FORMS AND DISTRIBUTIONS OF HURRICANE IKE BACKFLOW AND SCOUR FEATURES:
BOLIVAR PENINSULA, TEXAS

A Thesis

by

MICHAEL KILGORE POTTs

Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Geography
FORMS AND DISTRIBUTIONS OF HURRICANE
IKE BACKFLOW AND SCOUR FEATURES:
BOLIVAR PENINSULA, TEXAS

A Thesis
by
MICHAEL KILLOGORE POTTs

Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Approved by:
Chair of Committee, Douglas J. Sherman
Committee Members, Chris A. Houser
Hongxing Liu
Vatche P. Tchakerian
Head of Department, Douglas J. Sherman

May 2010

Major Subject: Geography
ABSTRACT

Forms and Distributions of
Hurricane Ike Backflow and Scour Features:
Bolivar Peninsula, Texas. (May 2010)

Michael Killgore Potts, B.S., College of Geosciences, Texas A&M University
Chair of Advisory Committee: Dr. Douglas J. Sherman

The storm surge from Hurricane Ike inundated Bolivar Peninsula as well as pooled up (~4 meters above sea level) in the Galveston Bay System behind Bolivar. After the hurricane passed, this water flowed back over the peninsula for about 19 hours, causing a great deal of coastal destruction. Analysis of post-Hurricane Ike aerial photography and Lidar data revealed the development of dramatically different scour and backflow features in the beach and dune environments along Bolivar Peninsula, Texas. Using Ward’s cluster analysis, the 454 identified features were grouped according to shape and size characteristics generated by an object-oriented shape analysis program. Five distinct groups of features emerged from the cluster analysis. Group 1 features were small and compact, distributed mostly in the west; Group 2 features were large and dendritic in nature, distributed where the peninsula was narrow. Group 3 features had a longshore orientation with many of them resembling piano keys, distributed in the east. Group 4 features were oriented longshore and ornate in shape. Many of them were similar in shape to Group 2 or 3 features though statistically
different enough to be grouped alone; they were distributed mostly in the eastern half of the study area. Group 5 features tended to be elongated, oriented cross-shore, non-branching, and distributed mostly in the east.

At least four flow environments caused characteristic forms. The first flow environment is typified by seaward flowing water encountering a road parallel with the coastline. The water flowing over the road scours deeply on the leeward side (seaward side), denuding beach sediments down to the resistant mud layer (Groups 3 and 4). The second flow environment was caused by a geotube, which breached during the storm and channelized flow through the breaches (Groups 2 and 5). The third flow environment had a comparatively high elevation, high development, and shore-perpendicular roads (Group 2). The fourth flow environment was typified by wide beaches backed by dunes (lost in the storm) as well as flat vegetated areas. Water flowing seaward over the vegetation scoured deeply into troughs after it came off the vegetation (Groups 1, 3, and 4).
ACKNOWLEDGEMENTS

I would like to thank Yige Gao, Pallav Negi, and Qiusheng Wu for their technical expertise. I would also like to thank Dustin Fehrle for moral support.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xv</td>
</tr>
<tr>
<td>CHAPTER I - INTRODUCTION: HURRICANE IMPACTS</td>
<td>1</td>
</tr>
<tr>
<td>Objectives</td>
<td>11</td>
</tr>
<tr>
<td>CHAPTER II - BACKGROUND</td>
<td>18</td>
</tr>
<tr>
<td>Hurricanes and Storm Surges</td>
<td>19</td>
</tr>
<tr>
<td>Hurricane Ike Storm Surge</td>
<td>21</td>
</tr>
<tr>
<td>Estimated Backflow Velocities</td>
<td>23</td>
</tr>
<tr>
<td>Scouring in Non-Cohesive Sediments</td>
<td>28</td>
</tr>
<tr>
<td>Washover/Overwash</td>
<td>39</td>
</tr>
<tr>
<td>General Impacts of Hurricanes on Barriers</td>
<td>41</td>
</tr>
<tr>
<td>Backflow and Scour Features</td>
<td>42</td>
</tr>
<tr>
<td>Tools</td>
<td>45</td>
</tr>
<tr>
<td>DEMs and/or DTM: History and Applications</td>
<td>46</td>
</tr>
<tr>
<td>Airborne Lidar Specifics</td>
<td>48</td>
</tr>
<tr>
<td>Lidar Uses</td>
<td>50</td>
</tr>
<tr>
<td>Aerial Photography</td>
<td>53</td>
</tr>
<tr>
<td>CHAPTER III - STUDY AREA AND METHODS</td>
<td>55</td>
</tr>
<tr>
<td>Study Site Description</td>
<td>55</td>
</tr>
<tr>
<td>Texas Barrier Islands</td>
<td>57</td>
</tr>
<tr>
<td>Data Sources</td>
<td>59</td>
</tr>
<tr>
<td>2008 Lidar</td>
<td>60</td>
</tr>
<tr>
<td>2008 Aerial Photographs</td>
<td>63</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>2006 Lidar</td>
<td>64</td>
</tr>
<tr>
<td>Change Detection Analysis Between 2006 and 2008</td>
<td>65</td>
</tr>
<tr>
<td>Buffer Zone</td>
<td>67</td>
</tr>
<tr>
<td>Determining Feature Boundaries</td>
<td>68</td>
</tr>
<tr>
<td>Object-Oriented Shape Analysis of Features</td>
<td>74</td>
</tr>
<tr>
<td>Cluster Analysis</td>
<td>76</td>
</tr>
<tr>
<td>Analysis of Features per Kilometer of Shoreline</td>
<td>78</td>
</tr>
<tr>
<td><strong>IV RESULTS</strong></td>
<td>79</td>
</tr>
<tr>
<td>Size and Shape Characteristics</td>
<td>81</td>
</tr>
<tr>
<td>Group 1</td>
<td>81</td>
</tr>
<tr>
<td>Group 2</td>
<td>88</td>
</tr>
<tr>
<td>Group 3</td>
<td>88</td>
</tr>
<tr>
<td>Group 4</td>
<td>90</td>
</tr>
<tr>
<td>Group 5</td>
<td>92</td>
</tr>
<tr>
<td>Distribution of Features</td>
<td>95</td>
</tr>
<tr>
<td>Group 1</td>
<td>95</td>
</tr>
<tr>
<td>Group 2</td>
<td>99</td>
</tr>
<tr>
<td>Group 3</td>
<td>99</td>
</tr>
<tr>
<td>Group 4</td>
<td>102</td>
</tr>
<tr>
<td>Group 5</td>
<td>102</td>
</tr>
<tr>
<td><strong>V SUMMARY AND CONCLUSIONS</strong></td>
<td>106</td>
</tr>
<tr>
<td>Flow Environments</td>
<td>106</td>
</tr>
<tr>
<td>Group 1</td>
<td>107</td>
</tr>
<tr>
<td>Group 2</td>
<td>112</td>
</tr>
<tr>
<td>Group 3</td>
<td>114</td>
</tr>
<tr>
<td>Group 4</td>
<td>117</td>
</tr>
<tr>
<td>Group 5</td>
<td>121</td>
</tr>
<tr>
<td>Cluster Analysis</td>
<td>123</td>
</tr>
<tr>
<td>Issues in Digitizing Features</td>
<td>124</td>
</tr>
<tr>
<td>Backflow Erosion</td>
<td>125</td>
</tr>
<tr>
<td>Conclusions</td>
<td>126</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------</td>
<td>------</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>130</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>136</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>178</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>180</td>
</tr>
<tr>
<td>VITA</td>
<td>185</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

| Figure 1.1 | Path of Hurricane Ike from first development | 3 |
| Figure 1.2 | Bolivar Peninsula lies northeast of Galveston, with the narrow Bolivar Roads Channel in between. Behind the peninsula is the Galveston Bay System, and in front is the Gulf of Mexico | 4 |
| Figure 1.3 | Comparison of long-term shoreline change and profile volume change caused by Tropical Storms Josephine (September 1994 to November 1997) and Frances (November 1997-1998). Red line shows long-term shoreline change rate, while dotted line with circles and solid line with triangles are volume change from Tropical Storms Josephine and Francis, respectively. Right half of figure is Bolivar Peninsula, which experiences erosion in the east and deposition in the west due to longshore drift | 5 |
| Figure 1.4 | Backflow channel in Gilchrist, Texas. Direction of water flow was away from viewer. Note scour is down to resistant mud layer; rubble from a parking lot as well as concrete slabs are also visible | 6 |
| Figure 1.5 | Backflow channel west of Rollover Pass. Note wooden stilts which supported a beach house. Flow was away from viewer | 7 |
| Figure 1.6 | Two views of the same beach. Pictures taken near the junction of Hwys 87 and 124, which has “piano key” formations. Foreshore of beach (top) is scoured down to peat layer, the dark patch. A thin veneer of sand and gravel remains and is lighter in color. In the backshore (bottom), rubble and gravel remain where a dune was. Hwy 87 is visible on right side. Backflow would have been from right to left in both pictures | 9 |
| Figure 1.7 | Water-filled troughs near Rettilon Rd, at western end of study area. View is landward. Vegetation and surviving dune system can be seen on horizon | 10 |
| Figure 1.8 | Examples of Hurricane Ike backflow and scour features on Bolivar Peninsula. All images are at same scale. Arrows point to examples of features | 12 |
Figure 1.9  Underwater features on Aukena Island, Gambier Islands, French Polynesia. Arrows point to examples of features………………………… 13

Figure 1.10  Storm runoff in meandering backshore channel (flow toward the viewer). Bank is 45 cm high. Note rotational slump blocks in both banks. Harrison County Beach, 22 January 1998……………… 14

Figure 1.11  Horn Island, Western Tip, October 16, 1969. USCGS aerial photo, October 16, 1969: two generations (A and B) of erosive and aggradational washover grooves and stripes………………… 15

Figure 1.12  W. Ship Island. USCGS aerial photo, October 16, 1969: three generations (A, B, C) of narrow, parallel, northward-tapering sand stripes and incised overwash-backwash grooves on the storm-flattened narrow western tip………………………………. 16

Figure 1.13  (1) West tip of Horn Island cut by Katrina storm channel; (2) new inlet, close by early 2007 by westward littoral drift; (3) ponds formed from storm-cut embayments, closed by subsequent westward spit growth on the Gulf side; (4) heavily wooded western Horn Island strandplain sector. Quickbird image, 2 February 2006…………………………………………………… 17

Figure 2.1  Interpolated maximum storm surge depth from tidal stations, Hurricane Ike. An elevation DEM was subtracted from the interpolated maximum storm surge height, creating storm surge depth. White areas on land were not inundated. Labeled points are tidal stations…………………………………………………… 22

Figure 2.2  Tide Gauge data for stations GAL 001 (blue line) and GAL 002 (red line) during and after Hurricane Ike. Two overland backflow stages can be seen corresponding to average post-storm dune elevations of 2.3 m and 1.2 m (solid black line). The rest of the water likely flowed out Bolivar Roads Channel, around the peninsula. Trendlines (orange) are shown for each backflow stage………………………………………………………… 25

Figure 2.3  Forces acting on a particle resting on a granular bed subject to a steady current………………………………………………………… 29

Figure 2.4  Threshold of movement and mode of transport of quartz-density
solids in water (after A. Shields and R.A. Bagnold). X axis is grain size; Y axis is dimensionless stress. The line between no bed movement and suspension or bed movement represents threshold conditions.

Figure 2.5 Lift force due to the Bernoulli effect on a particle on a granular bed subject to fluid shear. The fluid pressure is greater on the underside of the particle (plus signs), where the fluid velocity is low, than over the upper surface (minus signs), where a high velocity obtains.

Figure 2.6 Hypothetical sequence of morphologies illustrating the development of a channel network through instability of sheet flow over a smooth mud substrate. This is an analogy of how channels might have formed on Bolivar.

Figure 2.7 Some examples of flow separation in steady currents. S is the separation point, and A is the attachment point along the time-average streamline patterns. Shown are (a) an upward transverse step, (b) a downward transverse step, and (c) a sharp bend in a conduit or open channel.

Figure 2.8 Schematic representation of the properties of a separated flow at a transverse downward step. Shown are (a) instantaneous impression of the transverse vortices developed by the rolling up of the shear layer between the external stream (ornamented) and the separation bubble, (b) variation in the relative intensity of turbulence, and (c) variation in the Reynolds stress.

Figure 2.9 Secondary flow consisting of pairs of oppositely rotating corkscrew vortices.

Figure 2.10 Overwash surges during storm conditions (top) and resulting washover fans (bottom).

