EFFECT OF BARRIER HEIGHT ON MAGNITUDE AND CHARACTER OF HURRICANE HARVEY WASHOVER FANS, MATAGORDA PENINSULA, TEXAS

Bradley J. Rains, B.S.

Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

August 2020

APPROVED:

Harry Williams, Major Professor
Paul Hudak, Committee Member
Lu Liang, Committee Member
Steven Wolverton, Chair of the Department of Geography and the Environment
Tamara L. Brown, Executive Dean of the College of Liberal Arts and Social Sciences
Victor Prybutok, Dean of the Toulouse Graduate School

Rains, Bradley J. *Effect of Barrier Height on Magnitude and Character of Hurricane Harvey Washover Fans, Matagorda Peninsula, Texas*. Master of Science (Applied Geography), August 2020, 32 pp., 3 tables, 10 figures, references, 25 titles.

This study uses topographic profiles, washover fan volumes, and shoreline retreat rates to explore relationships between barrier types and Hurricane Harvey storm washover sedimentation. Pre- and post-Hurricane Harvey topographic profiles were created on 15 transects using Bare Earth LiDAR (2016) and surveyed elevations (2019). Depth and area of washover fan measurements were collected to estimate washover fan volumes. An inverse relationship was found between washover fan volume and pre- and post-storm barrier heights. Based on the topographic profiles, one section of shoreline had a scarp up to 3m high which blocked overwash, but appears to have increased shoreline erosion. In contrast, a low-lying section of shoreline generated relatively large washover fans, but experienced less shoreline retreat. Shoreline retreat was further quantified between 2014 and 2019 using Google Earth Imagery from 2014, 2016, 2017, and 2019 to track migration of the shoreline. The entire shoreline in the study area is undergoing relatively rapid retreat, but the results suggest that Hurricane Harvey increased erosional rates. The Colorado River Jetty borders the study area and may have acted as an anthropogenic barrier, likely reducing storm surge energy and contributing to marsh aggradation on transects in its close proximity. The study findings indicate that the identification and incorporation of other variables that influence washover magnitude would further the understanding of this complex natural system. The research results provide valuable information on the interaction of hurricane storm surge with natural and anthropogenic barriers, beach and dune erosion, and marsh aggradation along the coast of Texas.

ACKNOWLEDGEMENTS

This research is considered to be an extension of work supported by the National Science Foundation credited to Grant No. 1803526. I wanted to extend a special thanks to Harry Williams (University of North Texas, Professor of Geography) for providing the resources and counsel to conduct field work, contributing his knowledge and expertise, and for taking me on as a geography master's student. I would also like to thank Lu Liang (University of North Texas, Professor of Geography) and Paul Hudak (University of North Texas, Professor of Geography) for their feedback and support as committee members. Lastly, I would like to thank Denesa Rains-Northup and Desmond Rains for their continual support and love through my graduate program.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS ... iii

LIST OF TABLES ... v

LIST OF FIGURES ... vi

CHAPTER 1. INTRODUCTION ... 1

1.1 Hurricane Impact ... 1

1.2 Washover Sedimentation and Barrier Island Erosion ... 2

1.3 Study Objectives ... 3

CHAPTER 2. STUDY AREA ... 5

CHAPTER 3. METHODS ... 7

3.1 Transect Establishment ... 7

3.2 Pre- and Post-Storm Topographic Profiles ... 7

3.3 Washover Fan Volumes ... 9

CHAPTER 4. RESULTS ... 12

4.1 Washover Fan Volume ... 12

4.2 Pre- and Post-Storm Topographic Profiles ... 13

4.3 Resurvey of 2018 Topographic Profiles ... 20

4.4 Shoreline Retreat ... 21

CHAPTER 5. DISCUSSION ... 23

5.1 Washover Volume vs. Pre- and Post-Storm Barrier Height ... 23

5.2 Scarp Erosion vs. Sloping Foredune Erosion ... 25

5.3 HW Resurveyed Topographic Profiles ... 25

5.4 Study Area Variables ... 26

CHAPTER 6. CONCLUSION ... 28

REFERENCES ... 31

LIST OF TABLES

Page

Table 4.1: Washover fan areas, depths, and volumes. 13

Table 4.2: Shoreline retreat rate (meters per month) transects between 2014 and 2018. 21

Table 5.1: Study area variables including their descriptions and field observations. 26

LIST OF FIGURES

Page

Figure 2.1: Study area. Imagery acquired March 2018, approximately 7 months after Hurricane Harvey. Transect lines used in the study are indicated. 6

Figure 3.1: The inland edge of a sandy washover fan overlying the existing marsh surface. 9

Figure 3.2: Distinct contact between marsh and washover sedimentation. 10

Figure 3.3: (a) Eastern end of the study area (Zone 1) with digitized washover fan areas, pit locations, and transects, (b) Central section of the study area (Zone 2), (c) Western end of the study area (Zone 3). 11

Figure 4.1: Topographic profiles T1-T15 displaying pre-storm LiDAR elevation (NOAA 2016) and post-storm surveyed topographic profiles (2019) (see Fig. 3.3). 18

Figure 4.2: Pre-storm barrier heights vs. post-storm washover fan volumes. 19

Figure 4.3: Post-storm barrier heights vs. post-storm washover fan volumes. 19

Figure 4.4: Pre-storm barrier height vs. post-storm barrier height elevations of all transects. 19

Figure 4.5: Topographic profiles from 2016, 2018, and 2019 (HW T1 and HW T2). 21

Figure 5.1: Scarp-like barrier in Zone 2 (left) and a sloping barrier in Zone 3(right). 24

CHAPTER 1

INTRODUCTION

1.1 Hurricane Impact

The Gulf of Mexico coastline is subjected to large storm events that remove sediment in some areas, while depositing sediment in other areas. One such area is the Chenier Plain in Louisiana, where 70-90% of marsh aggradation since 1957 is attributed to washover sedimentation from Hurricanes Rita and Audrey (Williams, 2011). Other studies agree that storm surge and the resulting inundation provides positive marsh accretion and stimulation to wetland vegetation growth (Rejmánek et. al., 1988; Cahoon, 1996; McKee & Cherry, 2009). Areas subject to storm inundation and storm surge overwash have a dependence on storms to provide sufficient sedimentation to counteract sea-level rise submerging the marsh environments (Stumpf, 1983; Williams 2011; Williams, 2013) It is important to identify marshes that have a storm dominated environment and to understand how floodwaters, transported sediments, and the marsh surfaces interact during storms (Stumpf, 1983). Studies suggest that large, storm-dominated marshes may receive more sediment accretion from a single Category 5 hurricane than from two entire seasons of cold fronts (Cahoon et. al., 1995). However, some marsh areas rely on sedimentation from large hurricanes and their contribution to long-term aggradation (Williams, 2013; Ma et. al., 2014). These studies show that it is essential to understand storm sediment accretion dynamics across the Texas and Louisiana coastlines, in terms of sediment gain and loss of both organic and inorganic sediments, particularly in view of detrimental anthropogenic impacts that are accelerating the rate of marsh transition to open water (Wilkinson & McGowen, 1977; Hatton, 1983; Turner, 1990; Reese et. al., 2008; Williams, 2011; Williams, 2013).

One component of sedimentation dynamics along the Gulf Coast is the effect of natural and artificial barriers on washover sediment magnitude. Williams examined washover sediment beds in the lee of coastal foredunes in southeastern Texas. The study found an average 40% reduction in sediment volume and an average reduction in inland extent of deposits of 505 m, in the lee of a higher and wider foredune barrier, compared to a lower and narrower foredune barrier (Williams, 2017). Williams concluded that even relatively subtle increases in barrier dimensions can cause substantial reductions in the magnitude of washover sedimentation in marshes (Williams, 2017).

1.2 Washover Sedimentation and Barrier Island Erosion

Southeast Texas has been subjected to many storm surge events which have contributed a significant portion of the sediment deposition on the Texas Gulf Coast (Cahoon, 1995; Williams, 2013). There is a necessary balance of vegetation, sedimentation, and sea-level rise rate in order for marshes to aggregate and survive (Walters & Kirwan, 2016). The resiliency of a marsh environment is contingent on sediment either brought from inland areas by flooding or coastal sediments brought by storm surge. Washover fan deposits are characterized by their sandy composition and stark white appearance on the marsh surface (Wang & Horowitz, 2007; Williams, 2011; Williams, 2015). The washover sediment is derived from the upper and lower shoreface, and shallow offshore environments (Hawkes, 2012).

The differing sediment type can be interpreted as a change in factors controlling the depositional environment (Stumpf, 1983). Contacts between washover sediment and underlying marsh can be described as significant changes in color, sediment type, and organic content. A distinct change in composition alludes to different energy-levels of deposition. Establishing contacts between storm event and other sedimentation processes can prove to be difficult because inundation and bioturbation alter final preservation of sediment deposits (Shinn, 1993).

The ability of washover sediment to be transported to wetlands is contingent on dune elevation being low enough for washover to occur (Williams, 2015; Williams, 2017). The dune elevation influences the volume of sediment deposited on the wetland surface from storm surge (Williams, 2015; Williams, 2017). Overall accretion rates are affected by existing variables such as dune height, vegetation cover, and magnitude of storm surge (Dingler & Reiss, 1995; Williams, 2015; Williams, 2017). These studies reference a relationship between the two phenomena, but have yet to explore the magnitude of influence of dune height to volume of washover sedimentation of a category 5 hurricane event. The magnitude of barrier elevation influence can be measured by recording pre-storm and post-storm erosion and quantifying sedimentation following the hurricane event. This study's objective is to collect informaton on the relationship between Hurricane Harvey washover fan magnitude and barrier height (Williams, 2015, Williams, 2017).

