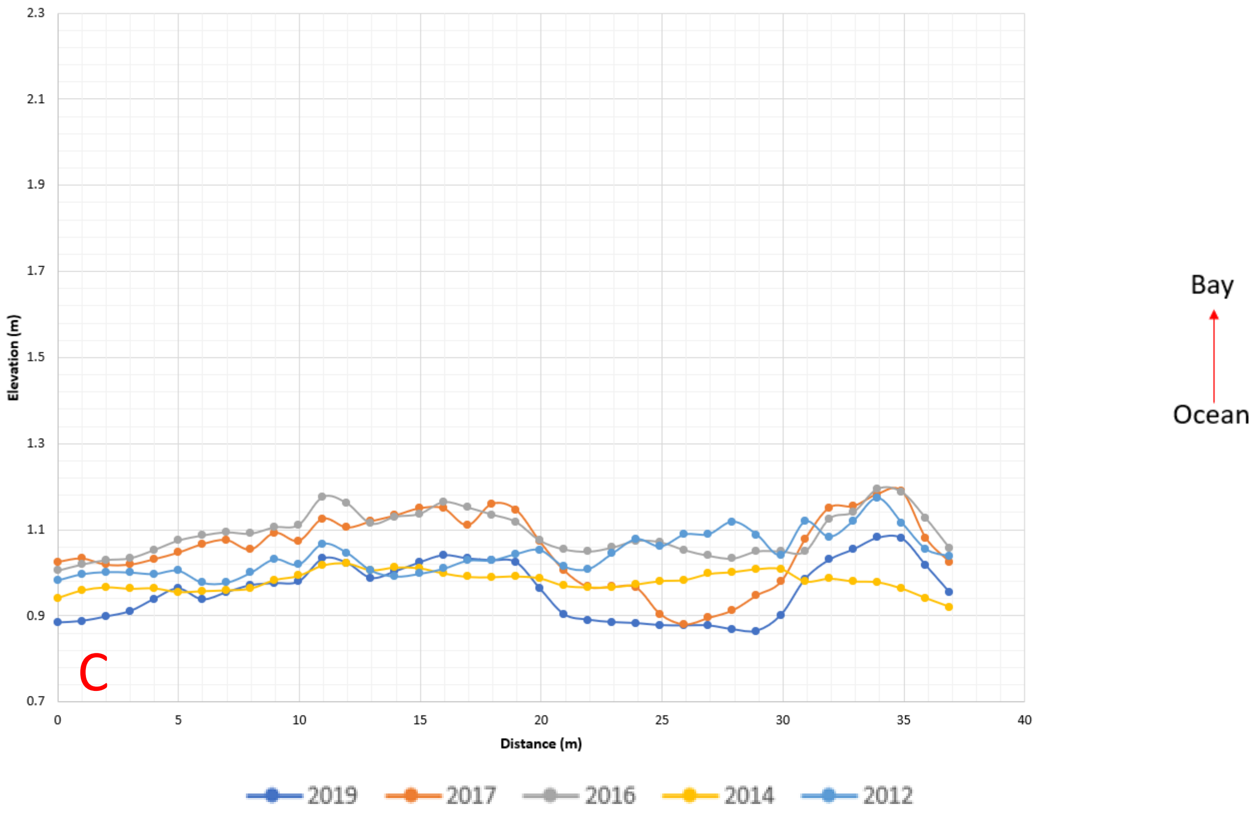


Figure 2.10: Cross-section profiles of the 75 fan throat at A: Lower throat B: Middle throat C: Upper throat

Throat - Between Fan Variability*:* Both throats had two channels (75: ~10-17 meters and 20- 30 meters distance, 85: ~15-25 meters and ~30-40 meters distance). In comparison to the upper throat, the middle of the throat tended to have a reasonably stable topographic shape, whereas the upper channel experienced more frequent erosional and depositional changes. No notable patterns exist within the upper throat cross-sections. The longitudinal profiles of the throat show an overall slope from the ocean towards the bay indicating minimal impacts from aeolian activities with minor topographic highs in some years near the bay in both fans, but periodically in the upper throat of the 75 fan. Step-like features

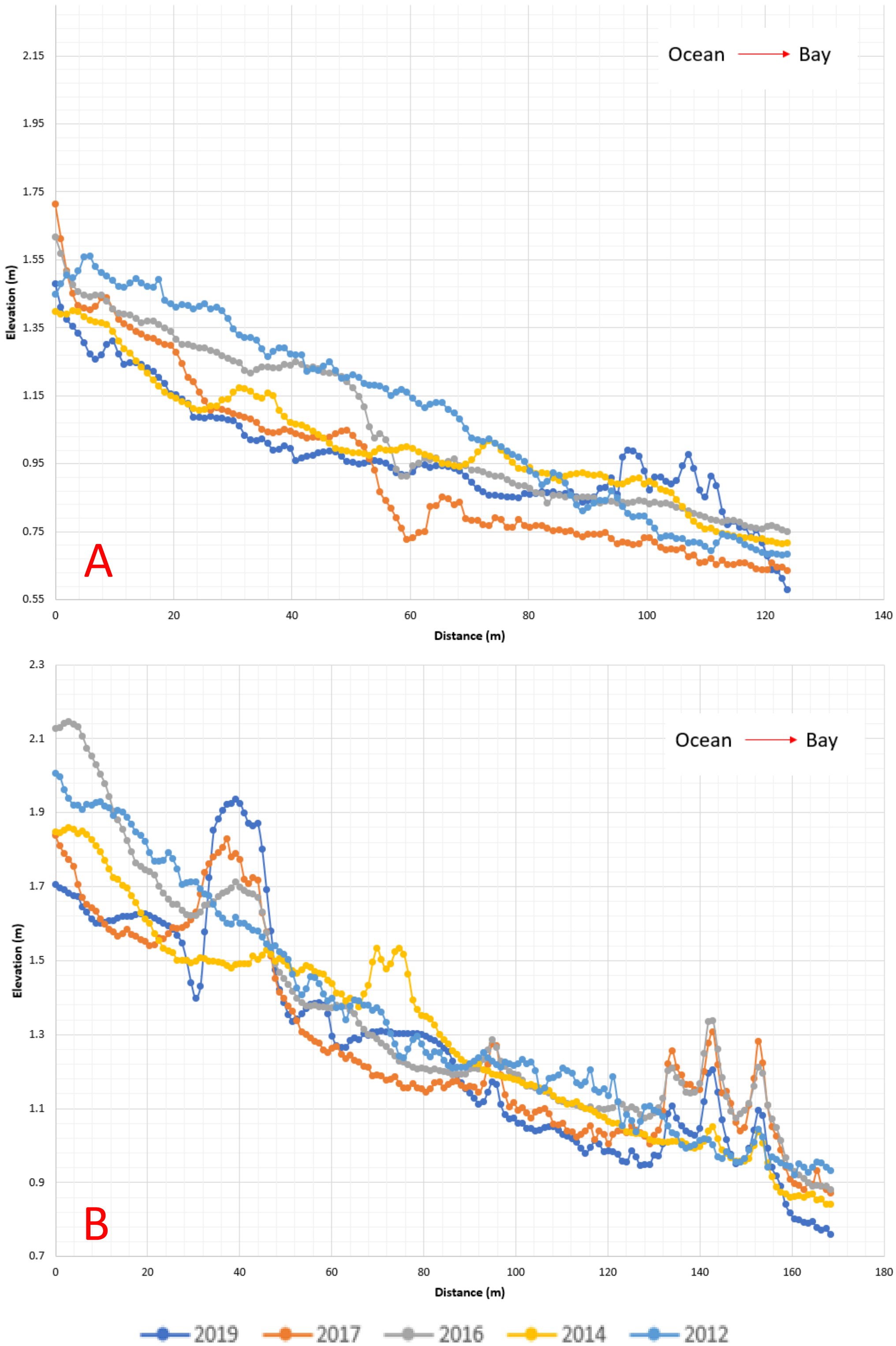
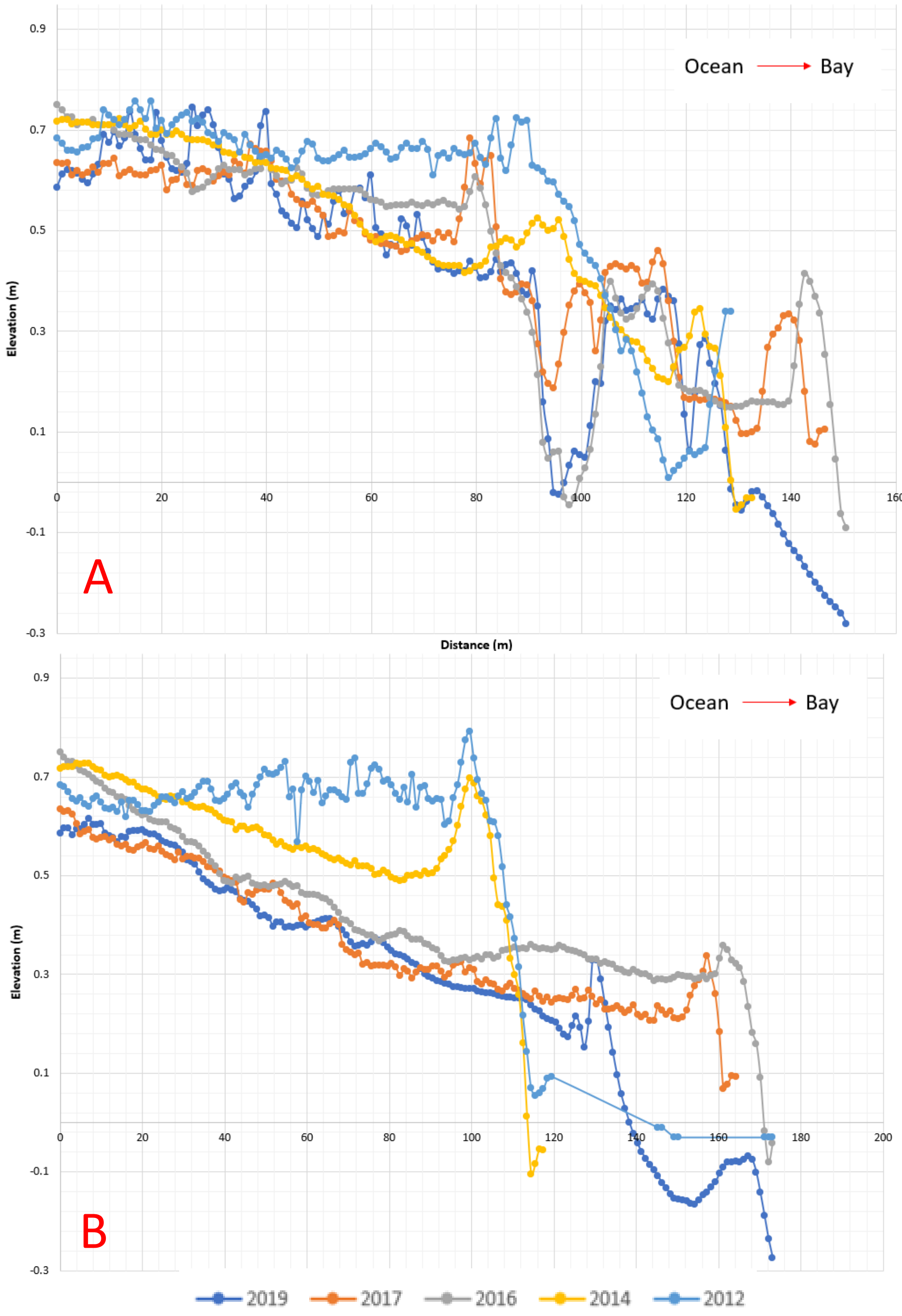