Figure 2.11 Sediments deposited in the inner-neritic zone (submerged area on the continental shelf near the shore) off central Padre Island, Texas, during and after Hurricane Carla, 1961. Based on a study of 36 grab samples and 42 cores collected on sampling grid before hurricane and 66 grab samples and 62 cores collected along same grid after storm. Note correlation between
distribution of these sediments and location of major hurricane and artificial channels......................................................... 44

Figure 2.12 Stages in the processing of Lidar data in support of geomorphological and hydraulic modeling......................... 52

Figure 3.1 The study area is the coastal zone on Bolivar Peninsula, from Rettilon Road, in the southwest, and the junction of Highways 87 and 124 in the northeast. The study area is divided into 3 reaches: 1) northeast, 2) central, and 3) southwest................................. 56

Figure 3.2 Nibble tool schematic. The 2008 Lidar dataset was INGRID1; MASK_GRID was also the 2008 Lidar dataset with holes marked as NODATA. If a cell in MASK_GRID is NODATA, then that corresponding cell in INGRID1 will be “nibbled” in the OUTGRID.................................................................................. 62

Figure 3.3 Process of determining feature boundaries. 2008 Lidar and its products were consulted along with aerial photos to digitize features........................................................................................................ 71

Figure 3.4 Data used in determining feature boundaries, (a) nibbled Lidar with feature boundaries, (b) slope map calculated from nibbled Lidar, and (c) aerial photo with feature boundaries................. 72

Figure 4.1 Dendrogram produced using Ward’s clustering method and squared Euclidean as the distance. Distance measures dissimilarity between groups. Arrows point to breaks between groups of features; each group is labeled with the number of features within each group................................................................. 80

Figure 4.2 Average and standard deviation of area, perimeter, and orientation provided for each group................................. 82

Figure 4.3 Average and standard deviation of shape attributes per group..... 83

Figure 4.4 Coefficient of variation for all statistics per group...................... 84

Figure 4.5 Group 1 feature shapes; note some features (bottom) have more complex shapes; blue line is shoreline................................. 87
<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>Group 2 feature shape types</td>
<td>89</td>
</tr>
<tr>
<td>4.7</td>
<td>Group 3 feature shape types</td>
<td>91</td>
</tr>
<tr>
<td>4.8</td>
<td>Group 4 feature shape types</td>
<td>93</td>
</tr>
<tr>
<td>4.9</td>
<td>Group 5 feature shape types</td>
<td>94</td>
</tr>
<tr>
<td>4.10</td>
<td>Shows distributions of the mean and standard deviation of feature centroids by group. Square indicates average location of centroid along the study area, and line is one standard deviation in length from average centroid. Also provided are kurtosis and skewness values for each group.</td>
<td>96</td>
</tr>
<tr>
<td>4.11</td>
<td>Feature distributions for all groups by km-long division</td>
<td>97</td>
</tr>
<tr>
<td>4.12</td>
<td>Group 1 distribution by km-long division</td>
<td>98</td>
</tr>
<tr>
<td>4.13</td>
<td>Group 2 distribution by km-long division</td>
<td>100</td>
</tr>
<tr>
<td>4.14</td>
<td>Group 3 distribution by km-long division</td>
<td>101</td>
</tr>
<tr>
<td>4.15</td>
<td>Group 4 distribution by km-long division</td>
<td>103</td>
</tr>
<tr>
<td>4.16</td>
<td>Group 5 distribution by km-long division</td>
<td>105</td>
</tr>
<tr>
<td>5.1</td>
<td>Group 1 feature concentration: vertical bars represent number of features per km division</td>
<td>109</td>
</tr>
<tr>
<td>5.2</td>
<td>Group 1 features are more common at this wide beach. Vertical bars represent number of features per km division</td>
<td>111</td>
</tr>
<tr>
<td>5.3</td>
<td>Group 2 feature concentration: vertical bars represent number of features per km division</td>
<td>113</td>
</tr>
<tr>
<td>5.4</td>
<td>Group 3 feature concentration: vertical bars represent number of features per km division</td>
<td>115</td>
</tr>
<tr>
<td>5.5</td>
<td>Group 4 feature concentration: vertical bars represent number of features per km division</td>
<td>118</td>
</tr>
</tbody>
</table>
Figure 5.6  Group 4 features are more common at this wide beach. Vertical bars represent number of features per km division  119

Figure 5.7  Group 4 Features  120

Figure 5.8  Group 5 feature concentration: vertical bars represent number of features per km division  122
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Backflow velocities for Bolivar Peninsula after Hurricane Ike were calculated with a discharge equation as well as with Manning’s equation. The input values are in the following table. For Manning’s, average velocity as well as maximum velocity were calculated.</td>
<td>24</td>
</tr>
<tr>
<td>Table 4.1:</td>
<td>Summary planimetric and shape statistics used in cluster analysis of features; (a) statistics by group, (b) total area of each group, (c) average, min, max, and standard deviation for all features.</td>
<td>85</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>Summary table of shape and size qualities by group.</td>
<td>108</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION:

HURRICANE IMPACTS

Hurricanes have a tremendous impact potential on coastal systems. A hurricane’s winds, storm surge, and waves can fundamentally alter the coastal zone within a short period of time, causing overwash of low-lying areas, breaching of barriers to form new inlets, and extensive shoreline change (Zhang et al, 2005). Other erosional and aggradational features are also produced by hurricanes; these include backflow channels, wave scour features, overwash deposits, and dune breaches (Leatherman, 1981; Otvos and Carter, 2008). Some anthropogenic features (houses, roads, and even “protective” structures) tend to exacerbate erosion during hurricane events. For instance, roads in close proximity to the shoreline can channelize onshore and offshore flow (if perpendicular to the shoreline) or induce scour on the leeward side of the road during a flow; a geotube (a sand-filled protective structure) can be breached in a storm, causing flow to channelize through the breaches. It is important for coastal scientists, lawmakers, and coastal populations to understand hurricanes, specifically how they interact with different types of landcover, and what impacts they can have on development. If coastal systems are misunderstood, the “crumbly hills of fine shifting dust” that pervade in beach environments will be “forever dropping houses into the sea” (Vidal, 1968, p. 208).

This thesis follows the style of Earth Surface Processes and Landforms.
Hurricane Ike made landfall (Figure 1.1) on Galveston Island (just southwest of Bolivar Peninsula) around 2:10 a.m. on 13 September 2008 as a category 2 hurricane on the Saffir-Simpson scale, with maximum sustained winds of 110 mph (177 km/hr), and a minimum central pressure of 953 mb. The eye of the storm was 46 mi (74 km) wide, and the total hurricane was 600 mi (965 km) in diameter. The radius to maximum winds was 23 mi (37 km). As the eye of Ike struck to the southwest, Bolivar Peninsula was in the “feared northeastern quadrant”: the area with the most powerful shoreward winds and storm surge (Donnelly et al., 2006; Toernqvist and Meffert, 2008). The highest storm surge recorded on the peninsula was 14.93 ft (4.55 m) above NAVD88 in the eastern part of the peninsula (East et al., 2008). The storm surge produced by Ike extended back into the Galveston Bay System during the storm, and after the storm passed onto land, the super-elevated water surface was unable to sustain itself and drained back out to sea over Bolivar Peninsula as well as around.

Because of the hurricane’s location and the angle of incoming waves, longshore sediment transport on Bolivar Peninsula (Figure 1.2) was likely from east to west, though the southwestern portion of the peninsula experienced shoreline loss. This pattern of erosion/deposition is in keeping with the general trends (Figure 1.3) for the peninsula as well as for sediment movement caused by Tropical Storms Josephine and Frances on Bolivar (Gibeaut et al., 2002). All told, the flooding, winds, overwash, and backflow resulting from the hurricane significantly reshaped the beach and dune systems and wiped out entire communities on Bolivar, leaving undermined concrete slabs (Figure 1.4), splintered wooden stilts (Figure 1.5), and a trail of debris. Hurricane Ike, though
Figure 1.1: Path of Hurricane Ike from first development.

(National Hurricane Center)
Figure 1.2: Bolivar Peninsula lies northeast of Galveston, with the narrow Bolivar Roads Channel in between. Behind the peninsula is the Galveston Bay System, and in front is the Gulf of Mexico.
Figure 1.3: Comparison of long-term shoreline change and profile volume change caused by Tropical Storms Josephine (September 1994 to November 1997) and Frances (November 1997-1998). Red line shows long-term shoreline change rate, while dotted line with circles and solid line with triangles are volume change from Tropical Storms Josephine and Francis, respectively. Right half of figure is Bolivar Peninsula, which experiences erosion in the east and deposition in the west due to longshore drift.

(Gibeaut et al., 2002)
Figure 1.4: Backflow channel in Gilchrist, Texas. Direction of water flow was away from viewer. Note scour is down to resistant mud layer; rubble from a parking lot as well as concrete slabs are also visible.
Figure 1.5: Backflow channel west of Rollover Pass. Note wooden stilts which supported a beach house. Flow was away from viewer.
only a category 2 storm, had a surge of a much more powerful hurricane. Conditions like those of Bolivar Peninsula, combined with the path and intensity of Ike, tend to accentuate the storm tide, thus contributing to greater damage; these include the hurricane’s large size, path focusing the northeastern quadrant into a large bay (Galveston Bay System), and shallow bathymetry of the Gulf of Mexico, (Riggs, 1976). After the storm passed, the surge stored behind the peninsula flowed back to sea, carving numerous scour features on beaches (Figures 1.6 and 1.7) and through overwash deposits (deposited during the storm); the backflow also carried sediment and debris out to sea.

After Hurricane Ike struck, reconnaissance revealed a large number of scour features on the beach, with some of the features extending to the backshore zone; dramatically different patterns of scour were seen in different locations. The features formed after the storm surge inundated Bolivar Peninsula and then drained back to the sea (backflow) after the storm had passed. The features studied here can be related to washover channels and back-drainage features (water flowing back to sea). Subsequent study of the literature indicated little or no attention had been given to similar features; therefore, this work was deemed worthwhile. This is the first known attempt to quantitatively detect and characterize backflow scour features on beaches.

Backflow features can be confused with other features which may form from different processes like groundwater return flow or rain-generated overland flow which drains to the sea. The features are under-studied phenomena and are merely mentioned in a few research projects dealing with coastal impacts of storms, indicated by an
Figure 1.6: Two views of the same beach. Pictures taken near the junction of Hwys 87 and 124, which has “piano key” formations. Foreshore of beach (top) is scoured down to peat layer, the dark patch. A thin veneer of sand and gravel remains and is lighter in color. In the backshore (bottom), rubble and gravel remain where a dune was. Hwy 87 is visible on right side. Backflow would have been from right to left in both pictures.
Figure 1.7: Water-filled troughs near Rettilon Rd, at western end of study area. View is landward. Vegetation and surviving dune system can be seen on horizon.
exhaustive background literature search (Dupre, 1985; Guidroz et al., 2006; Hayes, 1967; Otvos and Carter, 2008; Otvos, 1999; Scheffers and Scheffers, 2006). Consequently, little is known about the geomorphic characteristics of the features. In appearance from the air, some of the Bolivar features (Figure 1.8) are similar to underwater features seen on islands in the Pacific, specifically on Aukena Island in the Gambier Islands, French Polynesia (see Figure 1.9), as well as channels created by storm runoff on Gulf Coast barrier islands (see Figure 1.10). As depicted in Figures 1.11 and 1.12, there are also similar “washover grooves and stripes” which have been seen on Horn and West Ship Islands in the case of Hurricane Camille (Otvos and Carter, 2008). Similar features were seen also on Horn Island after Hurricane Katrina (Figure 1.13). This project will elucidate some of the unknowns about these features and will also provide quantitative information necessary to understand these features, as well as lay the groundwork for future studies.

Objectives

- This project will identify scour features on Bolivar Peninsula formed by the storm surge of Hurricane Ike.
- The project will categorize the shapes of the features using statistical methods.
- Finally, this project will examine the particular patterns of size, shape, and distribution based on the environments where they occur.
Figure 1.8: Examples of Hurricane Ike backflow and scour features on Bolivar Peninsula. All images are at same scale. Arrows point to examples of features.

(NOAA)
Figure 1.9: Underwater features on Aukena Island, Gambier Islands, French Polynesia. Arrows point to examples of features.

(GoogleEarth)
Figure 1.10: Storm runoff in meandering backshore channel (flow toward the viewer). Bank is 45 cm high. Note rotational slump blocks in both banks. Harrison County Beach, 22 January 1998.

(Otvos, 1999)
Figure 1.11: Horn Island, Western Tip, October 16, 1969. USCGS aerial photo, October 16, 1969: two generations (A and B) of erosive and aggradational washover grooves and stripes.

(Otvos and Carter, 2008)
Figure 1.12: W. Ship Island. USCGS aerial photo, October 16, 1969: three generations (A, B, C) of narrow, parallel, northward-tapering sand stripes and incised overwash-backwash grooves on the storm-flattened narrow western tip.

(Ótvos and Carter, 2008)
Figure 1.13: (1) West tip of Horn Island cut by Katrina storm channel; (2) new inlet, close by early 2007 by westward littoral drift; (3) ponds formed from storm-cut embayments, closed by subsequent westward spit growth on the Gulf side; (4) heavily wooded western Horn Island strandplain sector. Quickbird image, 2 February 2006.

(Otvos and Carter, 2008, p. 468)
CHAPTER II

BACKGROUND

This chapter will review statistics about Hurricane Ike, discuss hurricanes and their storm surges, characterize the storm surge from Ike and model the maximum extent of flooding caused by Hurricane Ike, estimate backflow velocities over Bolivar Peninsula after the storm, discuss how scouring takes place in non-cohesive sediments, distinguish between overwash and washover, discuss the impacts of hurricanes on barriers, discuss backflow and features, and finish with a description and a discussion of relevant tools, like DEMs, airborne Lidar, and aerial photography, used in the study of beach systems.