1.3 Study Objectives

As an extension of the work of Williams (2017), this study aims to examine the relationships between foredune barrier height and washover fan magnitudes on Matagorda Peninsula, Texas. Rapid Response Imagery obtained a few days after landfall of Hurricane Harvey in 2017, shows multiple washover fans deposited by the hurricane's storm surge at the eastern end of the peninsula. There are distinct contrasts in the areal extent of the fans along a ~2 km stretch of coastline. Within the study area, there are many large fans at the western end, few and smaller fans in the central section, and intermediate-sized fans at the eastern end. This study has the working hypothesis that these variations in fan dimensions result from washover of foredune barriers of contrasting dimensions. This study also investigates changes in beach, dune, and marsh topography during washover by comparing pre- and post-storm topographic profiles across selected barriers. Other facets of coastal information such as shoreline retreat and scarp and low foredune influence on washover sedimentation were included in the assessment to further understand the broader study area characteristics.

CHAPTER 2

STUDY AREA

The study area is located approximately 175km southwest of Houston on the Matagorda Peninsula (Fig. 2.1). The Peninsula primarily consists of wide sandy beaches, low discontinuous foredunes, and low-lying marsh. Evidence of washover fans, longshore sediment transport and beach erosion over time, including wave-cut scarps, suggests a vulnerability to storm erosion along this coastline (Wilkinson & McGowen, 1977). The study area consists of the eastern ~2km of the Matagorda Peninsula. Hurricane Harvey produced storm surge heights of 1.83 to 3.05m in bays east of the landfall location of northern San Jose Island (NOAA 2018). Data collected from storm surge height monitors recorded Seadrift, TX at 1.76m, Port Lavaca at 2.1m, Matagorda City at 1.08m (NOAA 2018). Rapid Response Imagery retrieved from NOAA from August 29th, 2019 shows many washover fans were formed in this area as a result of Hurricane Harvey's storm surge on August 26-27th, 2017. Near the study area, there is also small evidence of flooding sediment (Yao et. al., 2020) and scarp-like terrain indicating a high energy erosion on the landscape. An extensive wrack line (plant debris caught on bushes and trees) in higher ground inland from the shoreline was observed during fieldwork. Surveyed elevations of several points along the wrack line averaged 2.3 m (NAVD88; see methodology section). This suggests that Hurricane Harvey's storm surge peaked at 2.3 m in the study area. There are distinct variations in fan size: large fans are present in the west of the study area; smaller fans are seen in the central part of the study area; intermediate-sized fans are found in the east side of the study area (Fig. 2.1).

Figure 2.1: Study area. Imagery acquired March 2018, approximately 7 months after Hurricane Harvey. Transect lines used in the study are indicated.

CHAPTER 3

METHODS

The overall objectives of methodology include:

1. Create pre- and post-storm topographic profiles across fifteen fans in the study area, to assess pre- and post-storm barrier height and changes in beach, dune and marsh topography.
2. Determine volumes of the fifteen selected washover fans.
3. Examine the correlation between pre-storm barrier height and washover fan volume.

3.1 Transect Establishment

Based on contrasting fan size, the study area was divided into three zones: a western zone containing large fans; a central zone with small fans; an eastern zone with intermediate-sized fans (Fig. 2.1). Using a combination of Google Earth images, field observation and hand-held GPS, transects were established approximately along the central axis of 5 fans in each zone. Transects began on the beach and ended at a point inland, beyond the fan, that best represented the observed directional alignment of the fan (assumed equivalent to direction of storm surge) transects T1-T5 were located in the western zone, transects T6-T10 were located in the central zone and transects T11-T15 were located in the eastern zone (Fig 2.1).

3.2 Pre- and Post-Storm Topographic Profiles

BareEarth LiDAR data was used to construct a pre-storm topographic profile along each transect line. The LiDAR data was collected in August 2016, with RMSE of 10 cm, and referenced to NAVD88 (NOAA, year). In 2019 a surveyor's level was used to obtain post-storm topographic profiles along the same transect lines. The beginning and end point of each transect line was relocated using hand-held GPS. Surveyed profiles along transect T1-T6 were obtained in March 2019; Surveyed profiles along transects T7-T15 were obtained in June 2019. For transects in zones 1 and 2, elevations referenced to NAVD88 were collected by tying in the transects to "bench marks" established on the road running through the study area. Elevations of "bench marks" were obtained from the 2016 LiDAR data (it was assumed the road elevations had not significantly changed between 2016 and 2019). The road was too far from zone 3 to be used as a "bench mark". For transects in this zone, a second "bench mark" was established on top of the Colorado River Jetty. Elevation of this "bench mark" was also obtained from the 2016 LiDAR data (again assuming that the elevation of the jetty had not changed between 2016 and 2019). The surveyor's level was also used to estimate the elevation of a prominent wrack line found in the study area.

Comparison of the topographic profiles obtained from LiDAR in 2016 and surveying in 2019 provides a means to assess topographic changes resulting from Hurricane Harvey's landfall in August 2017. However, the LiDAR and survey datasets do not closely bracket landfall; the LiDAR data was collected ~12 months prior to landfall and the survey data was collected ~20 months after landfall. To explore the possibility that changes in topography may have occurred in the ~20-month period after landfall but prior to the collection of survey data in 2019, the surveyor's level was also used to resurvey 3 topographic profiles collected in March 2018 (Williams, unpublished data). These topographic profiles were located near transects T4, T6 and T12 (Figure 1). These resurveyed profiles provide a means to assess topographic changes unrelated to the impact of Hurricane Harvey (i.e. between March 2018 and March 2019).

To further assess topographic changes unrelated to hurricane impact, Google Earth images from November 2014, August 2017 (post landfall) and December 2018, and LiDAR data from August 2016, were used to estimate shoreline retreat or progradation for the periods 2014-2016, 2016-2017 and 2017-2018. For each period, Google Earth was used to measure the distance from an inland landmark (mainly the road running through the study area) to the shoreline (beach crest/vegetation line) along the 15 transect lines. Changes in these distances were used to calculate shoreline retreat or progradation rates in terms of meters per month.

3.3 Washover Fan Volumes

Washover fan boundaries are sharp and distinct for each fan on air photos (Figure 2.1). This was confirmed by field observations that many fans terminated in steep avalanche faces (Figure 3.1). The clear contrast between the marsh surface lithology to washover sediment lithology made the washover fans easily identifiable during the field sampling.

Figure 3.1: The inland edge of a sandy washover fan overlying the existing marsh surface.

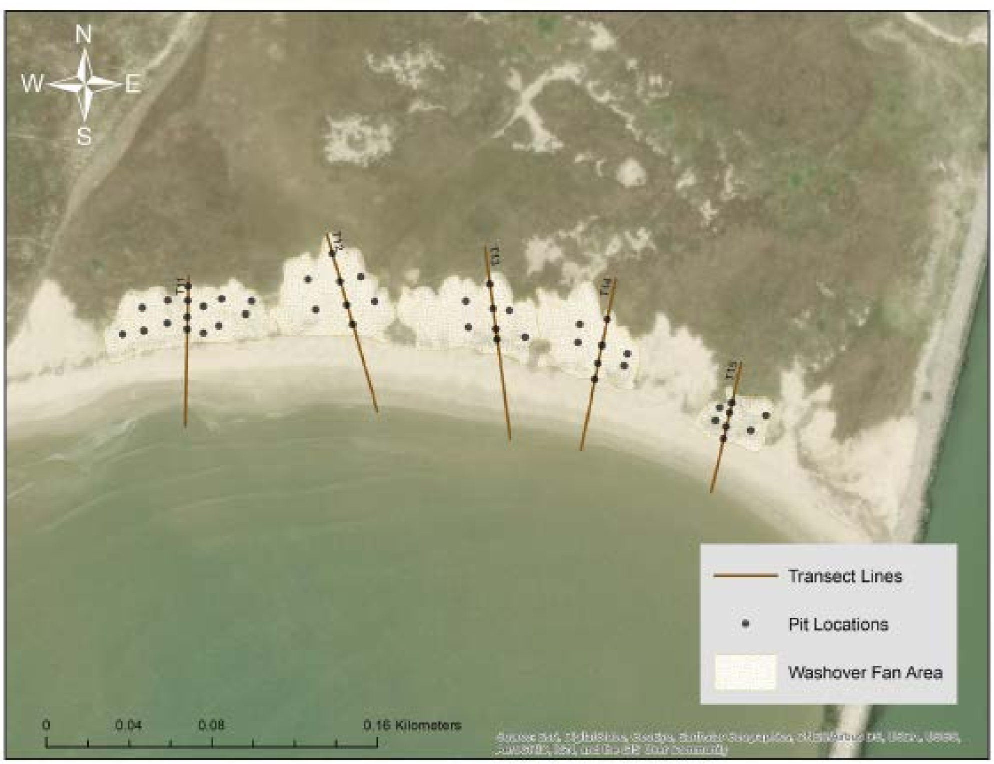
Using Rapid Response imagery obtained March 2018, washover fan perimeters were digitized in a GIS, allowing the area of each fan to be calculated. The average thickness of each fan was found by digging pits and finding the depth to the contact between washover sand and the buried marsh surface. The contact between Hurricane Harvey washover sediment and the buried marsh surface was mostly visible as a fine-grained, dark, organic-rich, marsh sediment in contact with white, sandy overwash sedimentation. (Fig. 3.2).

Based on field time constraints, it was planned to dig eight pits into each fan, to obtain an average thickness (4 pits along the fan's central axis and 2 either side). However, this plan was modified as follows: some smaller fans (a few square meters) seemed adequately covered by fewer pits (4-6); additional pits were excavated into three of the larger fans, bringing the total to 16, to explore the effect of increasing the number of pits on fan volumes (Figure 4).

Figure 3.2: Distinct contact between marsh and washover sedimentation.

(a)

(b)



(c)

Figure 3.3: (a) Eastern end of the study area (Zone 1) with digitized washover fan areas, pit locations, and transects, (b) Central section of the study area (Zone 2), (c) Western end of the study area (Zone 3).