Figure 2.11: Longitude profiles of A: 75 fan and B: 85 Fan

appear on the 85 fan indicating sediment movement in the throat, whereas the 75 fan has convex deposits of sediment (Figure 2.10). Both throats; however, have deposition occurring at the lateral extents of the throat surface. Lastly, the 75 fan was overall higher in elevation in comparison to the 85 fan.



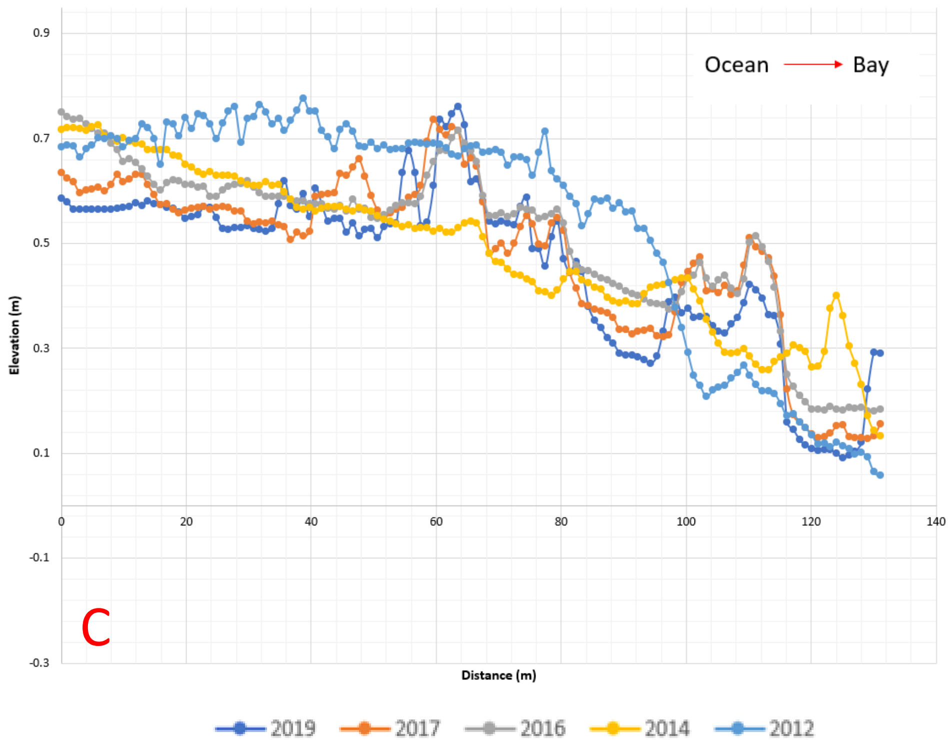
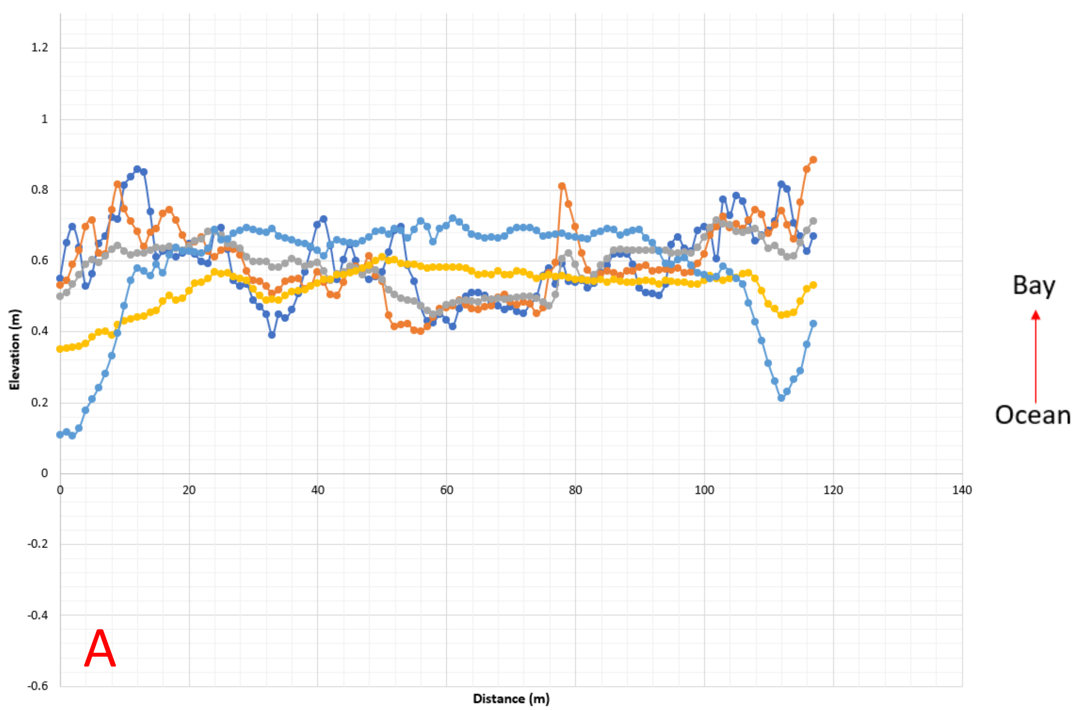