Hurricane Ike (the ninth named storm of the 2008 hurricane season) was first identified as a tropical depression on 1 September 2008, 1250 km west of the Cape Verde Islands. On the 4th of September, Ike was a category 4 storm (on the Saffir-Simpson scale) and had winds of 231 km/hr. Ike made landfall on several Caribbean islands, including Cuba on the 8th of September, before crossing the Gulf of Mexico (Doran et al., 2009). By the time it made landfall on northeastern Galveston Island at 2:10 AM on the 13th of September, it was downgraded to a strong category 2 hurricane and had maximum sustained winds of 177 km/hr, a minimum central pressure of 953 mb, an eye 74 km wide, a total hurricane diameter of 965 km, a significant wave height of 6 meters (Doran et al., 2009), and the radius to maximum winds was 37 km. Bolivar Peninsula was exposed to the northeastern quadrant of the storm, which is the most
damaging part of the storm, as it has the highest onshore winds and greatest storm surge (Donnelly et al., 2006; Toernqvist and Meffert, 2008).

A hurricane’s storm surge is mainly influenced by the low pressure storm system and winds. The storm surge rides in front of and under the hurricane as it travels over water (Leatherman, 1981). When the hurricane reaches land, that storm surge quickly dissipates, flowing back out to sea. In the case of Hurricane Ike, the storm surge completely inundated the Bolivar Peninsula as it traveled into Galveston and Trinity Bays. These bays provided the space for a very large volume of water to accumulate landward of Bolivar Peninsula. As Ike moved onto the mainland, the large volume of water (average of 3+ meters above sea level in the bays) that accumulated due to the storm was then able to drain back to the Gulf. However, Bolivar Peninsula stood in the way, and consequently, much of the water drained over the peninsula as though it were a weir, inducing scour on the peninsula.

**Hurricanes and Storm Surges**

Though hurricanes have substantial wind power, the bulk of destruction typically comes from the storm tide (defined as the net increase in sea level during a storm), of which the most significant component is the storm surge, defined as the “superelevation of the still-water surface” caused by “wind stresses and pressure gradients” from a storm (Simpson, 1981, p. 234). Another component of the storm tide includes wave setup, a product of radiation stress, which causes a depression of the water level at the breaker point and a rise towards the shore (see pages 232-234 in Komar, 1976 for details). Wave
runup can also increase the pre-storm water level as waves will travel from the
advancing storm and pile up long before the storm arrives. Other contributions to the
storm tide are from rivers, streams, and precipitation runoff (Simpson, 1981). A
hurricane’s total impact can be modulated by many factors, such as 1) the storm surge,
2) direction of storm movement, 3) tidal pattern and magnitude, 4) backbarrier water
bodies, 5) development of affected area, and 6) storm duration (Riggs, 1976). Hurricane
Ike’s storm tide (5.82 m (19.11 ft) above NAVD88) was sufficient to inundate all of
Bolivar because the characteristics of the storm and the area were conducive to
producing a large storm tide.

The storm surge is dependent upon a) wind speed; b) radius of maximum winds,
which reflects the storm’s size, as a larger storm will have a greater radius and storm
surge; c) the speed of forward motion, where a faster moving storm will have an
elevated storm surge; d) the storm’s central pressure (a low central pressure literally
sucks water up, creating a higher storm surge); and e) shoaling factor, where a shallow
continental shelf will result in a greater storm surge.

Direction of movement refers to whether a storm is landfalling, moving
longshore, or exiting a coastal area. If the storm is coming directly on land, it would
have a greater impact due to being unweakened (as an exiting storm would be
weakened), causing an increased storm surge and unabated onshore winds.

The tidal pattern and magnitude refer to the fact that a storm hitting a coast at
high tide will be more damaging as it will have a higher “base water level” with which to
start, meaning the storm surge will be higher, and waves will attack further inland. If it is
low tide, the storm will have a smaller net storm surge, with wave action restricted to coastal areas rather than inland areas.

Backbarrier water bodies can significantly augment flooding when present. If there is a large body of water behind the barrier, the storm surge and flooding may occur from both sides. This effect can be further augmented if there is a water source (like a river) in the backbarrier water body. Meade and Emery (1971) calculated that 21% of the sea level variation (sea level rise) in the Gulf of Mexico is due to river runoff. Though this is an old calculation, it demonstrates that the Gulf of Mexico water level is augmented by runoff.

The level of urbanization of the storm-affected area increases the damage potential of a storm simply because there is more property to destroy. Additionally, devegetation and anthropogenic structures result in increased hurricane damage as modified coastlines tend to be weaker and more susceptible to erosion (Stoddart, 1981).

**Hurricane Ike Storm Surge**

East et al. (2008) published tide gauge data for the Hurricane Ike storm surge around Bolivar Peninsula. Fourteen tidal stations were used to interpolate a storm surge DEM showing the maximum water levels during the storm (Figure 2.1). After the storm surge DEM was interpolated and smoothed, the formula below was used to calculate water depth (ArcTools: Raster Calculator): $S - E = wd$, where $S$ is the storm surge raster interpolated from the tidal stations, $E$ is the terrain elevation, and $wd$ is the water depth. The water depth raster reveals that all parts of the peninsula were completely
Figure 2.1: Interpolated maximum storm surge depth from tidal stations, Hurricane Ike. An elevation DEM was subtracted from the interpolated maximum storm surge height, creating storm surge depth. White areas on land were not inundated. Labeled points are tidal stations.
inundated by the storm. At the shoreline, the water was deepest in the northeast, averaging around 3.8 meters in depth, with the central reach, it was about 3.4 meters deep, and in the southwest, about 3.1 meters deep.

**Estimated Backflow Velocities**

Water levels at two tide gauge stations, one on the coastal side of Bolivar (GAL 001) and the other on the backbarrier in the Intracoastal Waterway (GAL 002), were recorded during the storm (East et al., 2008). The gauge locations are in Figure 2.1. Using these water levels, it was possible to estimate the backflow velocities occurring during the offshore flow of the surge (Table 2.1). Calculations were made assuming the water surface behind the peninsula was horizontal, and that the water directly behind the peninsula flowed mainly over the peninsula and trivially through Bolivar Roads Channel, the normal inlet for the Galveston Bay system. Taking average post-storm dune heights, two characteristic peninsula elevations were used for the analysis, corresponding to two stages of backflow roughly indicated by the tide gauge data as breaks in slope of the waning leg of the surge graph (Figure 2.2). The characteristic elevations are 1.2 meters for the 12.7 km stretch from High Island to Rollover Pass (northeast reach), and 2.3 meters for the 25 km stretch of the rest of the study area (central and southwest reach). Right after the storm passed, the water would have been freely flowing seaward over the entire peninsula during the first stage of backflow. During the second stage of backflow, the western part was sub-aerial, with water only
Table 2.1: Backflow velocities for Bolivar Peninsula after Hurricane Ike were calculated with a discharge equation as well as with Manning’s equation. The input values are in the following table. For Manning’s, average velocity as well as maximum velocity were calculated.

<table>
<thead>
<tr>
<th>Discharge</th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>Start Volume (m³)</td>
<td>5,108,000,000</td>
<td>5,108,000,000</td>
</tr>
<tr>
<td>End Volume (m³)</td>
<td>3,064,000,000</td>
<td>3,064,000,000</td>
</tr>
<tr>
<td>Total Q (m³)</td>
<td>2,044,000,000</td>
<td>2,044,000,000</td>
</tr>
<tr>
<td>Ht of flow (m)</td>
<td>1.20</td>
<td>2.30</td>
</tr>
<tr>
<td>Avg Ht (m)</td>
<td>0.60</td>
<td>1.15</td>
</tr>
<tr>
<td>Width (m)</td>
<td>25,015</td>
<td>12,688</td>
</tr>
<tr>
<td>X-Sxn Area (m²)</td>
<td>15,009.00</td>
<td>14,591.20</td>
</tr>
<tr>
<td>Flow Prop</td>
<td>0.51</td>
<td>0.49</td>
</tr>
<tr>
<td>Proportional Q (m³)</td>
<td>1,036,425,294</td>
<td>1,007,574,706</td>
</tr>
<tr>
<td>Time (s)</td>
<td>19800</td>
<td>19800</td>
</tr>
<tr>
<td>Q (m³/sec)</td>
<td>52344.71</td>
<td>50887.61</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>3.49</td>
<td>3.49</td>
</tr>
</tbody>
</table>

Manning's

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>n</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Avg A (m²)</td>
<td>15009</td>
<td>14591.2</td>
</tr>
<tr>
<td>Max A (m²)</td>
<td>30018</td>
<td>29182.4</td>
</tr>
<tr>
<td>P (m)</td>
<td>25015</td>
<td>12688</td>
</tr>
<tr>
<td>Avg R (m)</td>
<td>0.6</td>
<td>1.15</td>
</tr>
<tr>
<td>Max R (m)</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Run (m)</td>
<td>2176</td>
<td>2176</td>
</tr>
<tr>
<td>Rise (m)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>S</td>
<td>0.001608456</td>
<td>0.001608456</td>
</tr>
<tr>
<td>Avg V (m/s)</td>
<td>0.48</td>
<td>1.47</td>
</tr>
<tr>
<td>Max V</td>
<td>0.75</td>
<td>2.33</td>
</tr>
</tbody>
</table>
Figure 2.2: Tide Gauge data for stations GAL 001 (blue line) and GAL 002 (red line) during and after Hurricane Ike. Two overland backflow stages can be seen corresponding to average post-storm dune elevations of 2.3 m and 1.2 m (solid black line). The rest of the water likely flowed out Bolivar Roads Channel, around the peninsula. Trendlines (orange) are shown for each backflow stage.
flowing over the eastern part of the peninsula. After that, water would be draining through Bolivar Roads Channel.

Calculations of the amount of water behind Bolivar Peninsula that was likely to drain over the peninsula (using ArcMap’s 3D Analyst > Surface Analysis > Area and Volume) were based on modeling a water surface filling a DEM representing the Galveston Bay system (water volumes summarized in Table 2.1). Tide gauge GAL 002 shows a maximum lagoonal water height of 3.5 meters (calculated at 5,108,000,000 m$^3$ of water) and 3.5 meters water height for GAL 001 at 3:30 AM on 13 September 2008; at 9:00 AM, GAL 001 was already down to 0 meters and stayed down, while GAL 002 was 2.3 meters (3,064,000,000 m$^3$ of water) and then 1.2 meters (1,362,000,000 m$^3$) at 10:30 PM. Taking the differences between those numbers gives discharge (Q). In this case, 2,044,000,000 m$^3$ of water flowed over Bolivar Peninsula during the first stage of backflow, and then 1,702,000,000 m$^3$ of water during the second stage of backflow. In order to get velocity calculations (m/s), an average height for each of the cross sections of flow was determined by subtracting the water height from the average land height, giving the height during maximum flow, and then halving the number. The average height was multiplied by the width of each flow to get the cross section area of average flow. During the first stage of backflow, the flow proportion, or proportion of discharge, expected through each cross section of flow (east or west) was determined based on the proportional sizes of each cross section of flow. Then each discharge was calculated by multiplying total discharge by flow proportion. The amount of discharge per second was calculated by dividing the proportional discharge by the duration of flow in seconds.
Velocity was determined by dividing discharge per second by the average cross section area, yielding 3.5 m/s for both east and west during the first stage of backflow, then 5 m/s in the east for the second stage of backflow.

Backflow velocities were also estimated using Manning’s equation, $V = \frac{1}{n} R^{2/3} S^{1/2}$, where $V$ is velocity, $n$ is Manning’s roughness coefficient, $R$ is hydraulic radius (cross section area ($A$) / wetted perimeter ($P$)), and $S$ is slope. The roughness coefficients were taken from Chow (1959) and are .03 (for pasture with high grass) for the east and .06 (for light brush and trees, in summer) in the west, corresponding with the general land cover before the storm. Hydraulic radii were determined for max flow and average flow by dividing cross section area by wetted perimeter; the cross section areas were calculated based on the max height and average heights of the water. The wetted perimeter was the width of each cross section of flow. The slope was based on the difference in elevation between GAL 002 (3.5 during stage 1 and 2.3 during stage 2) and GAL 001 (0 after the storm) as well as the distance between the stations (2176 meters). Manning’s equation yielded velocities of 0.8 m/s for the west and 2.3 m/s for the east during the first stage and then 1.2 m/s for the second stage. All of these velocities (summarized in Table 2.1) are sufficient to entrain sand-size quartz grains, though there was a lack of sediment moving from the back barrier to the beach during the backflow stage.
Scouring in Non-Cohesive Sediments

Sand or other solid, transportable sediments can be entrained in motion and redistributed by fluids. Physical sedimentology, as a discipline, is the study of the interplay between the transportable particles and the fluids which transport them (Allen, 1985). In the coastal zone, the liquid of importance to physical sedimentology is the water found in the ocean, rain, in lakes or tidal pools, and in rivers. For this project, the interplay between water and beach sediments is of immediate interest. To understand that interplay, it is important to describe the forces and conditions which govern the entrainment and transport of sediment in the coastal zone.