CHAPTER 4

RESULTS

4.1 Washover Fan Volume

The washover fan volume table (Table 4.1) shows each transect number, their corresponding Zone, and the significant data collected such as average pit depth(cm), estimated area (m^2), and volume estimation (m^3) of 8 pits and 16 pits. In the table, there is also a column noting the volume measured with the additional 8 pits (16 pits in total). Upon sampling 16 pits instead of 8, there was a greatest difference of ±187.4m^3 from the 8-pit sampling method, and an average difference being ±112.1m^3. The mean percentage difference between fan volume calculations based on 8 pits and fan volume calculations based on 16 pits was 12%.

The highest average volume per fan was in Zone 1, supported by their lower barrier elevations, and broad, and contiguous shape. Zone 3 also had large volume measurements, but smaller areas along the coastline than Zone 1. Washover fans in Zone 3 were noticeably deeper than other segments of Zone 1 and Zone 2. The total volume of all fans documented in the study area was estimated to be 6900.0m^3 of sedimentation. Volumetric measurements are the first step to understanding the character and relationships of storm surge sediment deposition and barrier height.

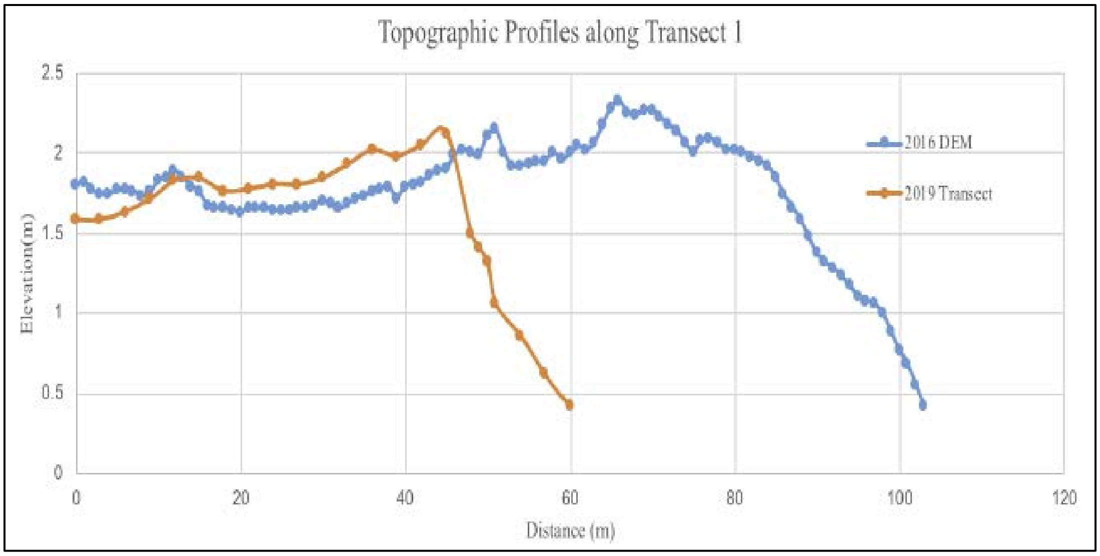
Fan perimeters were digitized in a GIS software, allowing fan areas to be measured. The imagery used is approximately 7 months after landfall (Fig. 2.1), but comparison to the August 29th, 2017 Rapid Response imagery shows little significant change in fan areas. Although washover fans were visible at these locations on the 2018 air photograph, fans were not visible in the field in 2019. This is probably the result of plant growth and bioturbation, mixing the sandy washover sediment with underlying sandy marsh deposits.

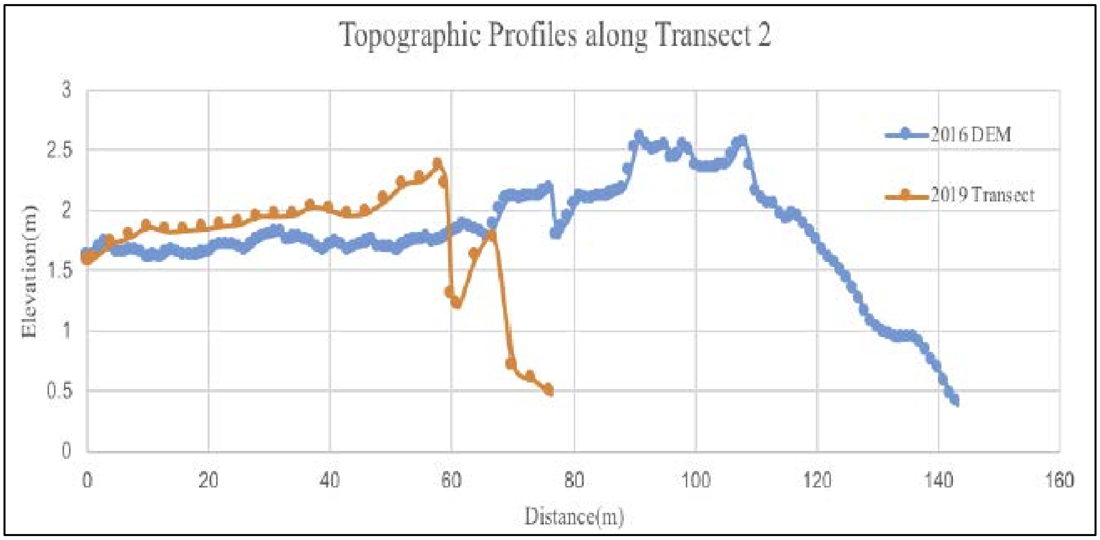
Table 4.1: Washover fan areas, depths, and volumes.

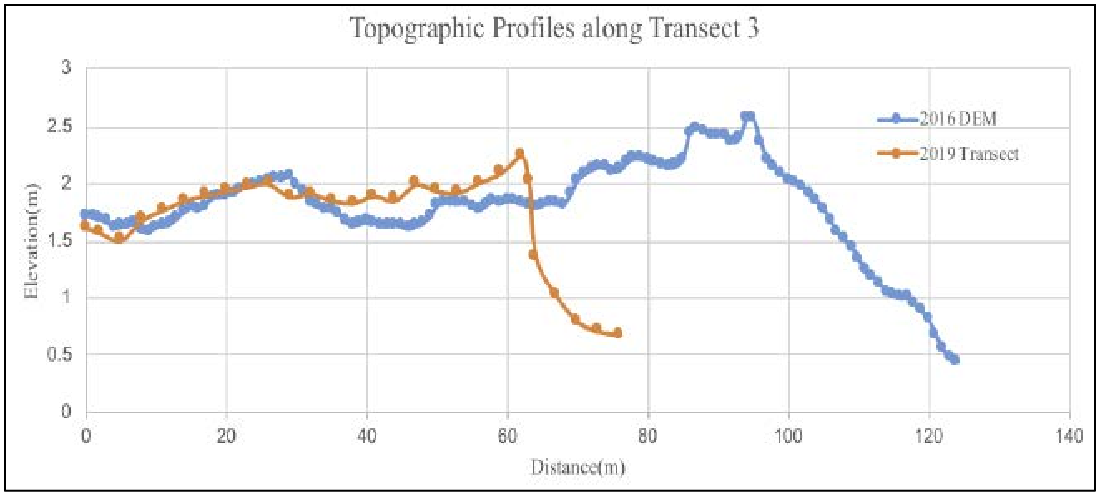
Zones	Transects	Average Pit Depth(cm)	Estimated Area(m^2)	Volume(m^3) 8 pits	Volume(m^3) 16 pits
Zone 1	T1	19.1	3411.5	653	N/A
	T2	18.3	4077.8	744.8	756
	T3	17.8	1822	323.4	N/A
	T4	34.4	3657.2	1257.2	1123.4
	T5	28	2327.9	651.8	N/A
Zone 2	T6	11	292.4	32.2	N/A
	T7	N/A	N/A	N/A	N/A
	T8	7.4	398	29.4	N/A
	T9	13.7	178.7	24.4	N/A
	T10	N/A	N/A	N/A	N/A
Zone 3	T11	29.7	2153.3	639.9	827.3
	T12	50.5	2077.7	1049.9	N/A
	T13	34.7	2063.9	715.9	N/A
	T14	32.6	1727.4	563.6	N/A
	T15	28.7	748.1	214.5	N/A

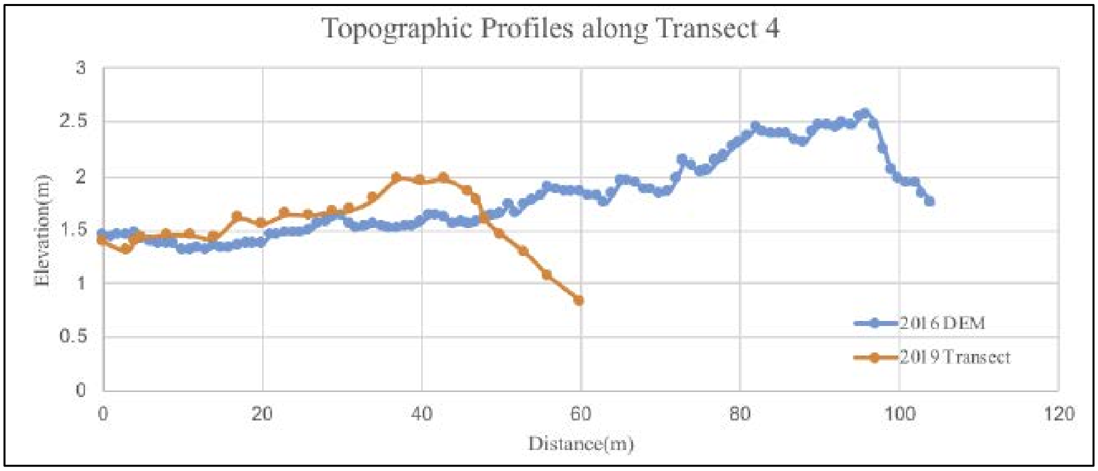
4.2 Pre- and Post-Storm Topographic Profiles