Figure 2.12: All figures correspond to the 85 fan A: Radial 25 B: Radial 50 C: Radial 75



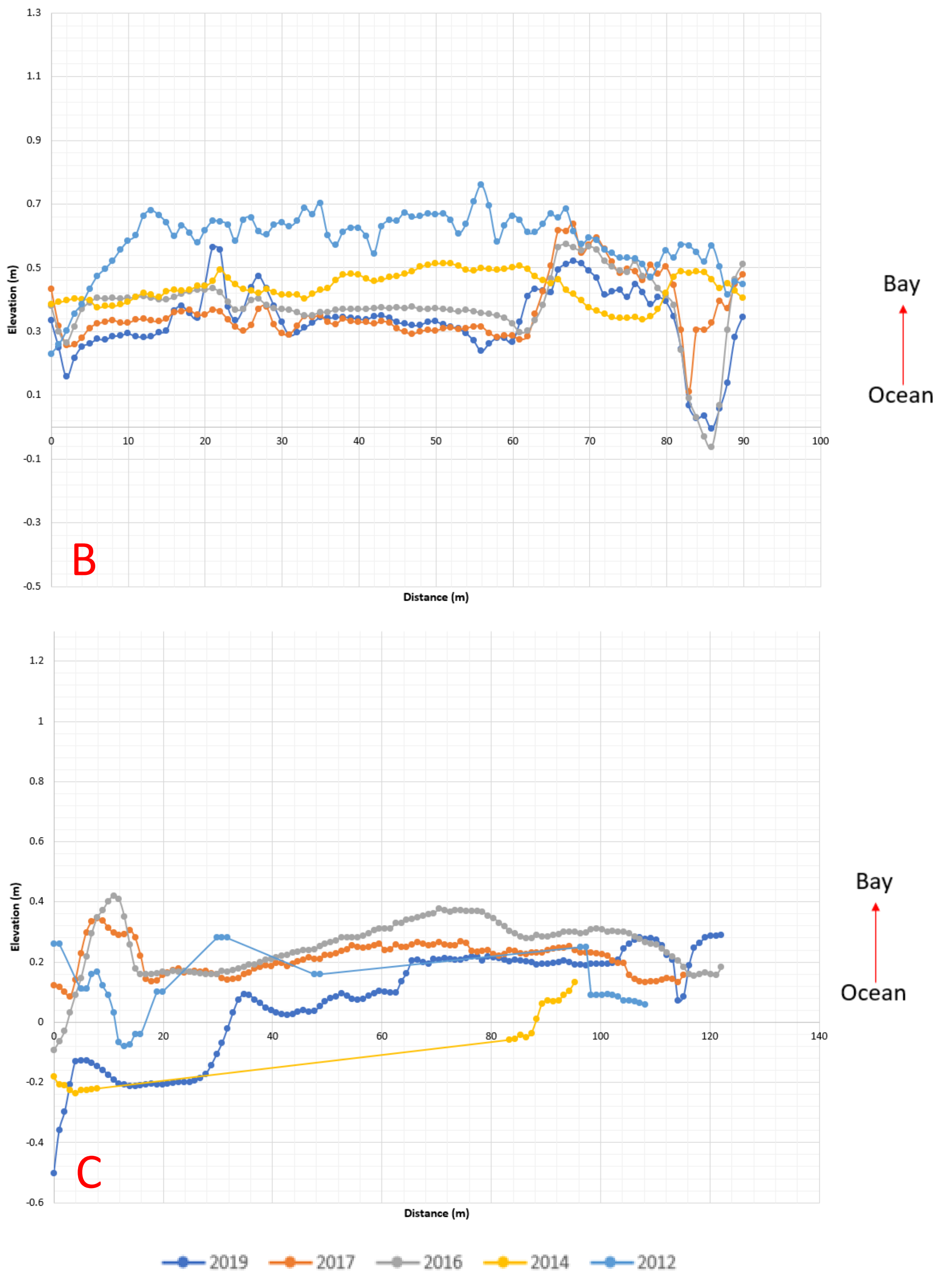
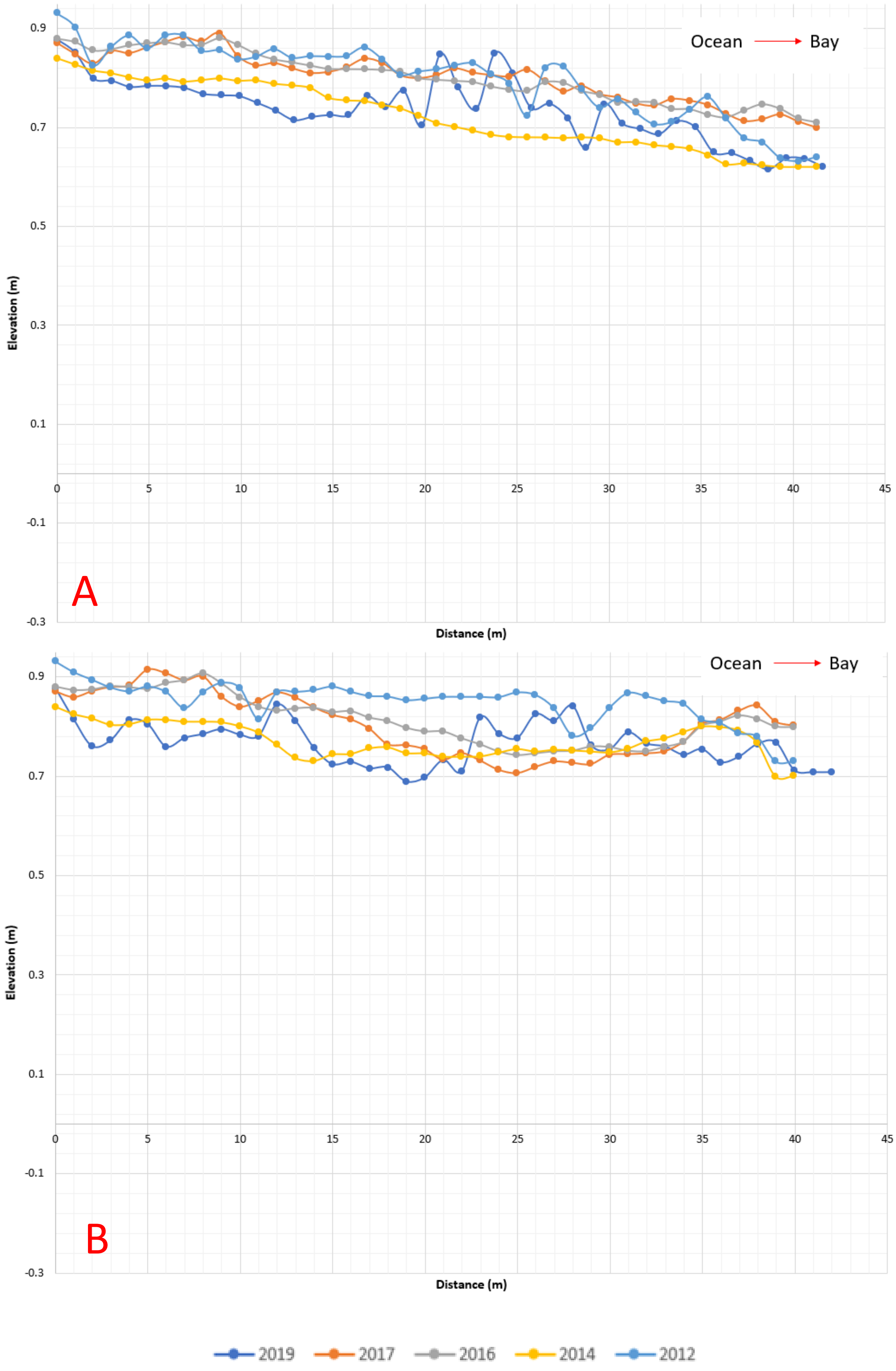


Figure 2.13: All figures correspond to the 85 fan A: Transverse 25 B: Transverse 50 C: Transverse: 75

Within Fan Variability (85 fan*):* The washover fan surface has a wedge like shape, thinning towards the bayside. Radial profiles 50 and 75 also exhibited two convex features on the washover fan surface (Figure 2.12). The topography along radial profile 25 was relatively flat in the upper and middle portion of the washover fan but becomes steeper and more complex towards the washover fan toe. The washover fan length increases in 2016 and a convex feature develops near the washover fan toe (141-145 meters distance). The convex feature erodes in 2019, and a steep slope develops in the bay-ward direction. Radial 50 continuously had a decline in sediment at the toe of the fan throughout 2012-2019, which was in all cases preceded by a large depositional mound of sediment.