Forces created by a current along its bed are often strong enough to entrain and transport particles. An idealized particle, atop a bed of identical particles surrounded by a steady current (Figure 2.3), may move based upon the balance of forces acting upon it. This balance of forces can be quantified: \( aF_L + bF_D = aF_W + cF_C \). For the particle to move, the forces of entrainment (fluid drag \( F_D \) and lift \( F_L \)), must exceed the resistive forces (particle immersed weight \( F_W \) and interparticle cohesion at the grain contacts \( F_C \)); the moment arms branching from the downstream pivot \( P \), about which motion will commence, are \( a \), \( b \), and \( c \) (Allen, 1994). For different types of particles, different forces are more important. For sand or larger particles (in most circumstances), interparticle cohesion plays a reduced role and is typically discounted. For small particles, like clay, interparticle cohesion is much more important as van der Waals and electrostatic forces like are more significant at a fine scale. Due to this, a higher amount of stress is needed to entrain small grains (Figure 2.4). The entrainment threshold is
Figure 2.3: Forces acting on a particle resting on a granular bed subject to a steady current.

(Allen, 1994)
Figure 2.4: Threshold of movement and mode of transport of quartz-density solids in water (after A. Shields and R.A. Bagnold). X axis is grain size; Y axis is dimensionless stress. The line between no bed movement and suspension or bed movement represents threshold conditions.

(Allen, 1970)
determined by a combination of the grain, fluid, and flow properties. Crooks and Pye (2000) found that the morphology of drainage networks in some coastal marshes in southeast England is controlled by the geotechnical (textural, mineralogical, and geochemical) properties of the sediments. These properties influence the ability of the sediments to resist the shear stresses acting to entrain particles. By determining geotechnical properties, like shear strength, porosity, carbonate content, etc., Crooks and Pye (2000) found that weaker sediments had higher drainage densities, and were more susceptible to erosion.

Fluid drag forces acting upon the particle push it in the direction of flow. Drag forces can be quantified in a number of ways, often by using a drag coefficient (more below). Lift forces acting upon the particle in Figure 2.5 are due to the Bernoulli effect, which predicts low pressure along the top of the particle, where the flow is faster, and higher pressure under the particle, where the fluid is flowing more slowly.

When water flows over unconsolidated sediment, it tends to channelize (likely due to local bed irregularities, though this is not completely understood), forming rills, and when the length and power of the stream are great enough, larger drainage networks will form. Evidence of channelized flow was seen on parts of Bolivar Peninsula (especially around Crystal Beach) after Hurricane Ike; Allen (1985) proposes a model for channelized flow: he describes that a smooth and slightly sloping mud surface exposed to even precipitation will develop channelized flow with characteristic depth-related spacings between channels (Figure 2.6). The deeper channels will be further spaced from each other than the shallower channels. Flow in open channels is driven by
Figure 2.5: Lift force due to the Bernoulli effect on a particle on a granular bed subject to fluid shear. The fluid pressure is greater on the underside of the particle (plus signs), where the fluid velocity is low, than over the upper surface (minus signs), where a high velocity obtains.

(Allen, 1994)
Figure 2.6: Hypothetical sequence of morphologies illustrating the development of a channel network through instability of sheet flow over a smooth mud substrate. This is an analogy of how channels might have formed on Bolivar.

(Allen, 1985)
gravity, with the weight of the liquid supplying the necessary potential energy (in exchange for kinetic energy) to initiate drainage. The motion of the water is limited by drag from the bed and banks of the channel. This drag enables the water to exert shear stress along its bed (thus giving it the ability to entrain sediment when the shear stress is great enough). The shear stress can be estimated by using the quadratic stress law that relates bed shear stress to the average fluid velocity squared: \( \tau_0 = \rho C_d U^2 \), where \( \tau_0 \) is the shear stress, \( \rho \) is the density of water or another fluid, \( C_d \) is the drag coefficient (which is not constant), and \( U \) is the average fluid velocity (Biron et al., 2004). This relationship shows that the stress will be increased with a greater flow velocity. The potential for a flow to move material can be calculated with the equation: \( \omega = \tau_0 U_{mean} \), where \( \omega \) is the power of the flow and \( U_{mean} \) is the mean flow velocity (Allen, 1970). Thus a faster flow can entrain and move more sediment than a slower one. In Ike’s case, faster backflowing water over Bolivar Peninsula would have scoured more than slower moving water.

When water flows past an abrupt change in bed configuration or when the flow boundary attitude is suddenly directed towards the bed by some irregularity in the bed, a separation of flow may occur, with a churning separation bubble below (Figure 2.7). This occurs because the fluid traveling near the bed travels more slowly than that above it (in both laminar and turbulent flows), and when the slower flow reaches a “regime of adverse pressure gradient” caused by the irregularity in the bed, it can halt in a separation bubble, which is separated from the faster flow by a free shear-layer, which often provides intense mixing (Allen, 1994, p. 47). In turbulent flows (applicable in the
Figure 2.7: Some examples of flow separation in steady currents. $S$ is the separation point, and $A$ is the attachment point along the time-average streamline patterns. Shown are (a) an upward transverse step, (b) a downward transverse step, and (c) a sharp bend in a conduit or open channel.

(Allen, 1994)
case of Hurricane Ike), the boundary layer encompassing the separation bubble can detach into a series of vortices billowing downstream (Figure 2.8). The vortices grow in size and eventually strike the bed, scouring deeply, often with double or triple the velocity of the attached boundary layer (Allen, 1994). Flow separation causes objects on a beach, like a shell or car to have a horseshoe-shaped vortex curving around the front and sides (Paola et al., 1986). If the flow is transverse to a road, and the road is elevated (as most are), a separation bubble will form, scouring the leeward side of the road. Thus, scouring can be increased around structures in non-cohesive sediments as the flow around the structure is affected, causing an increase in bed shear stress (Sumer and Vittori, 1999).

Secondary flows occur over a channel or a boundary layer; they are one or more corkscrew vortices oriented in the direction of flow (Figure 2.9). When there is more than one vortex, they are counter-rotating and usually in pairs. They are of importance in tidal areas as they can form erosional furrows in the direction of flow (Allen, 1994).

When water entrains sediment, it can do it much more effectively if it is not already carrying a sediment load. Once the water picks up grains in suspension, its capacity to pick up more is diminished. Due to this, water flowing over a loose bed of sediment will scour inversely proportionally to the amount of sediment already entrained by the water flow. For example, if water flowing over a barrier is relatively clean and suddenly encounters littoral material, like on a beach, it will scour deeply into that beach. Conversely, if the same water flow is already carrying a large amount of sediment, when it reaches the beach or sediment supply, it will scour less.
Figure 2.8: Schematic representation of the properties of a separated flow at a transverse downward step. Shown are (a) instantaneous impression of the transverse vortices developed by the rolling up of the shear layer between the external stream (ornamented) and the separation bubble, (b) variation in the relative intensity of turbulence, and (c) variation in the Reynolds stress.

(Allen, 1994)
Figure 2.9: Secondary flow consisting of pairs of oppositely rotating corkscrew vortices.

(Allen, 1994)
Washover/Overwash

According to Leatherman (1981), overwash is the process that causes washover, the geomorphological feature. Overwash is essentially the transfer of water and sand across a barrier from the coastal to the lagoonal side as the result of a storm tide and waves which overtop the “crown”, or the line connecting the highest points (berms or dunes) on a barrier. Washover, then, is deposition by overwash processes.

Overwash is a natural phenomenon which helps barrier islands respond to sea-level rise by transgressing (retreating inland). For example, assuming a rising sea level, waves will tend to erode the beach and deposit material on the other side of the barrier during overwash events—this phenomenon is known as barrier rollover if the sediment is deposited in the lagoon—which increase the width of the barrier and translate the barrier complex shoreward while typically preserving the volume of sand in the barrier system. During times of sea level fall, barriers will tend to prograde (develop in a seaward direction).

Washover channels (different from backflow channels) are produced when a storm tide overtops beach dunes and spills over into the back barrier area while cutting a channel through the dune. Overwash typically deposits sediment in a fan-like pattern through a washover channel (Figure 2.10). Depending on the specific circumstances, overwash can occur from the lagoonal to the coastal side of a barrier if a storm tide originates in the lagoon and travels seaward (especially if winds are heading offshore). Good examples of washover abound along the Atlantic and Gulf Coasts of the US, though it occurs in diverse locations all over the world (Donnelly et al., 2006).
Figure 2.10: Overwash surges during storm conditions (top) and resulting washover fans (bottom).

(Leatherman, 1981)
Many factors affect the quantity and shape of washover deposits: 1) height of beach berms, 2) water level, 3) wave height and runup height, 4) storm duration, 5) back barrier morphology, 6) vegetation, and 7) wind strength and direction (Donnelly et al., 2006). If the sum of the storm surge height and wave runup height is greater than the dune height, then overwash will occur. The relative difference in height will determine the extent of overwash. There are two basic types of overwash: runup overwash and inundation overwash. Runup overwash is less severe and normally builds washover fans and washover terraces. However, inundation overwash is extreme and occurs when the storm surge height and wave runup height together completely overtop the crown, inundating the entire barrier. Water then freely pours over the barrier as if it were a weir into the back barrier lagoon. In this scenario, sediment is eroded from the beach with concomitant shoreline retreat and deposited as a sheet on the barrier or even behind the barrier if the landward flow is great enough. The relationship between overwash and backflow is typically an intimate one: for backflow features to form on a barrier, water must first overwash the dunes and pool up on or behind the barrier in question; then it must drain back offshore and cut scour features as it flows. The water may also pool up on or behind the barrier by another mechanism, like bay flooding from wind, rivers, or rain, but it will still flow over the barrier to the sea (Dupre, 1985).

**General Impacts of Hurricanes on Barriers**

Barrier islands and spits are elongate agglomerations of sand dynamically responding to changes in sediment supply, sea level change, and wave energy.
Hurricanes tend to pound barriers with high-energy waves, eroding dunes and denuding the beach. When waves and/or the storm surge overtop the dunes, overwash and the inlet formation (formation of a permanent cut, bisecting the island or spit) will occur. If overwash occurs through narrow channels cut in the foredune, washover fans may form, but if the overwash is extensive, washover terraces (many washover fans combining into a large area of washover) may form. Inlet formation is important because it allows for the exchange of sediment and water between the open ocean and the lagoon. In the days and months after a hurricane, barriers will begin to recover by deflating washover deposits and rebuilding the beach and dune systems. A new equilibrium may be reached within a year or more, though the entire barrier may be translated landward (Ritter et al., 2002).

**Backflow and Scour Features**

Several authors have written on the geomorphological impacts of hurricanes on coastal areas (Riggs, 1976; Gibeaut et al., 2002; Otvos and Carter, 2008; Guidroz et al., 2006; Dupre, 1985). However, much of the literature on the coastal geomorphic impacts of hurricanes focuses primarily on barrier overwash processes and deposits and less on storm surge backflow, which seems to be less common, as it requires water building up behind a barrier and then flowing back to sea after the storm. The return flow of tsunami is termed backflow by some authors, though that is different from backflow as described here, as tsunami backflow is typically more cataclysmic since there may be one or more waves an order of magnitude larger than a storm tide, which quickly strike and then
drain back to sea, often via a different route from the onrush (Le Roux and Vargas, 2005). What was seen in the case of Hurricane Ike is a storm surge which completely inundated Bolivar Peninsula for many hours, but then after the storm passed, the flood water flowed back out to sea, carving features and carrying debris with it, often through overwash channels.

Hurricane Carla (in 1961), transported large amounts of material from depths of 50-80 feet deep offshore and scattered it across Padre Island. After the storm passed, strong currents flowed out recently-cut storm surge flood channels, evolved into density currents, and spread sand 1-3 cm thick at 48-60 feet deep and a 9 cm thick graded bed of turbidite (sand, silt, and clay) over the shelf (Hayes, 1967). Figure 2.11 shows this offshore deposition of material after Hurricane Carla. Otvos and Carter (2008) conducted an historical assessment of island change off the Mississippi and Alabama coasts and found backflow scour features on the Ship Islands (off the Mississippi coast) in historical imagery from 1969; this imagery is presented in Figures 1.5, 1.6, and 1.7. They called these features overwash-backwash grooves and washover grooves.

Guidroz et al. (2006) briefly discuss some return flow features caused by the storm surge ebb of Hurricane Rita (2005) as an afterthought to the sizable amount of washover features found along the Louisiana shoreline. However, where they appeared along the predominately marshland coast, the features were primarily subaqueous and highly branching. Dupre (1985) discusses the fact that some backflow features caused by Hurricane Alicia (1983) were not associated with a storm surge but rather with offshore flow from winds, due to the orientation of the storm to the shoreline. These
Figure 2.11: Sediments deposited in the inner-neritic zone (submerged area on the continental shelf near the shore) off central Padre Island, Texas, during and after Hurricane Carla, 1961. Based on a study of 36 grab samples and 42 cores collected on sampling grid before hurricane and 66 grab samples and 62 cores collected along same grid after storm. Note correlation between distribution of these sediments and location of major hurricane and artificial channels.

(Hayes, 1967)
channelized features were limited in their onshore extent by a road running parallel to the shoreline. However, the features were often associated with roads perpendicular to the coastline which caused breaks in the dune system, allowing for an easier path for offshore-flowing water.