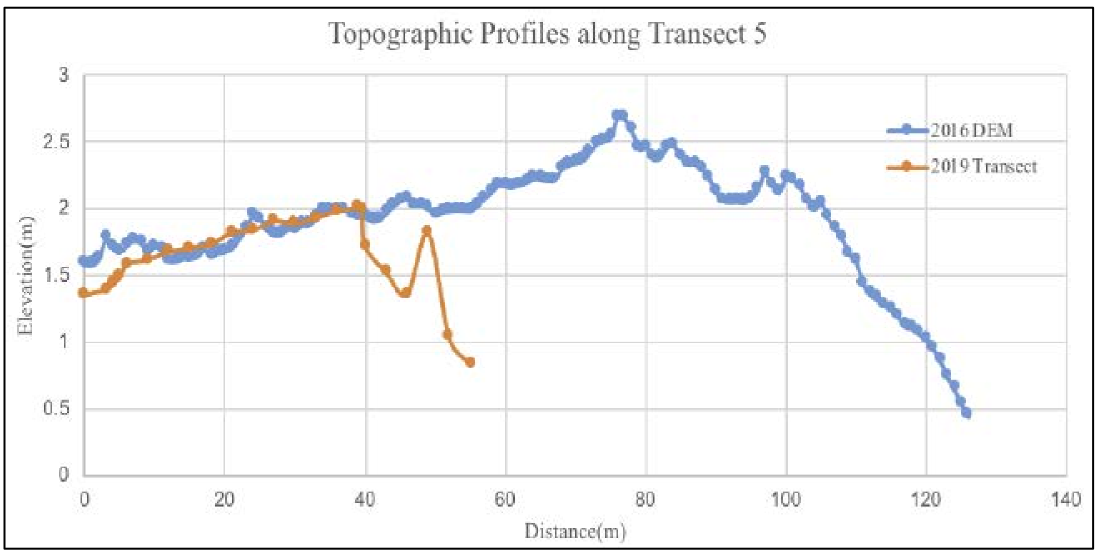
GPS coordinates of the transect endpoints were recorded and plotted on the March 2018 ArcMap 10.7.1 basemap imagery (Fig. 2.1). This mapping format was used in reference with the NOAA 2016 LiDAR DEM (NOAA 2016) to obtain elevation on the same profile line. The profiles derived from the digital elevation model from 2016 and field topographic profiles in 2019 were plotted against one another to result in 15 different graphs (Fig. 4.1). The profiles show shoreline retreat ranging from 15m near the jetty (see T11-T15 in Fig. 4.1) to 55m near the center section of the study area (see T6-T10 in Fig 4.1).

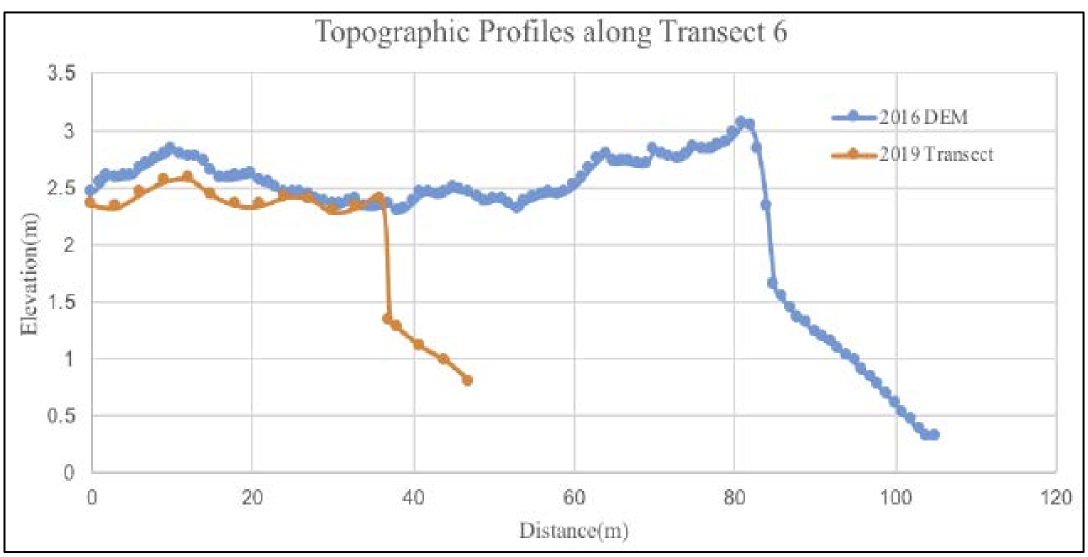

Topographic Profiles along Transect 1
2016 DEM
2019 Transect
Elevation(m)
Distance (m)

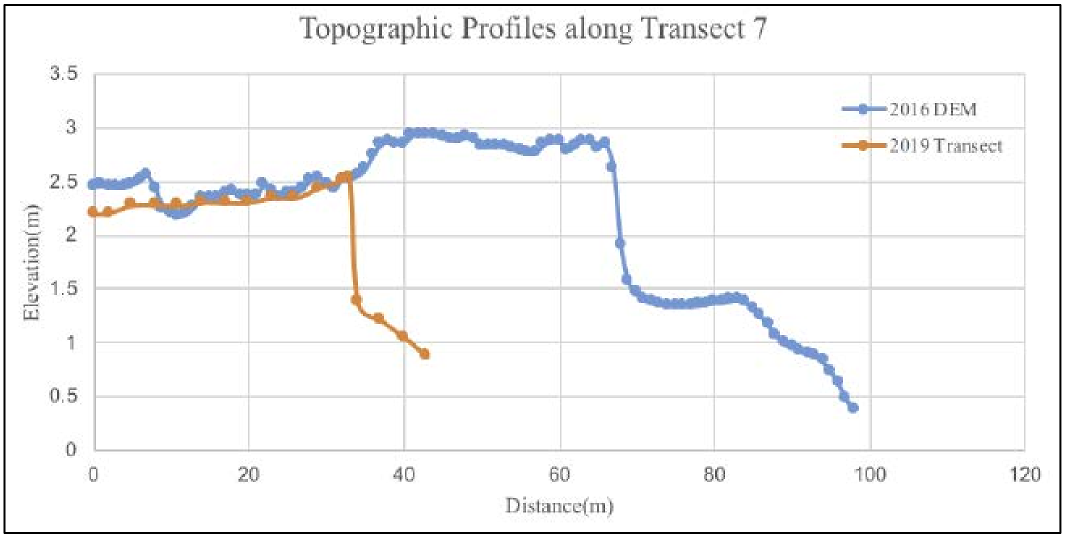

Topographic Profiles along Transect 2
2016 DEM
2019 Transect
Elevation(m)
Distance(m)

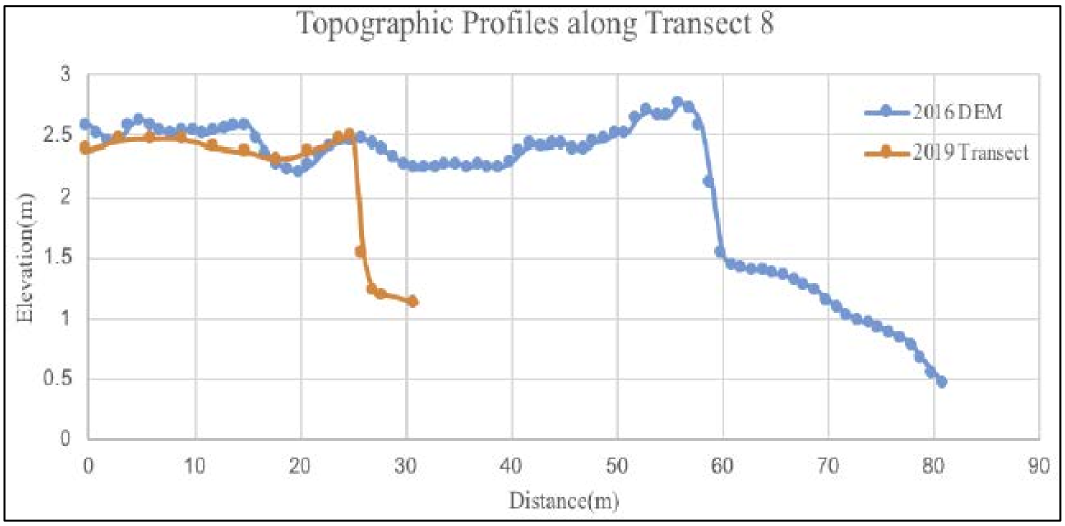

Topographic Profiles along Transect 3
2016 DEM
2019 Transect
Elevation(m)
Distance(m)