The width and backfill of sediment on the upper fan increase between 2012-2019 at transverse profile 25. The shape of the lower fan changes from a convex feature (2012) to a mostly flat feature with low spots (50-78 meters and 30-40 meters distance). The convexity of transverse profile 75 from distance 4-18 meters eroded by 2019 to become a topographic low in the washover fan (Figure 2.13).

Within Fan Variability (75 fan): Minor topographic lowering and raising occurs on the upper fan between 2012-2019, but a general reduction in topographic complexity is identified along radial profile 25 until 2019. The surface of radial profile 25 begins to smooth out with the exception of a few minor raising and lowering locales. However, in 2019,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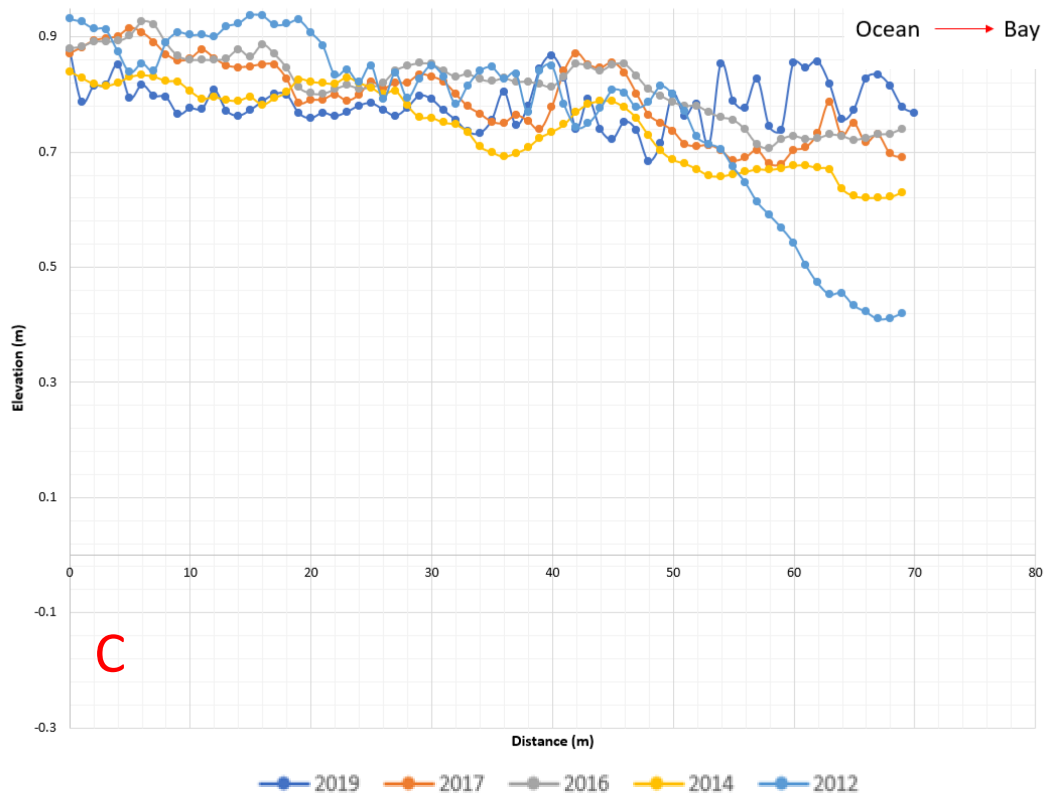

Figure 2.14: All figures correspond to the 75 fan A: Radial 25 B: Radial 50 C: Radial 75

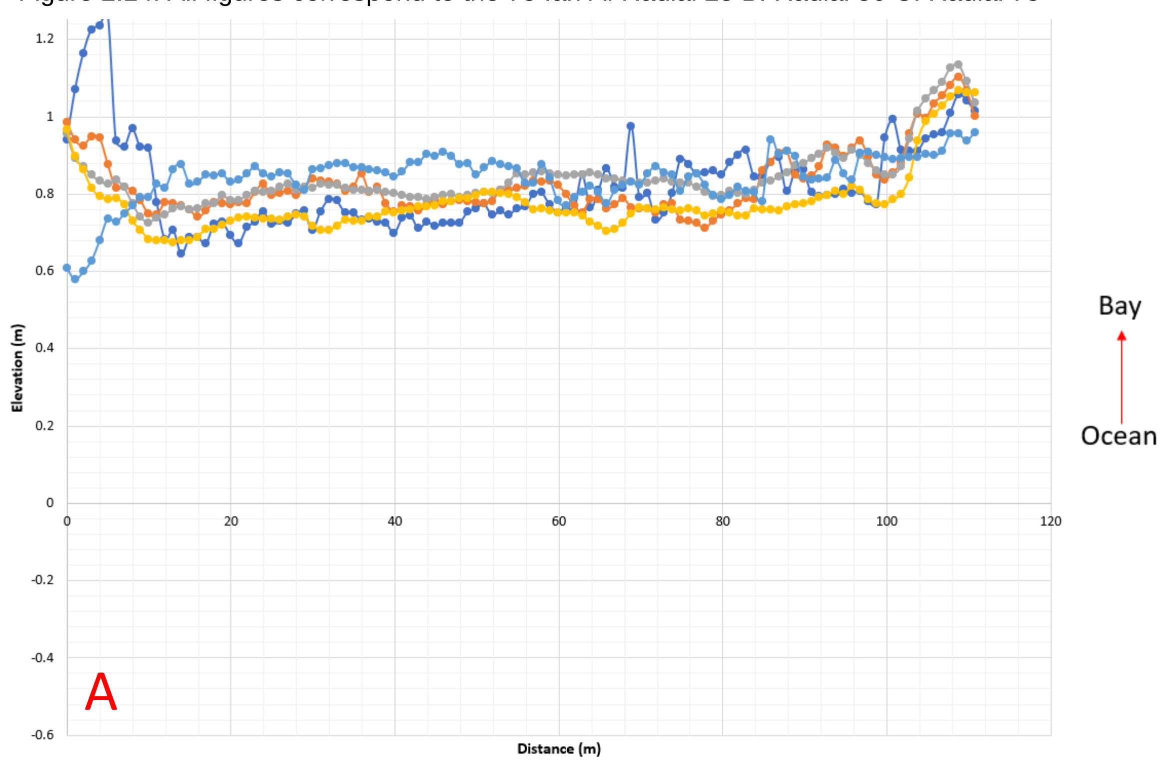

Figure 2.15: All figures correspond to the 75 fan A: Transverse 25 B: Transverse 50 C: Transverse 75

erosion occurred across the fan surface and creates multiple high and low spots. The heterogenous nature of the topography of the washover fan is likely a result of overwash as evidenced by erosion and deposition present on the site during fieldwork. A similar pattern is also evident along radial profile 50, which has a notable low spot in the middle fan that widens through 2017. Instead, deposition of sediment increased at the beginning and lateral extents of the washover fan. Similarly, radial profile 75 also exhibits topographic high and low throughout the washover fan’s surface between 2012-2019 (Figure 2.14).