Hurricane scour features on beaches are ephemeral and may be immediately reworked in the swash zone by waves and wind on the foreshore. These reasons likely contribute to their being understudied (Otvos, 1999). Additionally, the instrumental record of hurricanes is lacking (detailed information on storms in the distant past is nonexistent), as the latest tools which are used to collect a high volume of precise data (like Lidar, high-resolution satellite imagery, etc.) have only been available to researchers in the recent past. For example, a hurricane which occurred in 1900 may have caused scour features which were never surveyed or observed due to the short time they existed, their wide spatial extent, remoteness, limited tools of the day, and more pressing social issues such as rescue and recovery. The lack of historical data inhibits the ability to assess the impacts of previous storms as well as to make predictions about the impacts of future storms (Horton et al., 2009).

Tools

Multifarious remote sensing tools are available to study landforms at various scales (both temporal and spatial). The major groups of tools include satellite imagery, airborne instruments, and land-based surveying instruments, like Global Positioning System (GPS) units, which can accurately determine the elevation and location of any
place which has a clear view of the sky.

Representing topography with a digital terrain model (DTM) can help to automate and simplify landform classification. Specific types of landforms can be extracted and classified using specialized classification algorithms which can find edges of features as well as identify shapes (Reuter et al., 2006). The human eye can also pick out complex features which algorithms often miscategorize.

**DEMs and/or DTMs: History and Applications**

Most DEMs and DTMs tend to be in raster format, which is a regular gridded matrix (containing columns and rows) of elevation values (or some other variable, like brightness). Rasters are typically displayed as images, where each pixel (single box of column (j) and row (i) has a different color or shade corresponding to its value. All digital images are rasters. Though outside the scope of this project, DEMs and DTMs can also be represented as TINs (triangulated irregular networks). Many researchers tend to use DEM and DTM interchangeably, but this article will use the following definitions, making a note if an author strays from this definition.

- **DEM**: “A file or database containing elevation points over a contiguous area”.
- **DTM**: A file which contains “elevation information about the bare-Earth surface without the influence of vegetation or man-made structures” (Jensen 2007, 335).

Miller and Laflamme (1958) constructed the first DTM and associated theory
(Ebner, 1987). They recognized the need for a “convenient representation” of the Earth’s surface which would have many “engineering, scientific, and military” applications (Miller and Laflamme 1958, 434). They defined a DTM as a statistical representation of the ground with a large number of points in xyz coordinates plotted in an “arbitrary coordinate field” (Miller and Laflamme 1958, 435). Points were plotted on a Kelsh Plotter in a tedious, manual fashion, but the authors postulated an ever-increasing tendency towards efficiency which will make the photogrammetrist’s job easier. The DTM, once georeferenced to a coordinate system and sea-level datum, enables a user to know the exact location and elevation (within a margin of error) of any point on the surface of the Earth (as long as it falls within the bounds of the DTM). Any landform and its parts, once modeled, can thus be accurately located and evaluated.

Miller and Laflamme (1958) had the clairvoyance to postulate the high degree of automation possible by computers in constructing DTMs. They argued that the most efficient DTM form would contain points of regular spacing stored in parallel lines (which would result in a rectangle). Since 1958, DTM construction has evolved from the manual input of points (derived from contour maps or stereomodels recorded on computer input material into an electronic digital computer) into automated DTM construction by sophisticated softwares from data collected by high-resolution sensors (Gillespie et al. 2007).

Florinsky (1998) broadly defines a DTM as a digital representation of topographic surface variables. However defined, he recognizes the utility of DTMs for many diverse fields such as hazard studies, geobotany, geology, soil science, etc. In the
realm of landscape studies, topographic attributes can be used to 1) identify drainage networks and catchments, 2) map insolation, 3) recognize underlying geologic structures, and 4) identify landforms.

Florinsky (1998) notes several ways to derive DEMs (which contain the initial data from which DTMs are constructed): 1) ground surveys using various conventional tools, 2) overlapping two orthoimages with photogrammetric principles, and 3) digitizing topographic maps and extracting point elevations. Lidar systems are different from these methods of DEM creation as they are more automated, and standard photogrammetric techniques are not utilized. Florinsky (1998) usefully notes that the methods of DEM data collection and construction used for any project should take into account several factors: 1) the size of the study area, 2) cost of data production, 3) resolution desired, and 4) level of accuracy required. He explains that DTMs can be utilized to: 1) correct for topographic effects in images, 2) correct for image distortion, 3) classify images, 4) analyze landscape data, and 5) model 3-D landscapes.

**Airborne Lidar Specifics**

ATM (Airborne Topographic Mapper) or airborne Lidar data capture is a complicated process using a host of advanced tools, including a 1) laser scanning unit, 2) kinematic DGPS (Differential GPS), and 3) IMU (inertial measurement unit), in order to collect elevational data from a swath of land over which an aircraft flies. The laser is directed at an angle by a rotating mirror (commonly in an elliptical or zigzag pattern). From the equation: \( R = \frac{1}{2} t_c \), the range (R) or distance to the object can be found; \( t \) is the
travel time of the laser pulse, and \( c \) is the speed of light. The product of the travel time and speed of light must be divided by 2 as the laser must go to the ground or object and then bounce back. The Lidar sensor commonly uses an eye-safe near-infrared (1040 – 1060 nm) or blue-green (532 nm) laser. Most terrestrial applications use near-infrared while bathymetry mapping applications use the blue-green laser as it can penetrate water (Jensen, 2007; Sallenger et al., 2003).

Point spacing refers to the distance between any 2 Lidar points. A smaller point spacing allows for a finer resolution Lidar grid to be made. Point spacing \( P_{\text{spacing}} \) can be calculated as thus:

\[
P_{\text{spacing}} = \frac{h}{\cos^2(\theta_{\text{inst}})} \times \frac{\alpha_{\text{inst}}}{PRF},
\]

where \( h \) is height of the airplane about ground level, \( \alpha_{\text{inst}} \) is the instantaneous angular scanning speed in radians per second, \( \theta_{\text{inst}} \) is the instantaneous scanning angle, \( PRF \) is the pulse repetition frequency. Point spacings will vary with aircraft speed, though typical point spacings are about 1-2 per m\(^2\) (Jensen, 2007).

When the laser from an airborne-mounted Lidar system hits the ground, it does not hit the ground at one infinitesimally small point; it has a width (usually around 30 cm) and is called the instantaneous laser footprint \( (FP_{\text{inst}}) \). It is defined as:

\[
FP_{\text{inst}} = \frac{h}{\cos^2(\theta_{\text{inst}})} \gamma,
\]

where \( h \) is the aircraft’s altitude above ground level, \( \theta \) is the instantaneous scan angle, and \( \gamma \) is the divergence of the laser, which is commonly 1 mrad. As the laser footprint is typically 30 cm, multiple returns can occur from different parts of the footprint, each with its own return time. The first return is the highest object in the footprint, usually vegetation, or if it is bare ground, there will only be one return.
If there is a tree within the footprint, the first return may be the top of the tree, any intermediate returns will be branches or other smaller shrubs, and the last return will be the ground (provided the vegetation is not too thick). Filtering applied to remove all of the above-ground returns (all but the last returns) and then gridding the data yields a bare earth DEM.

The DGPS requires two GPS units: one collects locational data on-board the aircraft, and one is on the ground at an accurately surveyed site near the survey area. After the flight, the data are compared and processed together, such that the difference between the ground unit and its known location can be used to correct the perceived location recorded by the GPS unit aboard the aircraft and get a more accurate location of the aircraft (usually within 5-10 cm). The data recorded by the IMU are the roll, pitch, and yaw of the aircraft. This information allows the pulse vector to be properly oriented; thereby, the distance of the point from the laser can be accurately positioned in 3D space (NOAA Metadata File, 2006).

**Lidar Uses**

Many researchers have used Lidar systems for various geographical applications which require high-resolution data such as 1) beach shoreline and volume change (Robertson et al., 2007; Stockdon et al., 2002; Revell et al., 2002), 2) secliff studies (Palamara et al., 2007; Young and Ashford 2006), 3) geomorphological and hydraulic modeling (French 2003), 4) landslide activity and morphology (Glenn et al. 2006), and 5) forest structure and biomass calculations (Lim et al. 2003)—just to name a few of the
more common applications. However, Lidar is especially well-suited to coastal studies, as hundreds of kilometers of high-resolution, inexpensive data can be collected in a matter of hours, giving researchers quick access to coastal elevational data to use for mapping the current state of features as well as comparing different flights to calculate patterns and magnitudes of beach change after a storm or another major erosional/depositional event (Stockdon et al., 2002, Sallenger et al., 2003).

French (2003) claims that a detailed representation of topography (which he achieved with Lidar data) is necessary in geomorphological research since larger and more complex problems can be tackled with more accurate topographical data. Fine-scale Lidar data are desirable because they increase the precision of analysis. With high variability of beach features over small distances, a large scale study will identify smaller features than a small scale study of the same area. The physical size (and scale) of the features of interest then becomes vital, as does the resolution of the spatial data being used, which if too coarse (small scale), may not discern any potentially important features (French 2003).

French (2003) finds many uses for accurate and high resolution topographical data within the arena of hydraulic modeling. Figure 2.12 shows his stages of Lidar data processing, which results in data reduction followed by extraction. He touts the importance of data quality and the requisite cleaning and filtering of data. His filtering process purportedly does three things: 1) ensures elevational consistency, 2) reduces data volume, and 3) removes unnecessary data from the hydraulic model.

Glenn et al. (2006) argue that only Lidar data can allow for the necessary
Figure 2.12: Stages in the processing of Lidar data in support of geomorphological and hydraulic modeling.

(French, 2003)
“quantitative geomorphometric” analysis of “spatial scale-dependent processes” of their study on landslides (132). They claim that the standard 10 m DEMs commonly available for the U.S. are inadequate for their purposes, while Lidar have a much finer resolution. Glenn et al. (2006) were able to calculate 1) surface roughness, 2) slope, 3) semivariance, and 4) fractal dimension of the two landslides from their high resolution Lidar data.

Many types of coarse remote sensing data are falling to the wayside in coastal applications as Lidar only increases in popularity. Coastal studies are only benefited by Lidar. The only hindrances are the long processing times that large Lidar datasets require as well as data availability; U.S. coastal coverage is spotty, and there are no data at all in the distant past, before the technology was invented.

**Aerial Photography**

Uses of aerial photographic are numerous; applications can be for emergency response (seeing damaged areas in need of emergency services), government and military (locating insurgents, weapons stockpiles, etc.), commercial (identifying areas which might contain valuable resources), and research (identifying geomorphological features (as in this project), forest density, land cover, etc.). Users of aerial photography can interpret anthropoid features, perform land cover classifications, and in the field of photogrammetry, calculate object dimensions and produce DEMs from stereoimages (two images taken from different vantage points but overlapping to some degree).

Aerial photographs can be taken from an aircraft or a satellite (though that type is
usually called satellite imagery). Most aerial photography contains spectral information in the visible bands of light, from the wavelengths of 400-700 nanometers (wavelengths of 400-500 are blue, 500-700 are green, and 600-700 are red). Other common wavelengths are in the near infrared range (NIR), useful for vegetation analyses, while many other wavelengths are used for advanced applications (Jensen, 2005). Aerial photography has advanced in the previous decades from using analog celluloid film cameras to digital cameras using different types of arrays of charge-coupled devices (CCDs), which are electric sensors that sense light of specific wavelengths. Array types and digital camera technology have improved to have a spatial resolution (the ability to distinguish separate features of a given size or distance on the ground) often better than the highest quality analog film cameras. Other types of resolution are relevant to aerial photographs, like temporal and radiometric, where temporal refers to the time difference between successive photographs, and radiometric refers to the ability of the sensor to detect differences in light wavelengths (Jensen, 2005).
CHAPTER III

STUDY AREA AND METHODS

Study Site Description

The study area for this project, the Bolivar Peninsula (Figure 3.1), is situated just northeast of Galveston Island and runs parallel to the general trend of the mainland Texas coast, while blocking Galveston, Trinity, and East Bays from open access to the Gulf of Mexico. Bolivar Peninsula is attached to the mainland at the northeast, around the City of High Island. A segment of the Houston Ship Channel, the Bolivar Roads Channel, is in between the northern tip of Galveston Island and Port Bolivar, which lies on the western end of Bolivar Peninsula. The low-lying populated community of Gilchrist was protected by a ~10 km long geotube (also known as geotextile tube), which ran ~5 km from each side of Rollover Pass along the coastline. The geotube or geotextile tube (Figure 3.1) was a shore-parallel sand-filled seaside barrier (~2 meters high and ~9 meters in cross-section) placed along the back beach. It was installed in 1998 after Hurricane Frances (Gibeaut et al., 2003) but was largely breached (leading to characteristic scour patterns) during Hurricane Ike and has since been completely removed.