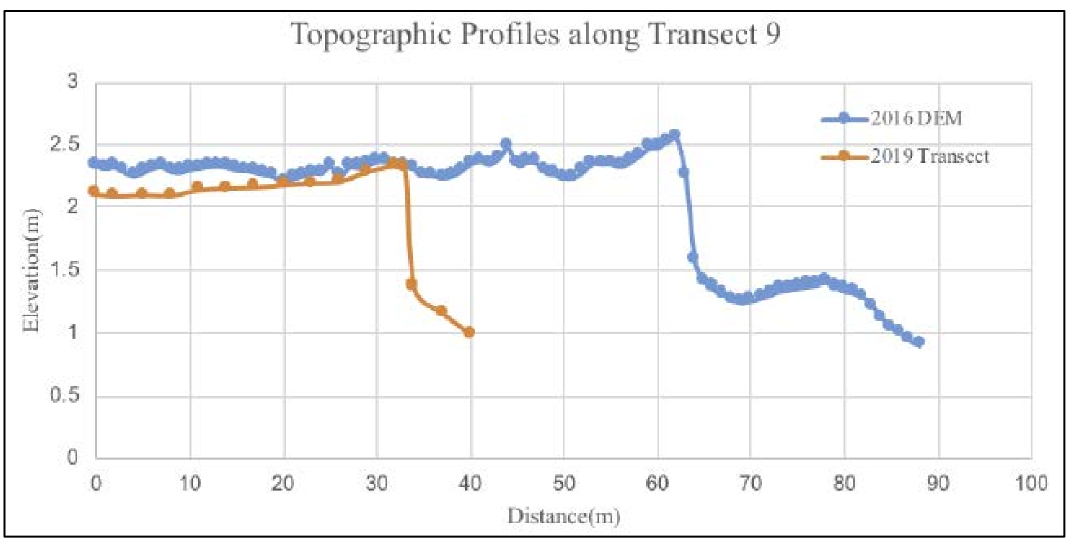

Topographic Profiles along Transect 4
Elevation(m)
Distance(m)
2016 DEM
2019 Transect
0
0.5
1
1.5
2
2.5
3
0
20
40
60
80
100
120

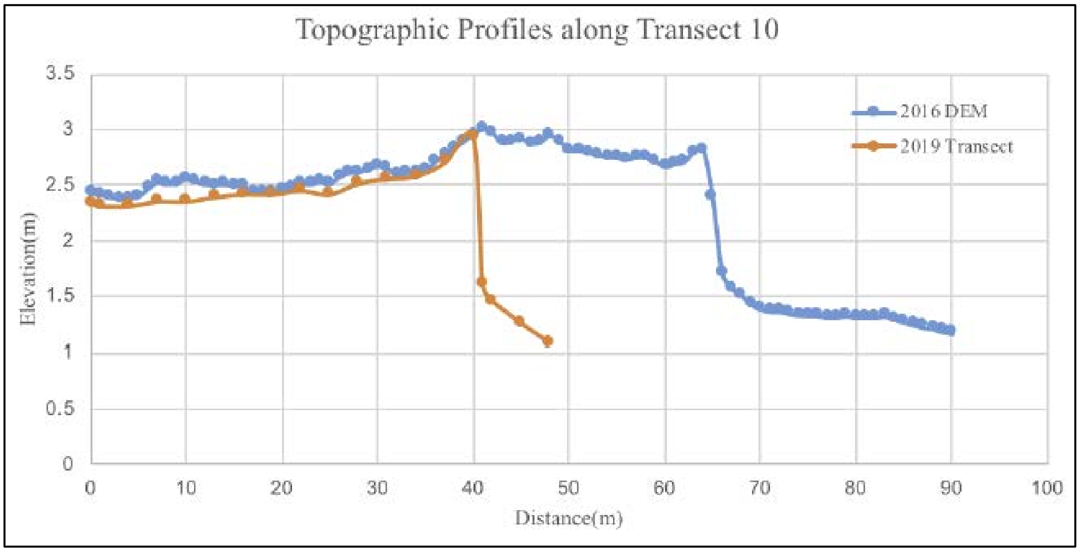

Topographic Profiles along Transect 5
Elevation(m)
Distance(m)
2016 DEM
2019 Transect
0
0.5
1
1.5
2
2.5
3
0
20
40
60
80
100
120
140

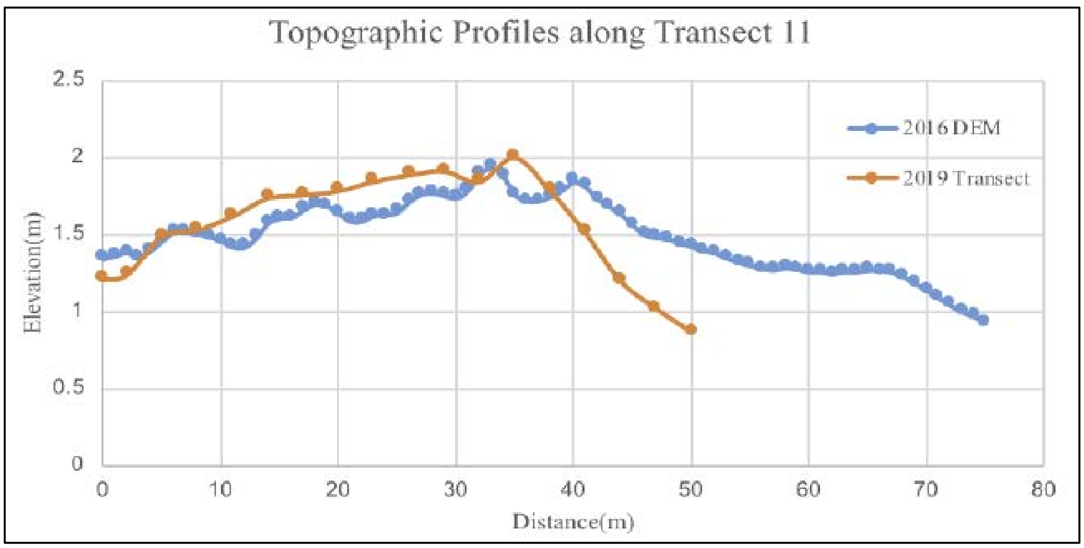

Topographic Profiles along Transect 6
Elevation(m)
Distance(m)
2016 DEM
2019 Transect
0
0.5
1
1.5
2
2.5
3
3.5
0
20
40
60
80
100
120

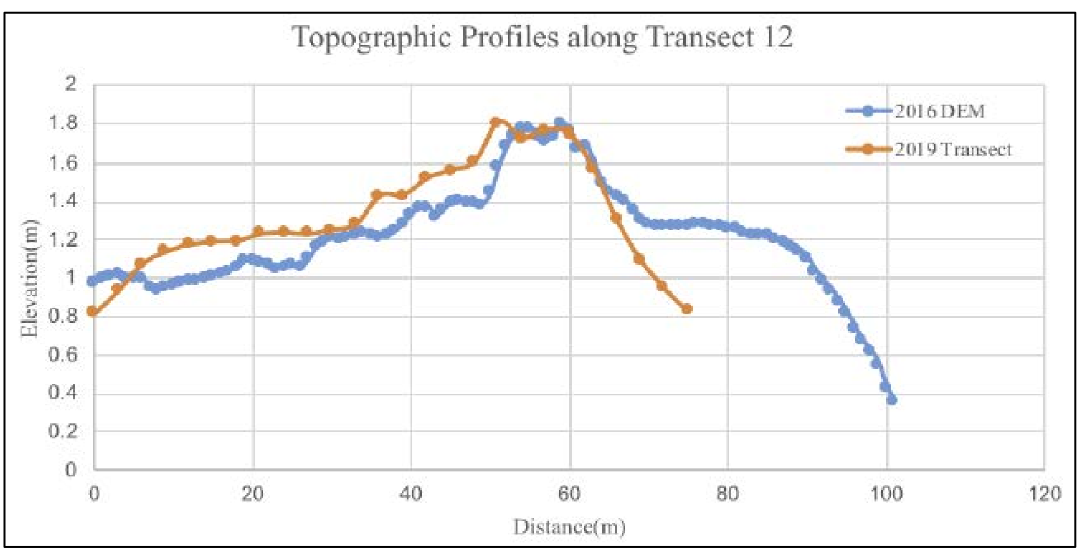

Topographic Profiles along Transect 7
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.5
1
1.5
2
2.5
3
3.5
0
20
40
60
80
100
120


Topographic Profiles along Transect 8
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70
80
90


Topographic Profiles along Transect 9
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70
80
90
100


Topographic Profiles along Transect 10
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.5
1
1.5
2
2.5
3
3.5
0
10
20
30
40
50
60
70
80
90
100


Topographic Profiles along Transect 11
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.5
1
1.5
2
2.5
0
10
20
30
40
50
60
70
80


Topographic Profiles along Transect 12
2016 DEM
2019 Transect
Elevation(m)
Distance(m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
20
40
60
80
100
120