The surface of the upper washover fan is relatively flat, with a slight incline towards the right side of the washover fan in transverse profile 25. Transverse profile 25 also experienced increased deposition on the lateral extents of the washover fan’s surface. Only data between 2012-2017 were captured for transverse profile 50 and 75 due to an insufficient capture space of the area taken with the UAV. A large convex feature formed in 2012 and migrated towards the left of the washover fan in 2014 and resided until 2017 (Figure 2.15).

Variability Between the 85 and 75 Fan*:* Radial profiles 25, 50, and 75 had a gentler slope towards the washover fan toe in the 75 fan when compared to the 85 fan. A higher degree of topographic variability occurred along the lateral extents of the 85 fan (Figure 2.12 and 2.14). The 85 fan experiences an overall convex shape, while the 75 fan is more concave in transverse profile 25. There are no identifiable patterns observed for transverse profile 50, but both fans have deposition in the middle of the fan for transverse profile 75 (upper washover fan) and the lateral extents show no true patten between the two (Figure 2.13 and 2.15).

Fan Profile	Mean	Standard Deviation	Kurtosis	Skewness
		2019		
Radial 25	.371	.277	-.516	.774
Radial 50	.282	.018	-.701	-.590
Radial 75	.459	.160	-.038	-.803
Transverse 25	.596	.170	.509	.632
Transverse 50	.332	.011	1.755	-.760
Transverse 75				
Throat 25	1.586	.284	-1.379	.519
Throat 50	1.162	.176	.277	.761
Throat 75	.902	.106	1.148	1.180
Throat Longitude	.976	.170	.509	.632
		2017		
Radial 25	.448	.173	-.775	-.647
Radial 50	.369	.136	-1.015	.286
Radial 75	.482	.157	.094	-.949
Transverse 25	.593	.104	-.314	.341
Transverse 50	.365	.093	1.304	1.114
Transverse 75	.212	.053	-.410	-.023
Throat 25	1.450	.285	1.338	1.334
Throat 50	1.124	.206	-.140	.449
Throat 75	.847	.098	.536	1.020
Throat Longitude	.935	.263	-.356	.830
		2016		
Radial 25	.436	.223	-.931	.589
Radial 50	.417	.147	.820	.134
Radial 75	.513	.151	.052	-.879
Transverse 25	.589	.069	-.901	-.340
Transverse 50	.379	.110	5.465	-1.724
Transverse 75	.252	.091	1.900	-.964
Throat 25	1.437	.271	2.501	1.852
Throat 50	1.139	.174	2.501	1.852
Throat 75	.901	.060	2.940	1.816
Throat Longitude	1.053	.238	-1.221	.428
		2014		
Radial 25	.492	.185	.531	-.869
Radial 50	.559	.163	7.016	-2.436
Radial 75	.489	.146	-.816	-.234
Transverse 25	.778	.082	4.972	2.190
Transverse 50	.583	.041	9.310	1.858
Transverse 75	-.072	.135	-1.684	.039
Throat 25	1.309	.220	-.227	1.271
Throat 50	1.100	.144	-.813	.689
Throat 75	.981	.109	-.341	.715
Throat Longitude	1.007	.179	-.262	.446
		2012		
Radial 25	.566	.207	1.164	-1.593
Radial 50	.585	.209	3.209	-2.156
Radial 75	.548	.019	-.609	-1.016
Transverse 25	.581	.157	1.913	-1.741
Transverse 50	.586	.096	3.067	-1.569
Transverse 75	.110	.102	-.391	.034
Throat 25	1.336	.072	-.974	.245
Throat 50	1.120	.073	1.745	1.675
Throat 75	.841	.067	-.343	.124
Throat Longitude	1.096	.280	-1.375	-.023

Table 2.1 Descriptive statistics for 85 fan profiles

Fan Profile	Mean	Standard Deviation	Kurtosis	Skewness
		2019		
Radial 25	.737	.065	-.323	-.004
Radial 50	.764	.040	-.761	.074
Radial 75	.784	.039	.047	.222
Transverse 25	.825	.121	2.594	1.492

Transverse 50				
Transverse 75				
Throat 25	1.656	.284	-1.379	.519
Throat 50	1.223	.088	1.807	1.389
Throat 75	.960	.067	-1.311	.111
Throat Longitude	1.300	.290	-.624	.490
		2017		
Radial 25	.801	.051	-.803	-.284
Radial 50	.805	.063	-1.363	.059
Radial 75	.795	.067	-1.163	-.110
Transverse 25	.828	.083	1.586	1.410
Transverse 50	.716	.070	-.685	-.040
Transverse 75	.416	.058	.325	-.863
Throat 25	1.731	.317	-1.744	.185
Throat 50	1.259	.124	-.822	.286
Throat 75	1.055	.084	-.680	-.397
Throat Longitude	1.281	.263	-.822	.625
		2016		
Radial 25	.801	.053	-1.258	-.034
Radial 50	.814	.050	-1.237	.188
Radial 75	.817	.058	-.810	-.362
Transverse 25	.844	.077	4.636	2.048
Transverse 50	.704	.055	.319	-.085
Transverse 75	.473	.810	4.543	-1.856
Throat 25	1.810	.265	-1.685	.148
Throat 50	1.295	.102	-.915	.587
Throat 75	1.090	.050	-.875	.364
Throat Longitude	1.355	.315	-.006	.907
		2014		
Radial 25	.723	.069	-1.421	.030
Radial 50	.771	.034	-.680	.073
Radial 75	.746	.068	-1.277	-.360
Transverse 25	.778	.082	4.972	2.190
Transverse 50	.583	.041	9.310	1.858
Transverse 75	.365	.065	-.775	.521
Throat 25	1.653	.139	-1.688	-.053
Throat 50	1.227	.066	4.134	2.281
Throat 75	.980	.023	-.119	-.260
Throat Longitude	1.299	.278	-.970	.178
		2012		
Radial 25	.798	.076	-.383	-.681
Radial 50	.849	.042	1.737	-1.202
Radial 75	.771	.154	.340	-1.202
Transverse 25	.842	.066	4.542	-1.697
Transverse 50	.440	.075	.583	1.158
Transverse 75	.245	.053	-.860	-.014
Throat 25	1.593	.055	-1.082	.048
Throat 50	1.232	.062	-1.573	.036
Throat 75	1.042	.048	.054	.772
Throat Longitude	1.342	.311	-.843	.561

Table 2.2: Descriptive statistics for 75 fan profiles

Descriptive Statistics: Both fan 75 and 85 had overall higher elevation in the throat portion of the feature, in comparison to the fans surface. No true pattern was established regarding the skewness and kurtosis of each profile. The washover fan and throat both alternate between leptokurtic and platykurtic surface elevations. The throat longitudinal profiles of fan 85 decreases in elevation between 2012-2019, from 1.096 meters running average to a 0.976 meters. However, this is not true for fan 75, as the running mean fluctuates in elevation throughout the years. In both cases, the average height does not change dramatically, but rather by tens of centimeters. This is also proven by the small standard deviation observed for both fans (Table 2.1 and 2.2).