On Bolivar Peninsula, this project is specifically concerned with the coastal zone (the area within 500 meters of the shoreline) running from Rettilon Rd, on the western end of Bolivar’s Gulf coastline, to the intersection of Highways 87 and 124, just south of
Figure 3.1: The study area is the coastal zone on Bolivar Peninsula, from Rettilon Road, in the southwest, and the junction of Highways 87 and 124, in the northeast. The study area is divided into 3 reaches: 1) northeast, 2) central, and 3) southwest.
High Island, Texas. For ease of reference, the study area was divided into three reaches: 1) northeast, 2) central, and 3) southwest. The northeast reach extends from High Island to Rollover Pass. Part of this reach was very low (the maximum pre-Ike elevation was about 2 meters), with a beach about 40 m wide, and there was a small sand dune running along Highway 87 before the storm. The other part of the northeast reach contained half the extent of the geotube and had a beach width of about 60 m. There was a thin layer of sand overlying resistant mud deposits, which were exposed after the storm, in the northeast reach. The central reach extends from Rollover Pass to the narrow section of the peninsula around Crystal Beach, where a large sand dune (maximum elevation about 3.5 meters) that formed the backbone of southwestern Bolivar Peninsula ran close to the shoreline. This reach contained the southwest portion of the geotube (where the beach width was about 30 m). The rest of the coast in the central reach was backed by the large sand dune, and had a beach width of about 50 m. The southwest reach then includes the rest of the peninsula, to Rettilon Rd, which is marked by a wide beach (60-80 m) and low elevation. The large sand dune was far back from the beach in the southwest reach and had a maximum pre-storm elevation of about 3 meters.

**Texas Barrier Islands**

The Texas coast has around 370 miles of barriers (islands and spits) which protect the mainland from Gulf of Mexico storms and waves. During the last rise in sea level, Texas barriers transgressed as washover caused rollover, and the shoreline migrated inland. Fronting the upper Texas coast are Bolivar Peninsula and Galveston
Island. Texas barriers began to prograde as sea level rise slowed about 5000 years ago. However, oil, gas, and water extraction have led to large areas of subsidence in the Houston area, though only the western tip of Bolivar Peninsula is affected by subsidence, and that is on the order of about a foot (Zilkoski, 2006), thus exacerbating the sea level rise experienced in the Gulf in modern times. Given the gentle Texas coastal plain, a sea level increase of a foot will result in barrier landward migration on the order of 1000 and 1500 feet.

Bolivar Peninsula is in what Rezak et al. (1985) refer to as the “Central Area”; this encompasses the coast between Sabine Pass and Port Isabel and is typified by barriers separating lagoons and embayments from the open Gulf of Mexico. Bolivar sits on the Texas-Louisiana continental shelf and is dominated by terrigenous sediment (sand, silt, and clay). The San Jacinto and Trinity Rivers provide sediment to the area, as well as the Mississippi and other smaller rivers to the east, via longshore sediment drift; the Mississippi is the dominant provider of sediment to Bolivar. Unfortunately, dams along the San Jacinto River and others have starved the shore of sediment. The Trinity Delta, conversely, has prograded in recent geologic time (White and Tremblay, 1995). However, it is limited in its ability to expand by the size of Trinity Bay. Gulf Coast barrier islands are part of a heavily dynamical system, where islands can form, merge, and disappear in a short period of geologic time (Otvos, 1981).

Different barrier islands have dramatically different forms; however, if one examines an idealized barrier, it will have a beach facing the open ocean. The beach will be backed by a series of dunes, usually with the largest dune (foreset) directly behind
the beach, and smaller dunes or beach ridges behind. At the back of the barrier (facing a lagoon) will be a marsh with washover fans interspersed (Ritter et al., 2002). Bolivar Peninsula, though not actually an island, is a barrier spit extending from the mainland Texas coast around High Island. However, Bolivar functions as a barrier and, in many ways, is similar to the idealized barrier island model. Bolivar has beaches along the Gulf of Mexico, and along most of the shoreline, it was backed by a foredune (though that foredune was human-made in the northeast reach). In the southwest reach, a series of beach ridges was present before the storm, though the series of beach ridges did not extend into the central reach. The central reach appears to have lost so much shoreline that the remnant dune system in the southwest reach (which likely extended further northeast) was eroded from the shore. This dune system appears to be nonexistent in the northeast reach. In the northeast reach, the barrier was very flat across and did have some marshes backed by East Bay. The central and southwest reaches both were backed by extensive marshes. The southwest reach was most like the idealized barrier model, with the central and northeast reaches being less similar to the ideal.

Data Sources

Three data sources used in this project: 1) 2008 Lidar collected by the USGS, 2) 2008 high-resolution aerial photographs collected by NOAA, and 3) 2006 Lidar obtained from NOAA CSC. The 2008 Lidar, the 2008 high-resolution aerial photographs, and the scour feature outlines can be seen in Appendix A.
2008 Lidar

Though hurricanes can be extraordinarily destructive, their “fingerprints” on beaches are temporary: subaerial hurricane beach features are perishable, changing and possibly disappearing in the time after a storm. Consequently, collecting post-storm data in a timely fashion is vital (Horton et al., 2009). The USGS flew a Lidar mission on 17 September 2008, just four days after the storm. The 2008 dataset used here encompasses 34 km of coastline from the southern tip of Bolivar Peninsula up to just south of High Island; part of the northeastern reach of the study area has no coverage from the 2008 Lidar dataset. In Appendix A, which shows the 2008 Lidar, places where there is no coverage are marked “Data Unavailable”. This USGS Lidar DEM shows most of the hurricane features of interest, as most are on the scale of 20-30 meters wide. Unfortunately, some of the finer features are not visible in the post-storm Lidar dataset, but many of these features are visible in the aerial photographs described below.

The post-storm Lidar dataset has a point spacing of approximately 2 m and was gridded at 4.7 m. The dataset was corrected for errors before being released and is estimated to have a vertical accuracy of 0.15 m (though it is mentioned it is possible the errors could be 0.5 m or more (Plant, 2008)); the horizontal accuracy was not noted, though it is likely good as features which withstood the storm visually appear not to shift between the 2006 and 2008 datasets. However, before being released, the data were offset by 11.19 m in the horizontal plane to correct for calculated navigation errors. This dataset initially came in the projection ITRF 00 without being associated with a metadata file, and it was originally in 64 bit radiometric resolution, which is unnecessarily high
for this study. The 2008 data were thus first converted from 64 bit to 32 bit using the *Copy Raster* function in ArcToolbox, then the datum was defined for the dataset as WGS 84 using the *Project Define* function in ArcToolbox. Then they were subsequently projected into UTM 15N WGS 84 (to be compatible with the aerial photographs from NOAA) and extracted to the shoreline buffer. The next step was to mosaic the three preexisting tiles into a 2 m grid (to be compatible with the 2006 data) using the *Mosaic to New Raster* function in ArcToolbox. After the preprocessing steps, the formerly large Lidar tiles became manageable “snakes” of data hugging the coast.

In the 2008 Lidar DEM, many holes existed where objects (like buildings and trees) stood after the storm had passed. These holes made it difficult to run any analysis (like *Watershed* or *Stream Flow*) with the data. To fix the holes, Arc’s *Nibble* tool was used (Figure 3.2). *Nibble* has two input rasters and one output raster. The first input raster is the one to be nibbled, in this case, the 2008 Lidar dataset. The second raster is a mask which corresponds to the first input raster; if a cell in the mask raster has a value of *no data*, then its corresponding cell in the first raster will be nibbled in the output raster.

The data type of the first input raster must be *integer*, so the 2008 Lidar were converted to *integer* type before running *Nibble*. This involved multiplying the grid by 1,000,000 and using the *Copy Raster* function in order to convert the data from *floating point* (with decimal places) to *integer*; *no data* values were given the value of -100,000,000 because any *no data* values in the input raster (not the mask) would be ignored by *Nibble*. The mask was simply the 2008 Lidar, with the values of the holes being *no data*. 
Figure 3.2: Nibble tool schematic. The 2008 Lidar dataset was INGRID1; MASK_GRID was also the 2008 Lidar dataset with holes marked as NODATA. If a cell in MASK_GRID is NODATA, then that corresponding cell in INGRID1 will be “nibbled” in the OUTGRID.

(ESRI)
The output raster then is made up of original values of the first input raster if the mask raster contained a value in the corresponding cell, and if there is no data in a cell of the mask raster, the output raster will have the nearest neighbor value from the first input raster as the output value. In summation, the 2008 Lidar data had holes, and corresponding to those holes in the mask raster were no data values. The holes were then filled with the nearest neighbor value (calculated by Euclidean distance) of the 2008 Lidar dataset. The last step was to apply a median filter to remove noise and instrument artifacts as well as smooth the nibbled areas.

2008 Aerial Photographs

NOAA published a series of high-resolution post-storm aerial photographs online which have been used in this project for visual as well as shape analysis. NOAA flew several missions in the weeks after the storm with mixed results. On some dates, there was too much haze, cloud cover, or other distortions, while the 14 September 2008 images were of very high quality. However, this coverage was limited in the central reach of the study area, and there was no coverage in the northeast reach. In order to achieve complete coverage of the study area, images from the 18th of September 2008 were selected as they were close in date and of better quality (though the lighting quality is lower than the images from the 14th) than other sets of images. The images are reproduced in Appendix A. Appendix A, Division 1 (top pane) contains an example from the later set of images, and Appendix A, Division 3 contains an image from the 14th, which is obviously of superior quality. The NOAA missions which produced the
images were flown with the same equipment at the same height and were gridded at the same resolution.

The images came in the sub-meter resolution range (~.37m) and overlapped 30% on the sides. The ~30 images for all of Bolivar Peninsula were combined into 6 different mosaics in order to make viewing easier. The mosaics were made using Arc’s Mosaic feature after first creating an empty raster which served to make the mosaicking process more efficient than the alternative Mosaic to New Raster function. The original resolution of .37 m was preserved in the mosaics for precise interpretation of hurricane feature boundaries.

2006 Lidar

In order to gain knowledge, for comparison, about pre-storm conditions like the coastline position, locations of buildings, proximity of dunes to the shoreline, and extent of the geotube, a 2 m resolution Lidar dataset from 2006 covering all of Bolivar peninsula was downloaded from the National Oceanographic and Atmospheric Administration Coastal Services Center (NOAA CSC).

The dataset has an unspecified horizontal accuracy, and a vertical accuracy of 0.18 m. Visual comparison between the 2006 and 2008 datasets shows that features are in the same locations in both, so the horizontal error must be negligible. No major hurricanes (other than Ike) have hit Bolivar since 2006 (Weather Research Center, www), so major changes seen between the 2006 and 2008 datasets would be due mainly to Ike and not another hurricane.
The 2006 Lidar data were gridded at 2 m, with an average point spacing of 1.5 m. They were initially downloaded in floating point grid format (extension: “.flt”) and were converted to a raster using the Float Grid function. Before being downloaded, UTM Zone 15 N was specified as the desired projection, so the data came pre-projected, a projection being a way to represent a 3D surface in 2D. However, the projection was undefined—meaning after the data were converted to raster, the Project Define function was used to assign their projection. The previous steps were automated using Python programming with ArcObjects (see Appendix B for the program code). In order to make the data more manageable, as the data were of all of Bolivar Peninsula, they were next extracted to the 500 m shoreline buffer using the Extract tool. Subsequently, they were projected from NAD 83 UTM 15 N to WGS 84 UTM 15 N (using the Project tool) to be compatible with the other data sources used in this project. The 10 separate tiles were then mosaicked using the ArcToolbox function Mosaic to New Raster. To remove noise and instrument artifacts, a median filter was applied.

Change Detection Analysis Between 2006 and 2008

In order to better understand the general patterns of feature erosion on Bolivar, raster-based change detection analysis was performed for Bolivar using the 2006 and 2008 Lidar datasets. For such analysis, it is important to ensure all datasets have the same spatial resolution, same projection, and same coverage, or else false differences could occur (Shrestha et al., 2005). This is why preprocessing the data was very important to the accuracy and usefulness of this project. As the 2006 Lidar dataset had
an original resolution of 2 m, it recorded fine pre-storm features, like the extent of the geotube, dimensions of houses, and prevalence of dunes. The 2008 Lidar dataset, originally with a resolution of 4.76 m, was upsampled to 2 m resolution to match the 2006 dataset. The projections had already been modified and both had been extracted to the shoreline buffer, thus fulfilling the prerequisites for change analysis.

After preprocessing, a difference map/change detection map (using “Band Math” in ArcToolbox) was calculated between the 2006 and 2008 datasets to show erosion and deposition by the storm. After initially processing the change detection map, it became apparent that objects like roads which should not have changed elevations between 2006 and 2008, in fact, had, and that systematically, the 2008 data had lower elevations for these objects. This pointed to vertical error within either of the datasets, but it is not clear which one. This type of vertical error between two datasets has been dealt with by Shrestha et al., (2005), and they used the same method described here to rectify the datasets. To rectify them for accurate change analysis, 34 control points were chosen along the wide Highway 87, which spans the length of Bolivar. The control points were chosen using the high-resolution aerial photographs so that overwash deposits on the road could be avoided and only clean, level road would be sampled. The control points averaged out to a 0.26 meter difference between the two datasets. The difference map then had the equation $chg = (08_{data} + 0.26m) - 06_{data}$ to account for this systematic error. See Appendix C for the simplified patterns of erosion and deposition. Visualization of the change detection map is achieved by applying a color table to the
change detection DEM, with light grey for erosion, medium grey for no change, and black for deposition.