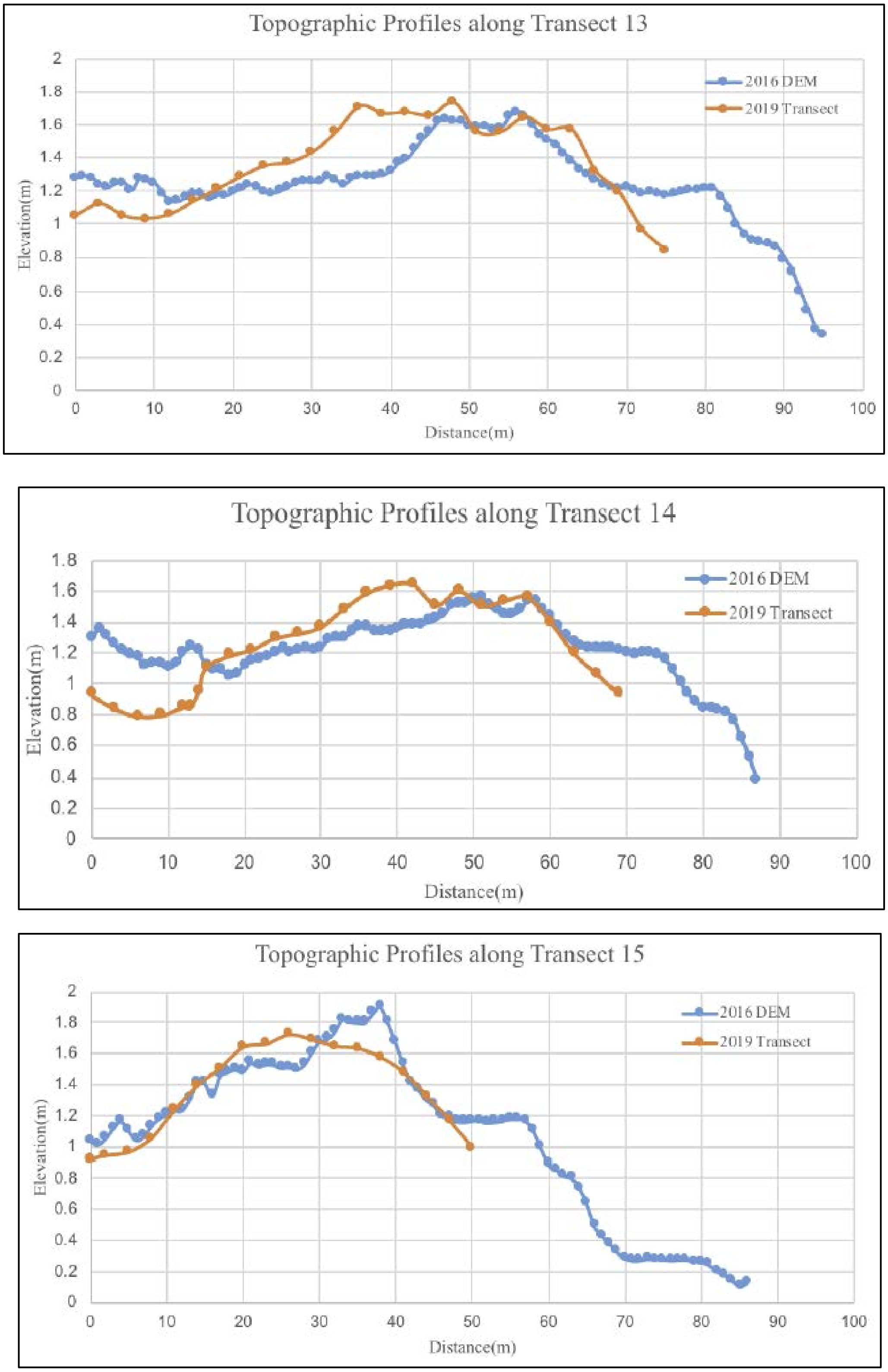


Figure 4.1: Topographic profiles T1-T15 displaying pre-storm LiDAR elevation (NOAA 2016) and post-storm surveyed topographic profiles (2019) (see Fig. 3.3).

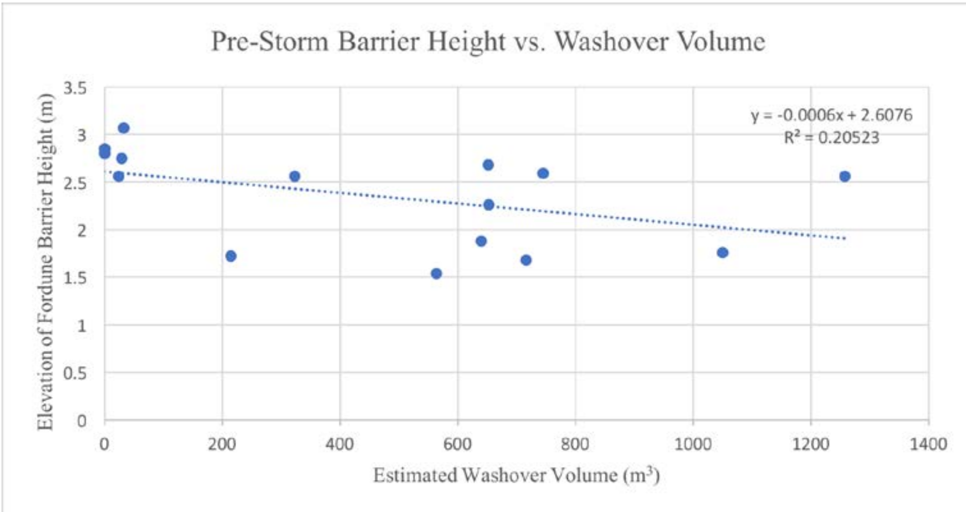


Figure 4.2: Pre-storm barrier heights vs. post-storm washover fan volumes.

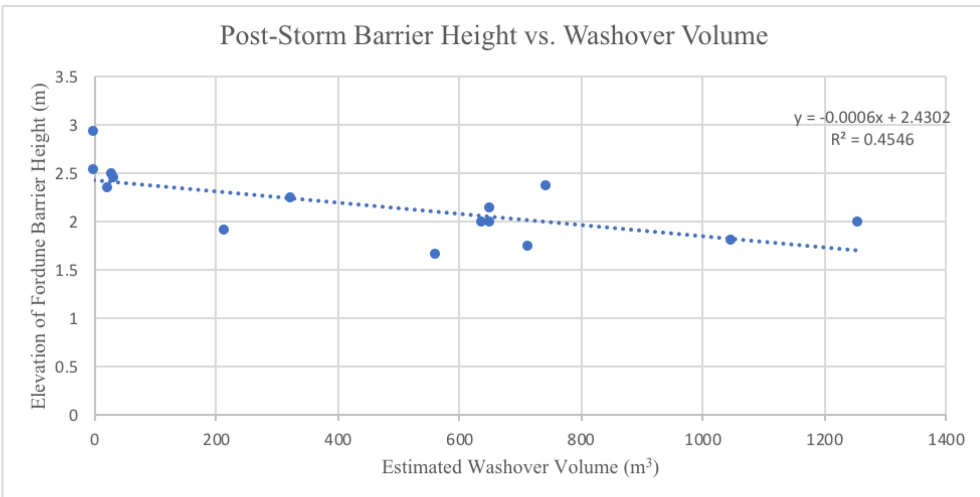


Figure 4.3: Post-storm barrier heights vs. post-storm washover fan volumes.

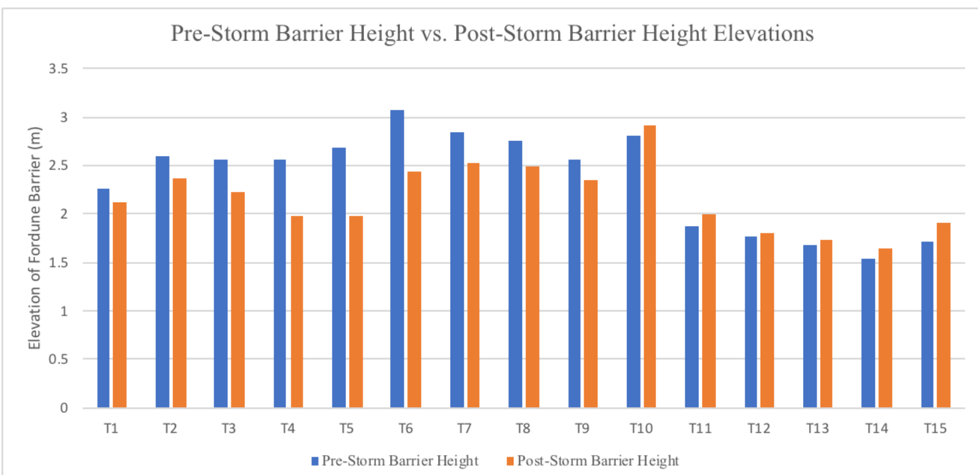
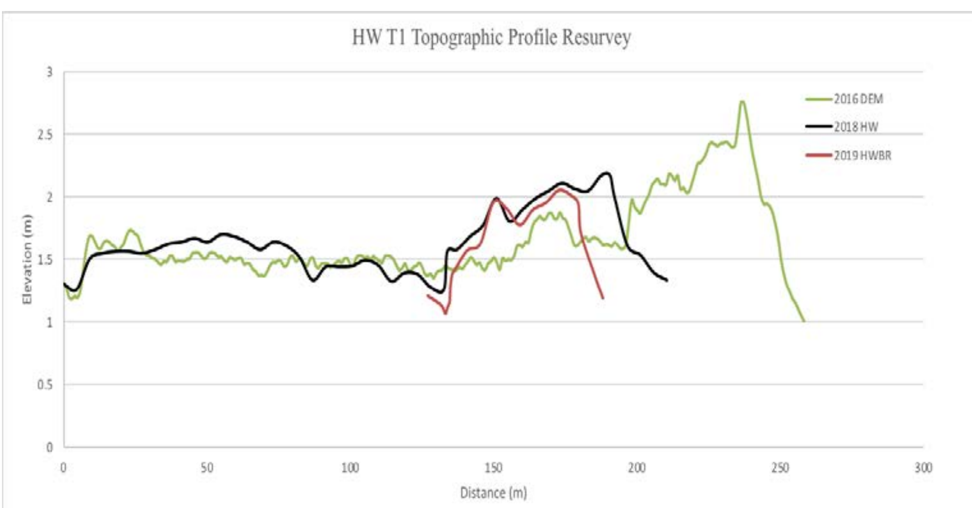


Figure 4.4: Pre-storm barrier height vs. post-storm barrier height elevations of all transects.

The R-squared value for the variables in pre-storm barrier height vs. washover volume (Fig. 4.2) was .21 and post-storm barrier height vs. volume (Fig. 4.3) was .45. The other relationship between pre- and post- barrier heights was represented in the bar graph in Figure 4.4. There is an average reduction in barrier height in T1-T9 of .38m between August 2016 and June 2019. Also, there was a small average increase in barrier height of .10m in transects T10-T15.

4.3 Resurvey of 2018 Topographic Profiles

There were resurveys conducted on profiles sampled in 2018 in addition to the newer topographic profiles sampled during fieldwork data collection. Plotting preliminary surveys of Dr. Harry Williams T1, T2, and T3 (HW T1, HW T2, and HW T3) 2018, the 2019 resurveyed profiles (HWBR), and the 2016 LiDAR DEM NOAA profiles resulted in timeline of erosion and deposition along two transect lines (Fig. 4.5). The two profiles, HW T1 and HW T2, exhibited 15-18m of shoreline retreat near the coastline between 2018 and 2019. HW T3, a transect near T12, was incorrectly aligned during the sampling process and could not be used.