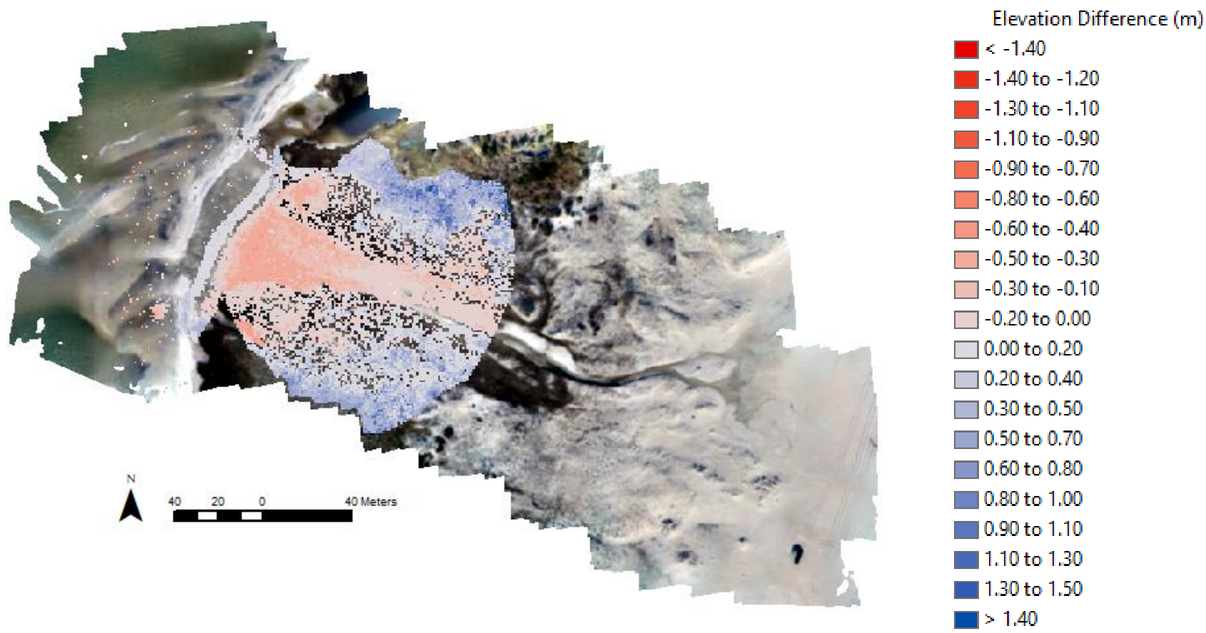

Figure 2.16: Geomorphic change detection of 85 fan between 2012-2019, where red shows erosion

Geomorphic Change Detection (85 fan*):* Between the years 2012-2019 the washover fan experienced mostly topographic raising as it grew in length and sediment volume. However, most areas that experienced erosion occurred around the center of the fan area (Table 2.3 and Figure 2.16). The 2016-2017 and 2012-2014 period are the only periods at which topographic lowering is dominant, but in all other years topographic raising is consistently higher than topographic lowering (Table 2.3). Despite the overall topographic raising, the surface features of the center of the washover fan experienced the most erosion (Figure 2.16), as the surface begins to lose topographic complexity, causing a flattening of the surface. On the other hand, deposition occurred on the left and right lateral extents of the fan's surface (Figure 2.16).

Surface Change	Volumetric Change	Error Volume	Percent Error
2014-2012			
Topographic Raising	551.61 m^3	± 166.10	28.98 %
Topographic Lowering	1,246.08 m^3	± 415.25	31.84 %
2016-2014			
Topographic Raising	1,317.33 m^3	± 419.15	32.85 %
Topographic Lowering	513.62 m^3	± 182.70	38.67 %
2017-2016			
Topographic Raising	493.96 m^3	± 179.30	42.07%
Topographic Lowering	721.65 m^3	± 321.15	57.69 %
2019-2017			
Topographic Raising	1,353.89 m^3	± 350.45	27.28 %
Topographic Lowering	1,244.63 m^3	± 252.55	21.78 %
2019-2012			
Topographic Raising	1,908.07 m^3	± 327.70	17.41 %
Topographic Lowering	1,102.20m^3	± 276.85	25.80 %

Table 2.3: Volumetric changes and associated errors of fan 85.

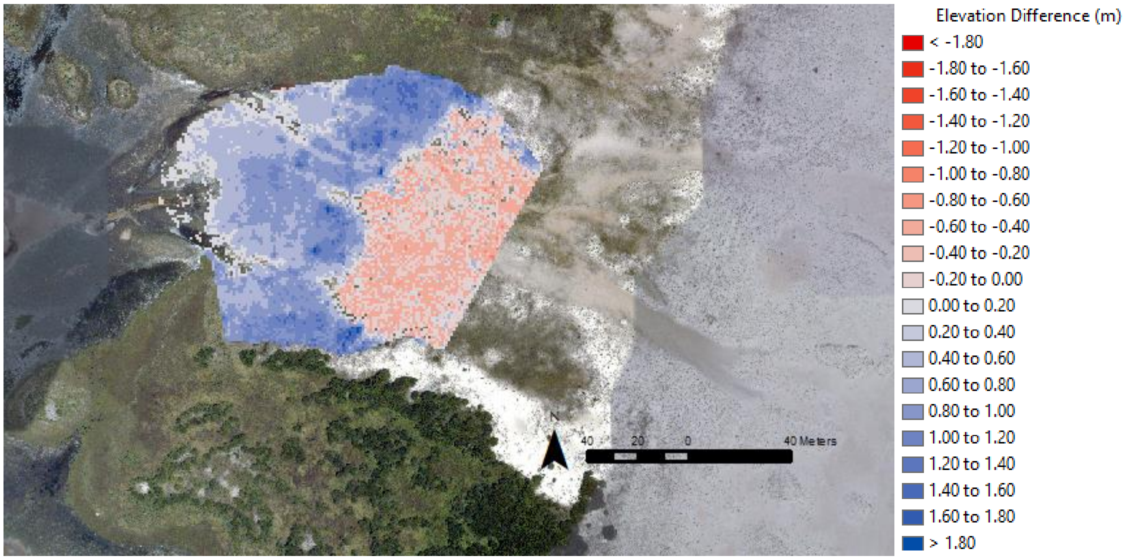

Figure 2.17: Geomorphic change detection of 75 fan between 2012-2019, where red shows erosion and blue represents deposition. GCD of 2019-2012 and 2017-2012 are both included to show entire area.

Geomorphic Change Detection (75 fan): The years 2017-2012 will be the focus of this study due to the lack of data associated with the 2019 survey. Topographic raising dominates this location between the years of 2012-2019. Deposition dominated the higher surrounding topography, most likely due to aeolian activity as sediment began to deposit on higher relief areas such as vegetation (Olson, 1958). In comparison, erosion was more prominent in the topographically lower areas (Figure 2.17). In almost every year, topographic raising dominated the overall topographic change of the washover fan with the exception of 2016-2017 which corresponds with Hurricane Hermine (Table 2.4). Between 2017-2012 the lateral extents of the fan have gained elevation, as sediment was being deposited from overwash, all the while the center of fan was being eroded (Figure 2.17). Due to the wedge-like nature of the fan, these observations demonstrate the fan flattening out over time.

Surface Change	Volumetric Change	Error Volume	Percent Error
2014-2012			
Topographic Raising	969.74 m^3	±330.50	35.84%
Topographic Lowering	382.21 m^3	±172.95	47.98%
2016-2014			
Topographic Raising	1,205.28 m^3	±498.50	43.23%
Topographic Lowering	27.22 m^3	±7.65	45.35%
2017-2016			
Topographic Raising	151.01 m^3	±57.35	57.88%
Topographic Lowering	421.96 m^3	±207.25	65.90%
2019-2017*			
Topographic Raising	30.99 m^3	±11.90	53.58%
Topographic Lowering	484.02 m^3	±201.35	43.35%
2019-2012*			
Topographic Raising	158.54 m^3	±38.15	25.26%
Topographic Lowering	499.59 m^3	±186.55	38.51%
2017-2012			
Topographic Raising	1,690.77 m^3	±398.65	24.04%
Topographic Lowering	196.13 m^3	±87.60	53.56%

Table 2.4: Volumetric changes and associated errors of fan 75. *Because UAV flight did not cover entire fan, values may be lower.

Between Fan Variability*:* Both fans exhibit overall topographic raising between 2012-2019, with the 75 fan experiencing the most depositional change. However, between the year of 2016-2017, both locations experienced overall topographic lowering. Each fan also experienced similar characteristics where increased erosion occurred at the center of the fan, and a majority of the deposition occurred at the lateral extents of the fan’s surface.

Discussion

Sediment tends to be deposited largely at the lateral extents of both washover fans, consistent with findings by Feagin and Williams (2008), Williams (2015), and Yovichin and Mattheus (2018). During this time, overwash would appear to have a higher velocity along the central axis of the fan and near the lateral extents of the fan. Although both sites experience convex features at the lateral extents of the fan, no profile patterns existed. The deposition at the lateral extents is likely some combination of overwash flow spreading and depositing sediment in the locales where there was dense grasses and shrubs and the addition of aeolian material as it moved from the beach, dunes, and fans into this more densely vegetated portion of the fan. The topographic complexity and vegetation likely reduce velocity and lead to sediment deposition that is represented in the topographic raising evident in the profiles and 3D volumetric changes (Williams, 2015).