**Buffer Zone**

From post-storm aerial photographs collected by the USGS, it is clear the scour features seen on Bolivar Peninsula terminate less than 500 meters inland of the shoreline; therefore, a zone 500 meters from the shoreline contains all of the beach features, and it can serve as the definition of the study area. It should be noted that in different regions of the world, hurricane features may extend different distances from the shore, so this distance will not be applicable to all hurricane-prone areas. As the study area is a narrow, concentrated sliver of the coast, and the 2008 Lidar data contained information outside the extent of the study area, the 2008 Lidar dataset was clipped to the buffer zone (seen in Figure 3.1 in magenta outline). This had the added benefit of reducing irrelevant data, saving hard drive space, and decreasing computation time.

In order to create the buffer, the shoreline, by necessity, was determined. The shoreline was interpolated along a 0.37 m contour line (ArcToolbox: *Spatial Analyst* > *Surface Analysis* > *Contour*) of a 2006 Lidar dataset. That contour line represents the Mean High Water (MHW) level above the vertical datum NAVD88 based on tidal stations; MHW is used by the USGS to approximate a shoreline when the dataset is in the vertical datum NAVD88 (Weber et al., 2005). The shoreline buffer was created in ArcToolbox (Analysis Tools > Proximity > Buffer) by using the shoreline created in the previous step and selecting a buffer distance of 500 m. It was necessary to have the
buffer extend offshore to account for shoreline progradation; however, the software requires that the buffer be symmetrical, so the shoreline buffer extends 500 m onshore and offshore.

**Determining Feature Boundaries**

Several techniques were explored for determining the boundaries of individual scour features. These included 1) object-oriented image analysis using ENVI, 2) using various edge-detection techniques like Sobel and Laplacian, and 3) a semi-automated hybrid method of deriving stream centerline features using Arc’s Hydrology Tools on the 2008 Lidar dataset and then tracing the feature boundaries by comparing the available data. Extracting the feature boundaries and performing object-oriented shape analysis is the goal of determining the feature boundaries.

1) The object-oriented image analysis was problematic due to the types of items (like debris, houses, and variations in vegetation tone) present on the ground, which confused the algorithm and gave spurious results. 2) Edge-detection techniques often yielded false edges of features for the same reasons above. 3) The semi-automated hybrid method achieved the most logical results in determining feature boundaries because it used automated techniques to determine where water would flow and user judgment in determining channel boundaries.

Arc’s Hydrology tools (Fill, Flow Direction, Flow Accumulation, Stream Definition, Stream Segmentation, and Stream to Feature) were used to automate the detection of the channel centerlines, which is the predicted path backflow followed.
Preprocessing was necessary to ready the data for hydrology modeling. The first step was to use the Fill tool to remove sinks in the data which would otherwise prevent water from flowing over the surface. The output surface is used as the input for the Flow Direction tool, which determines the steepest downhill direction leading out of every cell of a raster. Flow Accumulation requires a flow direction raster, and it tallies up the area contributing flow to any one cell. Stream Definition uses a threshold value to determine which areas have enough flow to be considered streams. The Stream Segmentation tool then assigns a value to streams as well as a different value for the background (non-streams); it outputs a raster containing a value of either 0 or 1. The last step is to convert the segmented stream raster into a polyline shapefile using Stream to Feature.

After the automated stream centerlines were produced, they were edited to remove spurious channels as well as artifacts from the processing techniques. A stream centerline was considered spurious if it was a geoprocessing artifact, for instance, some were straight lines with a 0 or 90 degree orientation and were not indicated in the aerial photos or apparent in the Lidar. Also removed were channels leading away from the shoreline. After the stream segments were finalized, they were considered “backbones” for the digitization of each scour feature into a polygon. The polygons represent the outlines of the features themselves, not the “watersheds” of each of the channels.

A slope map was used to delineate feature boundaries; it was calculated from the “nibbled” and “filled” Lidar dataset using ArcMap’s Slope Tool (3D Analyst > Surface Analysis > Slope). Contour lines were also used to help delineate feature boundaries;
they were made from the Lidar dataset using ArcMap’s Contour Tool (3D Analyst > Surface Analysis > Contour).

The feature boundaries were determined after comparing the data sources (the 2008 Lidar and aerial photos) as well as data products produced from the 2008 Lidar, such as 1) stream centerlines, 2) a slope map calculated from the 2008 Nibbled Lidar dataset, and 3) contour lines produced from the same dataset. Expert knowledge on scour features as well as first-hand observations of the features in the field were used as a way to understand the features; the feature boundaries were refined by consulting the different datasets. The process of determining feature boundaries is outlined in Figure 3.3.

To determine a feature boundary, one should alternately view the Lidar data and aerial photos with the stream centerlines overlaid, and then study the differences and similarities between the datasets. Figure 3.4 depicts an example of a digitized feature boundary. The stream centerline (blue line in Figure 3.4) represents the center of channelized flow, where the highest concentration of water is predicted to flow. The centerline helps to indicate where the feature is, though not the boundary of it. The slope map was often helpful in delineating the feature boundary, which could be seen as a break in slope between areas involved in channelized drainage and the interfluves (areas separating the channels). The contour lines were used alongside the slope map by overlaying them on the Lidar and aerial photos. Knowledge of contour lines (that where a stream crosses a contour, the “V” in the contour points upstream) was used to help verify the flow direction, while other bends in the contours indicated surface
Figure 3.3: Process of determining feature boundaries. 2008 Lidar and its products were consulted along with aerial photos to digitize features.
Figure 3.4: Data used in determining feature boundaries, (a) nibbled Lidar with feature boundaries, (b) slope map calculated from nibbled Lidar, and (c) aerial photo with feature boundaries.
characteristics, i.e., feature boundaries. In most cases, the feature boundaries were obvious in both datasets; however, in some cases, parts of boundaries were not clearly visible in one of the datasets. In those cases, the other dataset was used to delineate that part of the boundary.

Within the Lidar dataset alone, it is sometimes easy to see where the feature boundary is, but the Lidar products helped corroborate what the eye sees. The aerial photos, which were of a superior resolution (0.37 meters) to that of the Lidar (4.7 meters), were also used to determine and crosscheck the boundaries in the Lidar. However, the time difference between the different datasets means that some features were slightly changed, as the aerial photos were taken on either 14 or 18 September, and the Lidar was taken on 17 September. In cases where features had changed between the datasets, more weight was given to the earlier dataset, especially at the shoreline, where wave processes were actively changing the features. Most of the discrepancies were at or near the shoreline.

In many cases, the features extended past the backshore zone, so different cutoffs had to be used to limit feature extents. In the northeastern reach, Highway 87 was used as the landward extent of the features. In the central reach, where Highway 87 is far from the shore, a prominent back-barrier ditch was used as the cutoff. Whenever the features cross anthropogenic objects (like a highway or ditch) they are no longer strictly involved with active beach processes, and their flow pattern is consequently changed. The 2006 shoreline and geotube (more below) location were used as the general shoreward limit of the features. However, in the northeastern part of the northeastern
reach, it was common for features to extend past the 2006 shoreline, so there was no steadfast shoreward limit in that location. Rivers and canals were excluded from the study as they existed before the storm and were not caused by it. By digitizing the feature boundaries, a feature boundary shapefile containing all of the features was produced in ArcMap. This shapefile was used for further analysis of the features.

Object-Oriented Shape Analysis of Features

Using the algorithm and technique devised by Liu et al. (2008, in press), the features were analyzed in an object-oriented environment (a different software from ENVI’s object-oriented analysis software mentioned above) in order to derive shape, size, and other statistics: 1) area, 2) perimeter, 3) length, 4) width, 5) centroid point, 6) orientation, 7) compactness, 8) elongatedness, 9) asymmetry, 10) fractal dimension, 11) rectangularity, 12) ellipticity, and 13) triangularity. These terms are defined below. Liu et al.’s (2008, in press) algorithm 1) recognizes each feature as an individual object, 2) measures some of the channel’s attributes directly (e.g., area and perimeter), 3) fits a rectangle and ellipse to each channel, 4) then the rectangles and ellipses are used to compute more attributes (e.g., orientation and rectangularity).

Area is determined by counting the number of cells each object comprises and multiplying it by the grid cell size. Perimeter is determined by adding up the lengths of the boundary cell sides of each feature. Length is the length of the bounding rectangle, and 4) width is the width of the bounding rectangle. The centroid point is computed based upon averaging all the cell coordinates within a feature. Orientation is determined
based upon the direction of the major axis of the best-fit ellipse and is a value between 0 and 180 degrees. Compactness is based upon the formula: \(4\pi A/P^2\) (where \(A\) is area and \(P\) is perimeter) and measures how close an object is to the shape of a circle; higher numbers indicate a more compact form. Elongatedness is length/width, or the length of the bounding rectangle divided by the width of the bounding rectangle. Asymmetry is calculated by: \(1-(b/a)\), where \(a\) and \(b\) are the major and minor axes of the best-fit ellipse. Fractal dimension is a measure of how complex an object’s outline is, with more complex outlines having higher fractal dimensions. Rectangularity is how closely an object approximates the shape of a rectangle by dividing the area of the object by the area of the minimum bounding rectangle. Ellipticity and triangularity are also measures of how closely an object approximates the shape of an ellipse or triangle.

In order to run Liu et al.’s (2008, in press) software, a couple of pre-processing steps are necessary. In order to improve computation times, the study area was divided into seven zones for analysis. Second, the object-oriented software requires a 16 bit unsigned integer raster in Imagine format, so seven of those were produced, one for each zone. Creating those feature boundary rasters was a challenge because of bugs in ESRI’s software as well as several steps which had to be improvised. These steps were: 1) creating an 8 bit signed integer raster in GRID format from the feature boundary shapefile using Feature to Raster in Arc; 2) using the Reclass tool to assign feature values to 1 and the background to 0; and 3) the reclassed raster was then converted to a 16 bit unsigned integer raster in Imagine format using Copy Raster, outputting a usable feature boundary raster.
The feature boundary rasters were then inputs for the object-oriented software, which produced 1) object rasters of each object (each feature has a separate raster value), 2) minimum bounding rectangles, 3) minimum bounding ellipses, and 4) a table of attributes. The object rasters were used to identify each feature, and were joined to the attribute table produced in analysis. The minimum bounding rectangles and ellipses were useful for checking the analysis, as they are used to derive statistics like orientation, length, width, rectangularity, and ellipticity.

Cluster Analysis

In the previous section, object-oriented shape analysis produced a sizable dataset containing statistics for all the scour features. These statistics were analyzed in order to group similar features. It is natural for humans to group objects, as it is part of the learning process and helps humans to better understand the world. While humans can readily classify features together within 3 dimensions, more dimensions than that give us problems (Kaufman and Rousseeuw, 2005). A host of automated classification procedures has been developed to address the need to group large datasets with many dimensions, and the creation of such procedures has become an independent scientific discipline with a full-fledged periodical (the Journal of Classification).

Several automatic grouping procedures were explored for this project, but cluster analysis with Ward’s clustering method proved to be the best at grouping features that visually resembled one another. Also explored were Principal Component Analysis (PCA) and factor analysis, though those results were not as reliable at grouping visibly-
similar features. The goal of cluster analysis is to take a group of objects (hurricane features) and group them based on their attributes so that features within a group are more similar, and features outside of that group are as dissimilar as possible from features within the group. It is important to note that the groupings are by no means simple, and there is a great deal of variety within each group.

Ward’s clustering method is minimum-distance and hierarchical; it calculates the sum of squared Euclidean distances from each cluster and groups clusters which increase the sum of the squared Euclidean distance the least. Hierarchical clustering uses a sequence of nested partitions, and in this case starts with all cases in one group and creates groups within the cases (Xu and Wunsch, 2009). The distance is considered in multi-dimensional space.

Ward’s method considers cluster analysis as an analysis of variance. It uses an agglomerative clustering algorithm, whereby it starts out at the “leaves” (each hurricane scour feature) of a tree and works its way into the “trunk” (all features) to produce the groupings. It starts with every feature being in a separate group, and groups them sequentially until there is the specified number of groups remaining (in this case 5). It looks for groups of leaves to form branches, and groups of branches to form limbs, then limbs that will form the trunk (Xu and Wunsch, 2009).

Ward’s starts with n clusters each of size 1. The first step makes n-1 clusters, then the error sum of squares and \( r^2 \) values are computed. The pair of samples which yield the smallest error sum of squares or largest \( r^2 \) value will be the first cluster. The algorithm then recursively progresses, forming n-2 clusters with minimized error and
maximized $r^2$ values. The algorithm stops when all samples are in a cluster of size $n$ (Zupan, 1982).

The algorithm started with 454 features in 454 clusters. It calculated the distance (amount of dissimilarity) between each feature and then grouped the closest two into a single cluster. It then recalculated the distance between the remaining groups and grouped the next closest two. It did this over and over again until the desired number of clusters remains.