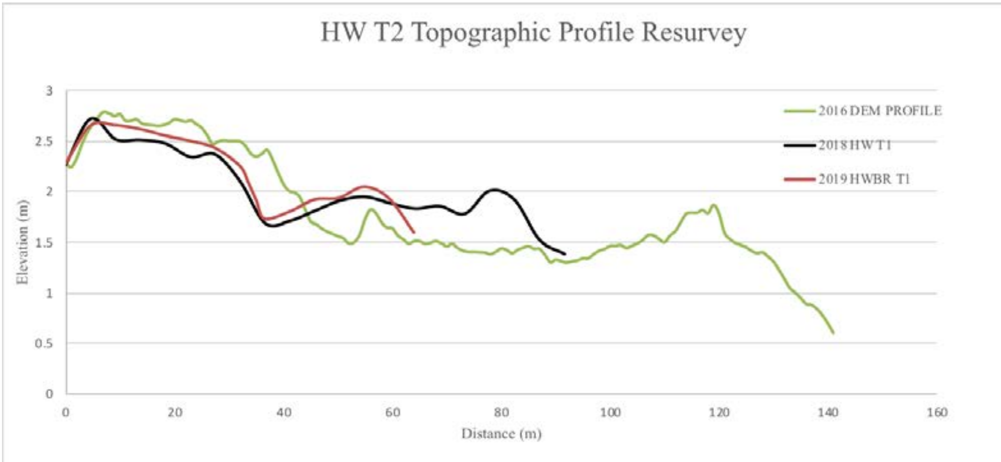


Figure 4.5: Topographic profiles from 2016, 2018, and 2019 (HW T1 and HW T2).

4.4 Shoreline Retreat

The coastal erosion seen in southeast Texas is some of the greatest erosion recorded in the Gulf of Mexico (Morton, 1977; Turner, 1990; USACE, 2012). The importance of denoting erosion is to establish a reference point for non-storm erosion over time to contrast storm event erosion. When the magnitude of shoreline erosion became apparent, it was decided to assess it on all transects because it could explain some of the changes in topography such as barrier position and height, and fan area and volume. Given this consideration, shoreline retreat was measured by recording distances from benchmark GPS points from the road as extensions of the transect lines. Four different maps were used to gauge the receding coastline they were observed on GoogleEarth Imagery from 2014, 2016, 2017, and 2018. The total amount of erosion that took place between each time period was measured in meters per month.

Table 4.2: Shoreline retreat rate (meters per month) transects between 2014 and 2018.

Transects	2014-2016	2016-2017*	2017-2018
T1	1.71	1.92	0.13
T2	2.00	2.50	0.00
T3	2.00	1.92	-0.06
T4	1.71	2.42	0.56

Transects	2014-2016	2016-2017*	2017-2018
T5	1.33	3.08	0.63
T6	1.38	2.75	0.75
T7	2.05	1.75	0.31
T8	1.95	1.58	0.31
T9	1.33	3.00	0.13
T10	1.19	2.75	0.06
T11	0.90	1.42	-0.19
T12	1.33	1.42	-0.13
T13	0.10	2.92	-0.56
T14	0.81	1.92	-0.63
T15	0.19	2.17	-0.56

* Includes landfall of Hurricane Harvey

CHAPTER 5

DISCUSSION

5.1 Washover Volume vs. Pre- and Post-Storm Barrier Height

The use of pre-storm barrier height based on 2016 (DEM) and post-storm barrier height based on 2019 (fieldwork survey) characterized how the barrier heights changed, confirmed the presence of washover, and displayed a rough estimate of shoreline retreat. The relationships found were minimal barrier height changes pre- and post- Hurricane Harvey storm surge (average change was ±.27m)(Fig. 4.4), higher volumes were located on profiles relatively lower in barrier heights, and higher barriers indicated greater shoreline retreat. The wrackline measurement of 2.3m indicated that the majority of storm surge was below that elevation. Barrier height exceeding that elevation in the pre-storm profiles exhibited significantly less overwash volume than profiles below that threshold. If the storm surge was lower than the barrier height, then would that energy be expended on eroding that barrier? In that case, barriers exceeding 2.3m experienced higher lateral erosion rates of 40-45m (See T6 and T7 in Fig. 4.1). Conversely, barriers significantly below that elevation threshold experienced minimal lateral erosion and greater widespread overwashed sedimentation (Zone 3). When overwash occurred, the surge and waves carried sand inland to form large washover fans. There is much less retreat in this zone suggesting wave energy was used transporting sediment (rather than eroding the beach) or waves were smaller because of shelter provided by the jetty.

The 8-pit to 16-pit sampling methodology used in the field has substantial implications of sampling bias. During the data collection time period, sample locations and the number of pits changed according to characteristics of the fan and field conditions. A common issue among researchers is determining how many samples to take and if the amount of data yielded significant results. The time and budget constraints for this study limited the sample number of pits to approximately eight per fan. Additionally, it limited the topographic surveys to 15 profiles, and reduced consideration to quantify other variables influencing barrier height and washover volume (Fig. 5.1). In future studies, other forms of pit information and statistical significance could improve the accuracy and validity of the volumetric estimates. Spatial interpolation methods such as using Thessian polygon, spline, IDW (Inverse Distance Weighted), or kriging models also have the potential to yield a more comprehensive record of washover volume. These methods have the capacity to further illustrate the character of microtopgraphy on the marsh surface beyond the results of this study.

The topography of each zone attributed to the character of washover and erosional tendencies during Hurricane Harvey storm surge. Zone 3 was observed to have a gradually sloping foredune and beach, whereas transects in Zone 2 were comprised of a low beach elevation leading to a sharp elevation increase produced from a scarp-like barrier (Fig. 5.1) Therefore, foredune topography at steeper slopes versus shallower slopes appears to be an important influence on characterizing washover sedimentation and foredune erosion.

Figure 5.1: Scarp-like barrier in Zone 2 (left) and a sloping barrier in Zone 3(right).

5.2 Scarp Erosion vs. Sloping Foredune Erosion

Higher elevation scarp areas were found in the middle of the study area near T6-T10 and reduced washover sedimentation in this zone. All transects 6-10 have a similar topography of a scarp-like terrain as you move from the beach to the foredune segment of each profile. The areas in study area devoid of overwash have considerably high elevation reaching up to 3m in some areas. Overwash from Hurricane Harvey's storm surge could have been completely stopped by this higher elevation barrier. Based on figure 4.4, there is a correlation between higher pre-storm barriers and a greater reduction in their height in the post-storm measurements; in other words, higher barriers appear to promote greater erosion. Another common terrain influenced pattern seen in the profiles is the progression from sloping foredunes to scarp-like barriers at T6-T10. This type of erosion could implicate a difference in marsh lithology resistance, a sudden erosional event or other environmental changes. In addition, low-lying barriers (T11-T15) experienced sediment accumulation and an overall increase to their post-storm barrier height. These lower barrier areas also exhibited less shoreline retreat on average compared to other zones with scarp topography. Proximity to the Colorado River Jetty is likely an important distinction helping to explain variation in erosion rates along this coastline.

5.3 HW Resurveyed Topographic Profiles

The transects measured by Dr. Harry Williams in March 2018 were used as a reference to understand non-Hurricane Harvey related erosion that took place on the fans in the time period between March 2018 and June 2019. Determining if there were erosional rates that were not hurricane related could affect the field study measurement of washover fan volume and elevation profiles. Further investigation into HW T1 and HW T2 revealed consistent erosional rates at the shoreline elevation level. These rates were consistent with those found in the earlier assessment of shoreline retreat rates from GoogleEarth Imagery (Table 4.2). Two of the resurveyed profiles had similar topography in 2018 and 2019 with some minor departures due to DEM and topographical measuring error. The washover fans from HW T1 and HW T2 showed minor erosion to the washover sedimentation on the inland portion of the profile behind the foredune. Though the barrier heights and washover fans were altered minimally, data from March 2018 was used to measure fan areas assuming insignificant erosion took place. The majority of profiles recorded in this study including the resurvey profiles converge further inland indicating the consistent inland topography with no indication of erosion or deposition (See GPS Road Benchmark Fig. 2.1). The resurvey made of the profile located near transect T12 (HW T3) suffered from errors made in the field in relocating the seaward end of the profile; consequently, this new profile did not align to the position of the earlier profile and was unusable.

5.4 Study Area Variables

Initially, the research of washover sedimentation was simplistic and confined to a few important variables (e.g. pre- and post-Hurricane Harvey barrier elevations, storm surge magnitude, shoreline retreat, and general topographical implications), but was determined to have a multitude of variables (Table 5.1) that could influence the hypothesized relationships. For example, sediment supply is a variable that can heavily influence the character of washover sedimentation through contrasting sediment supply volume in different locations along the coastline. It was assumed that barrier height was an important contributing factor when assessing washover sedimentation.

Table 5.1: Study area variables including their descriptions and field observations.

Variables	Variable Description with Observations
Anthropogenic Influences	The Colorado River Jetty may have reduced storm surge energy. Other anthropogenic influences on erosion and volume of washover fans included grazing of farm cattle and human activity in the upper shoreface.