Sediment cores at the lateral extents of the washover fans could proivde an opportunity to investigate if these convex features contain increased amounts of heavy minerals in comparison to the remaining fan edge. The buildup of sediment on the lateral extents could be mostly composed of these heavy materials, thus being deposited in the 85% region due to the velocity of overwash slowing down and depositing these materials, due to their heavier mass in comparison to fine grain sands. Transects of sediment cores could also be used to examine the variability in the caliber, magnitude, and architecture of materials being deposited which could supply further information of the types of processes dominant in these locations.

The lack of patterns towards the toe of the fan are most likely contributed to infrequent overwash occurrences capable of transporting sediment to the furthest extents, creating a longer time span for sediment pattern development. In combination with infrequent overwash explanation is the observation that wave erosion and flooding are both depositing and eroding sediment near the toe of the washover fan, particularly in the 85 fan.

Both of the washover fan throats have a wedge-like morphology (Figure 2.9), where the height of the washover fan decreases toward the back side of the barrier island. This data could be explained by the pre-existing morphology as elevations along the dune line tend to be higher than the back barrier where the washover fan becomes flatter. The 75 fan's gentler slope, wedge-like feature, is most likely explained by the proximity of the fan to the bay. This is characteristic of an overwash dominated beach area where overwash is moving laterally from the ocean to the bay creating the wedge-like feature. These findings correlate with Kochel and Wampfler (1989), as they too discovered Assateague Island to be an overwash dominated beach. However, this study focuses on washover fans located on the northern end of Assateague in comparison to their study of washover fans along the entirety of Assateague. The wave and tide heights (Table 2.5) obtained by NOAA indicate 2012-2019 to be years of possible overwash also aiding in the finding of an overwash dominated zone. Further research could investigate whether the throat would begin to incise further at the beginning to create an even height/width of the entirety of the washover fan's throat.

The throat portion of the washover fan also had similarities in their topography. The channel located in the lower throat tended to be shallower than those located in the upper and middle throat. This observation could result from their close proximity to the bayside, causing a decrease in velocity of overwash as it moves through the throat, thus creating less scouring of the surface and a less defined channel. The middle to right side of the lower-throat profile, on the 75 fan, tended to have increased deposition which could be contributed to the channel meandering or pre-existing topography. It also could correlate to the wind patterns associated with Assateague Island, where southwesterly winds dominate summer months and northwesterly in the winter months. The continuous wind speed direction can help transport sediment across an area and build up along pre-existing topography, causing a surface change in elevation.

The 75 fan was also part of the first trial of the constructed berm channel project on Assateague Island. The channelized foredune was created to allow overwash in the northern portions of the island and prevent island breaching. This project was also created to build new habitat for the endangered piping plover species (Schupp et al., 2013). Schupp et al. (2013) collected data that corresponds with the most recent data collected (Figure 2.18). The topography from the Schupp et al. (2013) figure shows the topography remains relatively consistent with current topography from the study, where the strong wedge-shape and undulations through the dune are present in current profiles. Note the current study's data only show from 150 meters to 500 meters on the Schupp et al. (2013) graph. The topographic patterns also persist on the 85 fan and it is noted that even the sharp topographic change near the end of the fan (likely associated with wave action on the bay side of the island) is present in both features. The noted topographic similarities show that despite the use of human designed channels the system response is similar to what is occurring naturally within these environments. The system continues to respond in similar fashion even beyond the initial human designed channel that was not evident during the fieldwork conducted for this study. The similarities lend credence to the experimental design of Schupp et al. (2013) and show that the attempt to bring back some dynamism within the system produces corresponding changes that mimic the “natural” setting.

When observing the imagery from the 85 fan, a recognizable pattern was

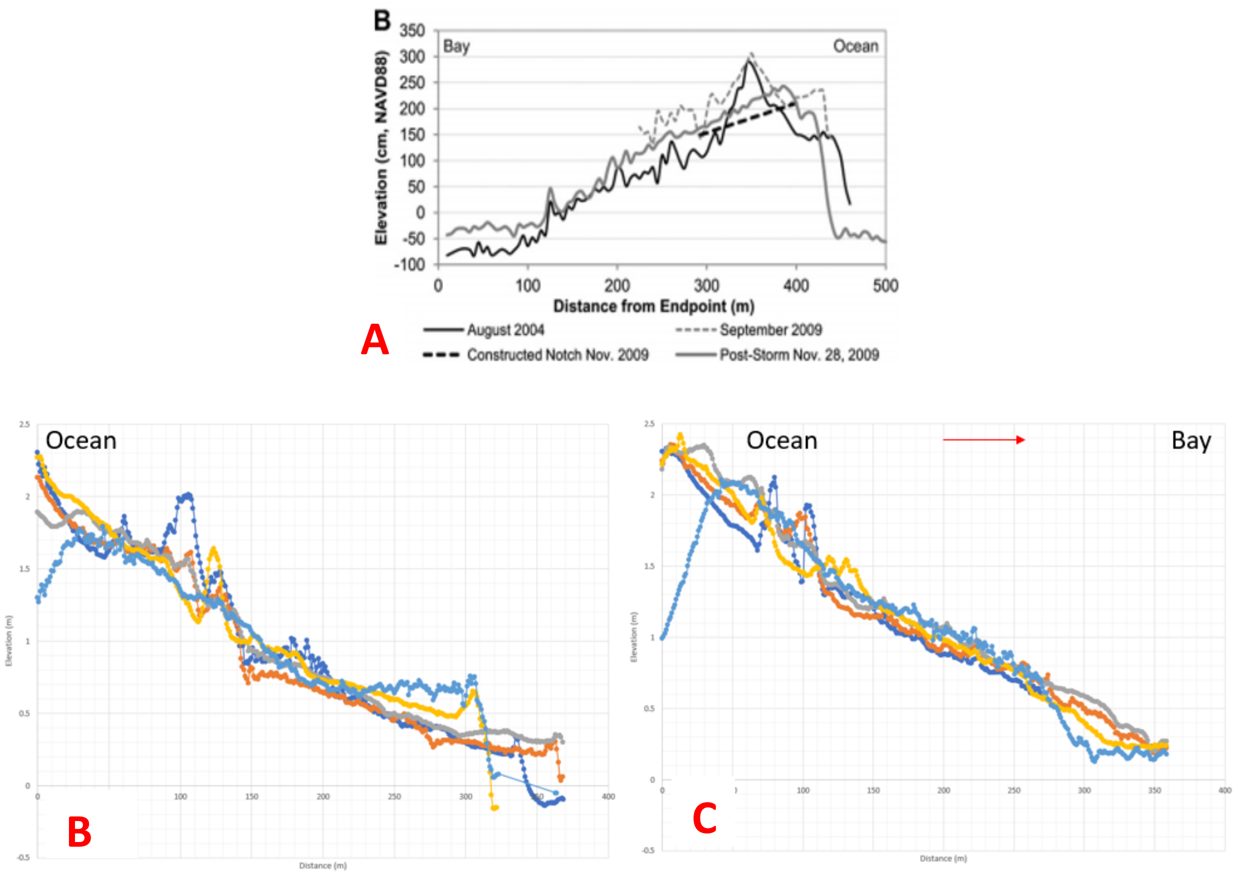

Figure 2.18: Longitudinal profiles of A: Shupp et al.’s team (2013) B: 85 Fan and C: 75 Fan indicating a wedge-like feature.

revealed. Within the middle of the throat's surface was a braided channel-like appearance. This could be explained by smaller overwash events with enough strength to only deposit sediment in the throats channel until the sediment reaches a certain threshold and therefore the overwash maneuvers around the deposited sediment, creating the braided-like appearance.

Both washover fans experienced increased erosion from 2016-2017 (Table 2.3 and Table 2.4). Hurricane Hermine stuck Maryland's East Coast in 2016 causing coastal erosion, storm surges, and wave and tidal height leading to overwash processes. The hurricane shows the potential impact of larger magnitude storms when compared to the topographic raising identified with smaller storms. This has implications for the long-term behavior of the island under climate change and has potential implications for habitats in this locale.

NOAA Tides and Currents and NOAA's National Data Buoy Center (buoy OCSM2) was used to find historical wave data for the LiDAR downloaded from NOAA Access Viewer. However, this was difficult to find because there is no exact date of flight in the metadata attached to the LiDAR. The following data was recorded regarding highest wave height and highest tide height:

Year	Highest Tide	Highest Wave Height
2011	**0.62 meters** *September*	**N/A**
2012	**0.61 meters** *October*	**N/A**
2013	**0.63 meters**	**2.83 meters**

	October	*February*
2014	**0.61 meters** *December*	**2.77 meters** *December*
2015	**0.63 meters** *October*	**3.29 meters** *October*
2016	**0.66 meters** *September*	**3.05 meters** *September*
2017	**0.68 meters** *September*	**3.34 meters** *January*
2018	**0.71 meters** *September*	**3.05 meters** *October*
2019	**0.73 meters** *October*	**2.72 meters** *November*

Table 2.5: Highest tide and highest wave recorded for each year along with which month they were recorded.

According to Leatherman and Williams (1983), in order for overwash to occur on Assateague Island, MD, waves must be at least 1.8 meters in height and have a storm surge of 0.3 meters. The data collected from NOAA supports these findings as the highest tides were above 0.6 meters and had highest waves reaching 2 meters and above (Table 2.5). With climate change and sea level rise, storm intensities are increasing, causing increased wave heights capable of overwash. Washover fans will continue to grow in length towards the backside of the island, aiding in landward migration of the barrier, ultimately minimizing natural barriers protecting the mainland from many coastal storms.

The results found in this study reveal active landward migration of the barrier island because the length of the washover fan increases with time towards the back barrier and bay. These processes have not been halted since at least 2012 and have dated back even further (Leatherman, 1979), concluding that the northern end of Assateague Island, MD is still migrating landward despite beach nourishment projects.

NOAA Storm Event Database was then used to collect an understanding of the weather occurrences during this time. The following disturbances were recorded:

- October 28th, 2012: coastal flood, tropical cyclone Sandy, storm surge, extreme wave action, beach erosion, and breaching
- January 7th, 2017: heavy snow and strong winds

Hurricane Hermine of 2016 was not listed in this data base; however, LiDAR data was collected in the Assateague area after this storm.

Overall, this area of the island seems to experience higher frequency small events instead of larger magnitude events resulting in overwash. Since the island still has active washover fans and has not experienced a severe storm in the past few years, Assateague Island may become more favorable of an overwash area as sea levels continue to rise, bringing along larger wave and surge heights. Smaller waves have the ability to affect this area and the tides may be more responsible for overwash.

Conclusion

Two washover fan sites located on Assateague Island, MD were observed between the years 2012-2019, using LiDAR from NOAA, available for 2012-2017 and high-resolution point clouds from SfM taken with DJI Phantom 4 Pro in 2019. These data were compared to determine morphological changes between the two washover fans to help further the understanding of washover fan evolution. The surfaces of the two fans exhibited similar patterns of topographic change over the extent of the observations, but the timing of the responses were different. Systematic aggradation of the washover fans was evident at the lateral extent of the fan and overall surface raising was observed, despite the pattern of erosion down the central axis of the washover fans. The small volume of changes is likely associated with the lack of substantial storms that would generate enough overwash in this area.

The formation of channels allows for a stronger pathway of overwash to cross the throat and washover fan surface. Both washover fans had channels within their throat and fan surface, while the lateral extents only had one channel, the upper and middle fan had two. The shape of these channels differs between each of the washover fans, where the 75 fan has a more rectangular shape compared to the 85 fan's catenary or V-shaped.

In conclusion, both fans experience similar erosional, depositional, and morphological changes. Erosion typically occurred within the throat surface and middle fan area, while deposition occurred mostly on the lateral extents of the fan. Despite the human disturbance of the 75 fan, it behaved similarly to the 85 natural fan.

This information obtained from this research will inform NPS staff on how the barrier island is responding to recent storms and associated overwash. The Ocean City jetty has caused the Northern Assateague Island to move landward because of the interruption of longshore sediment transport (Leatherman, 1979). The washover fans represent a significant source of sediment and are an important sink and source of sediment to consider to further understand the mechanisms in how the barrier island is moving landward. Small pulses of sediment and topographic raising and lowering have dominated this system over the period examined in the current study. This indicates minimal growth of the washover and potential lower connectivity of sediment migration to the back barrier, which has the potential to reduce the heterogeneity of the habitat in this area and may have implications for nesting bird populations in the area.

CHAPTER 3: SUMMARY

Overview of Washover Fan Research: Two washover fans were chosen with the help of NPS members at Assateague Island National Seashore, Maryland. Legacy LiDAR data was obtained for the years 2012-2017 from NOAA Data Access Viewer for the two sites. 2019 data of washover fan 75 and 85 were collected by the ECU research team by the use of UAV and RTK-GNSS data collections. The imagery and control points were processed in Agisoft Metashape Pro and ArcGIS Desktop to compile profiles of various radials, transverses, throat profiles, and volumetric changes of these two fan sites. The data obtained were analyzed for similarities and differences in the fans evolution between 2012-2019 to gain knowledge in a broader time scale on how these features evolve, rather than focusing on pre- and post-storm data.

One recommended change to the current workflow would be the use of larger QCP targets. While the targets were identified, it was difficult finding them in the matching process of Agisoft Metashape Pro because of their small size and the reflectivity of the orange paint and white sand. Also, while the Phantom 4 Pro provided adequate imagery, a heavier duty UAV may be better suitable for the windier coastal environment and the time of year the UAV survey was conducted. Lastly, due to limited funding and timing for research collection, only two fans were investigated within close proximity to each other. Having increased distance between fan site and a larger sample size would help enhance the results of the data and solidify the research findings, eliminating similarities is response to the close relative location.

Evolutionary Morphological Findings: Smaller channels were found within each fan throat; however, the lower throat typically had only one shallower channel. Lobes of sediment deposition were identified at the lateral extents of the washover fans in both the transverse and radial profiles. The washover fans are characterized as a wedge-like feature in their longitudinal profile, where the height decreased closer to the back barrier. This is indicative of negative feedback mechanisms in operation as water during overwash events decelerate coming from the confined throat in the dunes and expand outward into the back barrier. This likely leads to the erosion of material, represented as topographic lowering in the results here, along the central axis of the fan and deposition, represented by the topographic raising, along the lateral extents of the washover fans. Overall, these two locations are growing in length, while the 85 fan has already reached the bay on the backside of Assateague Island. This data helps prove that this area of Assateague Island is currently still migrating landward. The data collected by the ECU Research team also corresponds to data collected on Assateague Island by the Army Corps of Engineers and National Park Service in regard to cross-profile and morphological patterns.

Future Research: The research presented in this thesis observed lobes of sediment commonly developed on the lateral extents of the washover fans consistently. Sediment lobes typically formed around the 85% mark of the fan’s length at both sites. These features developed at the beginning of the observation period, but disappeared from the fan at the same time towards the end of my observations. More research in the development of these lobes of sediment on washover fans should be conducted to help prove that this is a common feature development in fan evolution. Sites should be chosen at different locations along the east coast of the US to ensure that these features are not just a response to the close proximity of the fans studied in the current location. If these depositional lobes are found in other washover fan sites, further research could be done involving investigating what role these lobes play in constraining flow and causing the erosion along the central axis of the washover fan. This leads to several questions for future investigations. Does the volume of the lobe correlate with the increased washover fan width or length? Are there sediment size differences that exist between the lobes and the central axis of the fan and what does that mean for habitat in these locales?

Future research should also look at the different channel shape formations within the throats to determine if they have any influence on the speed and deposition of overwash. Does channel shape increase or decrease velocity of overwash? What causes one fan to have one channel type and the other a different? Time? Or Pre-existing topography?

Washover fans are complex coastal features found on barrier islands. The information obtained by this research will further help coastal scientists to understand the evolutionary mechanisms provided by washover fans such as sediment transportation within the fan, topographic raising and lowering, and throat morphology.

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