Barrier Height	Barrier height influences washover sedimentation by blocking storm surge energy. Larger barrier heights indicated less washover sedimentation than smaller barrier heights.
Beach and Dune Shape	Different shapes of dunes and beaches have the potential for storm surge to increase or decrease in elevation. This research assumed consistent storm surge in the study area (2.3m based on wrack line) which is subject to variability. High, scarp-like barriers (T6-10) appeared to reduce washover volume, whereas an increase in washover volume occurred at low, broad dune shapes (T11-T15).
Erosion of Washover Fan	Quantifying erosion of washover fans is important to determine the preservation of washover fans. It was significant to observe the preservation of the washover fan to verify the minimal change in volume over a 3-year period. Fans were mostly preserved behind the barrier seen from HW profiles and 2019 profiles.
Marsh Topography	Marsh topography is always subject to changes during storm events, seasonal winds, and wildlife interaction. There were minimal changes on the inland marsh topography on HW profiles and topographic profiles from 2016 to 2019.
Vegetation Density, Height, Type	Amount, type and density of vegetation influences the stability of a landscape or slope. Low shrubs and small grasses dominated the study area.
Variables	**Variable Description without Observations**
Dune Erodibility	Many factors go into this variable such as type of lithology, dune dimensions, and general topographical influences on dunes. It is difficult to quantify dune erodibility due to shoreline retreat and constant dune erosion and reformation.
Inundation Depth	Hurricane Harvey produced substantial amounts of flood water. The characterization of inundation would provide insight to hydrological implications of the study area.
Sediment Supply and Type	The sediment supply is derived from upper and lower shoreface and shallow offshore areas. Variability in sediment presence that can be moved directly influences washover volume.
Tide Level	Tide levels during Hurricane Harvey landfall could have changed the relative height of sea level prior to storm surge.
Wave Height, Frequency, and Direction	Wave height, frequency, and direction describe the nature of wave energy during non-storm time periods and during the studied storm event to contrast changes in wave propagation to the coastline.

CHAPTER 6

CONCLUSION

This study's objective was to further understand the relationship between the washover fan sedimentation and pre- and post-Hurricane Harvey barrier heights. Concluding evidence appears to display a prominent pattern to this relationship, where a decrease in barrier height would result in more washover sedimentation on average. This evidence supports the generally accepted argument that physical coastal barriers reduce the magnitude of washover sedimentation (Williams, 2017). There are unique characteristics of the study area to consider when acknowledging the interpretation deduced from this data such as proximity to the Colorado River Jetty, an anthropogenic barrier. In the study area, Zone 2 had significantly higher barriers than the washover threshold of 2.3m that reduced washover fan volume, but yielded the higher rates of shoreline retreat. According to shoreline retreat rates and topographic profile assessment, these barriers experienced greater energy and erosion from Hurricane Harvey. The artificial barrier, Colorado River Jetty, likely reduced wave energy, affecting the closest transects in Zone 3 based on its significantly lower shoreline retreat rates and overall increase in barrier height (greater accumulation of storm surge sedimentation). Zone 3 of the study area which was dominated by the anthropogenic barrier was observed to have marsh aggradation and reduced energy affecting the barrier, therefore anthropogenic barriers play a significant role in marsh aggradation and opposing continual marsh submergence. The highest observed retreat rates in Zone 3 were in period 2016-2017 which included Hurricane Harvey's landfall (Hurricane Harvey more than likely caused higher erosional rates). Periods before and after experienced low erosional rates, which entails lower elevation barriers result in less erosion. On average, barrier heights in Zone 1 were marginally less than in Zone 2 (about 0.5 m on average), yet much more washover sedimentation occurred in zone 1 than in Zone 2. This supports the contention of Williams (2017) that even subtle changes in barrier height can have significant impacts on washover and sedimentation.

There was a correlation of shape of the beach and foredune barrier having a significant effect on washover and sedimentation. A sloping beach, even if it reaches similar heights to a scarped beach, has a relationship to increased washover and transport of sediment inland. A scarped beach/dune is more effective at blocking washover and promoting shoreline erosion. The Colorado river jetty acted to some degree acted as a shelter to Zone 3, reducing retreat rates in this zone. It also appeared to promote recovery in this zone – in the period 2017-2018 all 5 transects in this zone displayed progradation of the shoreline and increased barrier heights.

Upon further consideration of other variables influencing washover volume estimates, barrier erosion and heights, and general topography, there was an increased complexity to the findings of the study. The abundance of variables included barrier height, height, type, and density of vegetation, beach and dune shape, anthropogenic influences, sediment supply and type, tide level, dune erodibility, height frequency and direction of waves, marsh topography, inundation depth, and erosion of washover fan. Time and budget constraints limited the potential to quantify or qualitatively assess each independent variable adequately. Future studies with improved rapid response data and spatial interpolation methodologies would provide more information on these variables and a greater understanding to the complexity of coastal geomorphology.

Further data availability of post-storm LiDAR, higher resolution Rapid Response Imagery, storm surge heights, and shoreline retreat have the potential to yield improved results advancing this study. Yet as a result of this study's findings, coastal landscape restoration efforts can be further informed on how hurricane phenomena interact with natural and anthropogenic barriers, beach and dune erosion, and marsh aggradation along the coast of southeast Texas.

REFERENCES

Al-Nasrawi, A.K., Jones, B.G., & Hamylton, S.M. (2016). GIS-based modelling of vulnerability of coastal wetland ecosystems to environmental changes: Comerong Island, southeastern Australia. *Journal of Coastal Research, 1*(75), 33-37.

Boldt, K.V., Lane, P., Woodruff, J.D., & Donnelly, J.P. (2010). Calibrating a sedimentary record of overwash from Southeastern New England using modeled historic hurricane surges. *Marine Geology*, *275*(1-4), 127-139.

Cahoon, D.R., D.J. Reed, and J.W. Day Jr. (1995). Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology*, *128*(1-2), 1-9.

Cahoon, D. R., Lynch, J.C., & Powell, A. (1996). Marsh vertical accretion in a southern California estuary, U.S.A. *Estuarine Coastal Shelf Science, 43*(1), 19-32.

Chen, Y., Wang, B., Pollino, C.A., Cuddy, S.M., Merrin, L.E., & Huang, C. (2014). Estimate of flood inundation and retention on wetlands using remote sensing and GIS. *Ecohydrology*, *7*(5), 1412-1420.

Crosby, M. K. & Reece, C. A. (2009). Geologic Evidence of Hurricane Rita recovered from Texas Point, TX. *Southeastern Geographer, 49*, 41-48.

Hatton, R. S., Delaune ,R. D., & Patrick Jr., W. H. (1983). Sedimentation, accretion and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceanography*, *28*(3), 494-502.

Hawkes, A.D. & Horton, B.P., (2012). Sedimentary record of storm deposits from Hurricane Ike, Galveston and San Luis Islands, Texas. *Geomorphology 171-17*2, 180-189.

Ma, Z., Ysebaert, T., van der Wal, D., de Jong, D.J., Li, X., & Herman, P.M.J. (2014). Long-term salt marsh vertical accretion in a tidal bay with reduced sediment supply. *Estuarine, Coastal and Shelf Science 146*(5), 14-23.

Morton, R. A., (1977). Historical shoreline changes and their causes, Texas Gulf Coast. Transactions- *Gulf Coast Association of Geological Societies* (27), 13 p.

NOAA (National Oceanic and Atmospheric Administration) (2016). National Ocean Service (NOS), Office for Coastal Management (OCM), 2006 Texas Water Development Board (TWDB) LIDAR: Jefferson County, Texas. https://coast.noaa.gov/dataviewer.

NOAA (2018). National Hurricane Center Tropical Cyclone Report, Hurricane Harvey. AL092017. https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf

Reese, C., Strange, T., Lynch, W., & Liu, K-b. (2008). Geologic Evidence of Hurricane Katrina Recovered from the Pearl River Marsh, MS/LA. *Journal of Coastal Research, 24*(6), 1601-1607.

Rejmánek, M., Sasser, C. E., & Peterson, G. W. (1988). Hurricane-induced sediment deposition in a Gulf Coast marsh. *Estuarine Coastal and Shelf Science, 27*(2), 217-222.

Shao, G., Young, D.R., Porter, J.H., & Hayden, B.P. (1998). An integration of remote sensing and GIS to examine the responses of shrub thicket distributions to shoreline changes on Virginia barrier islands. *Journal of Coastal Research, 14*(1), 299-307.

Stumpf, R. P. (1983). The process of sedimentation on the surface of a salt marsh. *Estuarine, Coastal and Shelf Science 17*(5), 495-508.

Turner, R. E., (1990). Landscape development and coastal wet-land losses in the Northern Gulf of Mexico. *American Zoologist, 30*(1), 89-105.

USACE (Unted States Army Corps of Engineers), (2012). Erosion Control and Environment Restoration Plan Development, Matagorda County, Texas. ERDR/CHL TR-12-11. https://apps.dtic.mil/dtic/tr/fulltext/u2/a571167.pdf

Vincenzi, S., Caramori, G., Rossi, R., & De Leo, G.A., (2006). A GIS-based habitat suitability model for commercial yield estimation of Tapes philippinarum in a Mediterranean coastal lagoon. *Ecological Modelling, 193*(1-2), 90-104.

Walters, D.C. & Kirwan, M.L. (2016). Optimal hurricane overwash thickness for maximizing marsh resilience to sea level rise. *Ecology and Evolution, 6*(9), 2948-2956.

Wang P., & Horwitz M. H. (2007). Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. *Sedimentology, 54*(3), 545-564.

Wilkinson, B.H. & McGowen, J.H. (1977). Geologic approaches to the determination of long-term coastal recession rates, matagorda peninsula, Texas. *Environmental Geology, 1*(6), 359-365.

Williams, H. F. L. (2015). Contrasting styles of Hurricane Irene washover sedimentation on three east coast barrier islands: Cape Lookout, North Carolina; Assateague Island, Virginia; and Fire Island, New York. *Geomorphology*, 231, 182-192.

Williams, H.F.L. (2017). Assessing the Effectiveness of Coastal Foredune Barriers in Reducing Hurricane Washover Sedimentation. *Journal of Coastal Research, 34*(3), 503-509.

Yao, Q., Liu, K., Williams, H., Joshi S., Bianchette, T. A., Ryu, J., & Dietz, M. (2020). Hurricane Harvey Storm Sedimentation in the San Bernard National Wildlife Refuge, Texas: Fluvial Versus Storm Surge Deposition. *Estuaries and Coasts, 43*, 971-983.