**Analysis of Features per Kilometer of Shoreline**

When producing the feature distribution figures (Figures 4.10-4.15), the coastline is considered in 41 kilometer-long divisions. However, there are only 38 km of coastline. The reason for this is computational. Liu et al.’s (2008, in press) software determined the centroid of each feature, so the distance from one centroid to the next was calculated and then added up along the extent of the study area. Every time a km of distance was accumulated, the features adding up to that km were placed in a discrete division. Because the centroids are not directly along the shoreline, but rather at varying distances from the shoreline, the total distance is longer. The results of this method are easily reproducible because the *object-oriented software* produced the centroids automatically, and no further GIS work was required to divide the features.
CHAPTER IV

RESULTS

Cluster analysis grouped the 454 features into 5 cluster groupings. When more than 5 groups were produced, similarly-shaped features would be assigned to different groups, while fewer groups produced resulted in many dissimilar features occupying a group. The groupings are based upon shape and size characteristics only and not upon any formative characteristics. Some statistics created by Liu et al.’s (2008) object-oriented program were derived from other statistics. For instance, rectangularity was calculated from the minimum bounding rectangle, which was calculated from the length and width. Whenever rectangularity and length and width were included in analysis, the clusters were strongly influenced by size. Rectangularity and other statistics can serve as proxies for the statistics which were stricken from analysis. Some statistics, like centroid point and asymmetry, did not seem like meaningful statistics to analyze and were therefore not included. Ellipticity was eliminated because it had a nearly perfect correlation with rectangularity. The variables which were used in the cluster analysis were 1) area, 2) perimeter, 3) orientation, 4) compactness, 5) elongatedness, 6) fractal dimension, 7) rectangularity, and 8) triangularity. The following statistics were omitted from analysis though they had been produced by the object-oriented shape analysis program: 1) length, 2) width, 3) centroid point, 4) asymmetry, and 5) ellipticity. The cluster analysis dendrogram can be viewed in Figure 4.1. As is visible in the dendrogram, there are levels of difference between the groups. The higher the group is
Figure 4.1: Dendrogram produced using Ward’s clustering method and squared Euclidean as the distance. Distance measures dissimilarity between groups. Arrows point to breaks between groups of features; each group is labeled with the number of features within each group.
branched, the more dissimilarity is within that group. Within some groups, it is easy to see that there are sizable subgroups. For instance, Group 2 has a large subgroup which is larger than Group 4 altogether.

**Size and Shape Characteristics**

The features within the study area have a wide variety of size and shape characteristics. Some features are small and round, some are branching and resemble small streams, some are wide and resemble piano keys, some are long and thin, and some are ovular. Several figures were produced in order to graphically summarize the differences between the groups. Figure 4.2 displays the average and standard deviation planimetric attributes of the different groups of features. Figure 4.3 displays the average and standard deviation shape attributes of the different groups of features. Figure 4.4 displays the coefficient of variation \( \text{coeff var} = \frac{\text{standard deviation}}{\text{average}} \); this is useful for understanding how the variation within a group compares to the variation between the other groups. Table 4.1 contains the summary statistics on all the groups of features.

**Group 1**

Group 1 contains 63 features, which tend to be small and compact. These features have an average area of 747 meters\(^2\) and an average perimeter of 142 meters. However, the standard deviation of the area is 614 meters\(^2\), giving the features a coefficient of variation of 0.82; thus, there is a great variability in the size of the features. The features have an average compactness of 0.44, which is the highest of any of the
Figure 4.2: Average and standard deviation of area, perimeter, and orientation provided for each group.
Figure 4.3: Average and standard deviation of shape attributes per group.
Figure 4.4: Coefficient of variation for all statistics per group.
Table 4.1: Summary planimetric and shape statistics used in cluster analysis of features; (a) statistics by group, (b) total area of each group, (c) average, min, max, and standard deviation for all features.

(a)

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th></th>
<th></th>
<th>Group 2</th>
<th></th>
<th></th>
<th>Group 3</th>
<th></th>
<th></th>
<th>Group 4</th>
<th></th>
<th></th>
<th>Group 5</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>747</td>
<td>614</td>
<td>3754</td>
<td>3431</td>
<td>3124</td>
<td>2635</td>
<td>2468</td>
<td>1433</td>
<td>1227</td>
<td>910</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perimeter (m)</td>
<td>142</td>
<td>71</td>
<td>671</td>
<td>416</td>
<td>400</td>
<td>248</td>
<td>419</td>
<td>161</td>
<td>281</td>
<td>133</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orientation (deg)</td>
<td>85</td>
<td>53</td>
<td>109</td>
<td>51</td>
<td>109</td>
<td>45</td>
<td>150</td>
<td>19</td>
<td>149</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compactness</td>
<td>0.44</td>
<td>0.10</td>
<td>0.11</td>
<td>0.04</td>
<td>0.26</td>
<td>0.09</td>
<td>0.18</td>
<td>0.05</td>
<td>0.20</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongatedness</td>
<td>2.15</td>
<td>1.11</td>
<td>2.79</td>
<td>1.04</td>
<td>3.11</td>
<td>1.65</td>
<td>2.34</td>
<td>0.85</td>
<td>5.59</td>
<td>1.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fractal Dimension</td>
<td>1.09</td>
<td>0.06</td>
<td>1.22</td>
<td>0.05</td>
<td>1.14</td>
<td>0.05</td>
<td>1.17</td>
<td>0.05</td>
<td>1.20</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectangularity</td>
<td>0.69</td>
<td>0.06</td>
<td>0.33</td>
<td>0.08</td>
<td>0.63</td>
<td>0.07</td>
<td>0.48</td>
<td>0.08</td>
<td>0.59</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triangularity</td>
<td>0.82</td>
<td>0.08</td>
<td>0.27</td>
<td>0.13</td>
<td>0.83</td>
<td>0.12</td>
<td>0.56</td>
<td>0.18</td>
<td>0.76</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
<th>Group 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area (m²)</td>
<td>47060</td>
<td>457936</td>
<td>349840</td>
<td>133252</td>
<td>126336</td>
</tr>
</tbody>
</table>

(c)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Min</th>
<th>Max</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>2457</td>
<td>64</td>
<td>21793</td>
<td>2578</td>
</tr>
<tr>
<td>Perimeter</td>
<td>412</td>
<td>36</td>
<td>2656</td>
<td>318</td>
</tr>
<tr>
<td>Orientation</td>
<td>120</td>
<td>0</td>
<td>179</td>
<td>47</td>
</tr>
<tr>
<td>Compactness</td>
<td>0.22</td>
<td>0.04</td>
<td>0.65</td>
<td>0.12</td>
</tr>
<tr>
<td>Elongatedness</td>
<td>3.36</td>
<td>1.07</td>
<td>11.33</td>
<td>1.85</td>
</tr>
<tr>
<td>Fractal Dimension</td>
<td>1.17</td>
<td>1.00</td>
<td>1.43</td>
<td>0.07</td>
</tr>
<tr>
<td>Rectangularity</td>
<td>2.12</td>
<td>0.55</td>
<td>3.14</td>
<td>0.62</td>
</tr>
<tr>
<td>Triangularity</td>
<td>0.63</td>
<td>0.05</td>
<td>1.00</td>
<td>0.27</td>
</tr>
</tbody>
</table>
groupings, and they have an average elongatedness of 2.15, which is the least of all the
groups. They also have the lowest fractal dimension, which means they have the least
complex boundaries. The smallest feature by area is 64 meters$^2$, while the largest is 2653
meters$^2$. Group 1 features also have the highest average rectangularity value, 0.69, and
the second-highest average triangularity of 0.82. The average orientation of these
features (85 degrees) is much smaller than those of the other groups, though the standard
deviation of orientation is 53 degrees, the largest variability of orientation. However,
these features have the least amount of orientation overlap with the other groups. The
other four groups have two average orientations between them (Groups 2 and 3 have an
orientation of 109 degrees and Groups 4 and 5 have an orientation of ~150 degrees),
making Group 1’s orientation unique.

Figure 4.5 shows examples of Group 1 features, which are small and compact;
the blue line in the figure represents the shoreline, and the features have been cut and
pasted from their original locations for this visualization. The features tend to have
smooth, uncomplicated outlines and fit very well to rectangles. Figure 4.3 shows that the
compactness, rectangularity, and triangularity are all higher than that of any of the other
groups. In Figure 4.5, the top row shows smaller features. The ones on the top right are
small, round, and compact. The left 3 have higher elongatedness values than other Group
1 features. The bottom row features are considerably larger. The right two are boxy and
are close in appearance to some Group 3 features. Two of the features in the middle of
the bottom row somewhat resemble shark teeth, while the others have variable and
inscrutable shapes.
Figure 4.5: Group 1 feature shapes; note some features (bottom) have more complex shapes; blue line is shoreline.
**Group 2**

Group 2 contains 122 features (the largest number in any group), and they tend to have complex, branching, and spindly shapes with the greatest fractal dimension (1.22). They tend to be the largest features, with the highest average area and greatest perimeter, 3754 meters$^2$ and 671 meters, respectively. Figure 4.2 illustrates the size of these features relative to the other groups. There is great size variance to the features, as the standard deviation for area is 3431 meters$^2$, giving the features a coefficient of variation of 0.91, the largest between all the groups. They have the lowest average compactness, with a value of 0.11. They have an average elongatedness of 2.79, which is the median value of all average values of the groups of features. They tend to be the least rectangular, with a value of 0.33, and the least triangular, with a triangularity of 0.27. Their average orientation is 109 degrees, though the standard deviation is 51 degrees, this range of variation overlaps with all of the other groups’s averages.

Figure 4.6 shows examples of the different shapes and sizes of these features. The largest 2 features in the study area are in Group 2 (the two leftmost features on the bottom row of Figure 4.6). Group 2 features are often branching or very curvy. They all seem to have narrow outlets (seaward edges of features).

**Group 3**

Group 3 contains 112 features. These tend to be large and blocky or ovular, with an average area of 3124 meters$^2$ and an average perimeter of 400 meters. There is a great variability in the perimeter of these features as the standard deviation of that statistic is
Figure 4.6: Group 2 feature shape types.
248 meters, and the coefficient of variation is 0.62, the highest of all the groups. They have the second-highest average compactness, 0.26. Additionally, the features have the second-highest average elongatedness value, 3.11. These features also have the second-highest rectangularity value, 0.63. They have the highest triangularity value of 0.83, and an average orientation of 109 degrees. Based on the statistics, Group 3 could be said to be a “second best group”.

Figure 4.7 shows examples of Group 3 features. The features in the top row are round; some are longer, and some are more compact. The bottom row contains piano key features. Some are thicker while some are more elongate in a shore-parallel direction.

**Group 4**

Group 4 contains 54 features, the smallest number in any of the groups. These features tend to be mid-range in size. This group of features seems to be a catchall, with markedly variable shapes but with somehow similar statistics. The average area of group 4 features is 2468 meters$^2$, and the average perimeter is 419 meters. They have small area and perimeter standard deviations, 1433 meters$^2$ and 161 meters, respectively, as well as the smallest coefficients of variation for area and perimeter, 0.58 and 0.39, respectively—meaning these features tend be about the same size. These features have the second-lowest compactness score of 0.18. They tend not to be very elongated, as they have the second-lowest elongatedness value, that of 2.34. They tend to not be very rectangular or triangular, as they have values of 0.48 and 0.56, respectively, and both of those values are the second-lowest between the groups. They have an average orientation
Figure 4.7: Group 3 feature shape types.
of 150 degrees with the second-smallest standard deviation (19 degrees) between all the groups.

Figure 4.8 displays Group 4 features. The top row features are similar to piano key features Group 4 features tend to have multiple branches, though ones that do not branch tend to have a snake-like form.

**Group 5**

Group 5 contains 103 features. These are long, narrow, straight, and not very large. They have the second-smallest average size, 1227 meters$^2$, as well as the second-smallest average perimeter of 281 meters. They tend to not be very compact, with a compactness of 0.20, which is the median average value between the groups. However, with an average elongatedness of 5.59, they are the most elongated features in this study. The features have the second-highest fractal dimension value of 1.2, meaning they tend to have complex boundaries. They also have median average rectangularity and triangularity values of 0.59 and 0.76, respectively. The features have the lowest standard deviation value for orientation, 17 degrees, and an average orientation of 149 degrees.

See Figure 4.9 for examples of Group 5 features. The top row is composed of small, straight features. The bottom row features are larger and sometimes branch; they also have visibly rougher boundaries than features from other groups.
Figure 4.8: Group 4 feature shape types.
Figure 4.9: Group 5 feature shape types.
Distribution of Features

The ability of water to overwash and then flow back over Bolivar Peninsula was dependent upon factors like dune height, structures and landcover, peninsula width, and water level. As these factors varied along the study area, different patterns of feature formation were seen. The differing distribution patterns hint that certain conditions and processes were more active in some places than others. For example, in the northeastern reach, backflow occurred for around 19 hours, causing extensive beach sediment loss, while in the central reach, there was less backflow (~5.5 hours), less beach denudation, and more developed channelization. Additionally, the geotube allowed for a local increased rate of washover deposition in the flooding stage, and then in the backflow stage, geotube breaches caused channelization.

Group 1

Group 1 features are distributed unevenly within the study area, with more features in the west and fewer in the east (Figure 4.10); there are very few Group 1 features in the center. There are 12 Group 1 features in the eastern part of the study area, where they are mainly associated with “piano key” formations, and they represent a low percentage of the total number of features within each kilometer-long division (Figure 4.11 shows the distributions of all the features together), making up an average of ~11% of the features in each km-long division they inhabit. There is a gap from the 15 km-24 km divisions where there are no Group 1 features (see Figure 4.12, which is similar to Figure 4.11 except it only shows Group 1 features). However, at the 25 km division,
Figure 4.10: Shows distributions of the mean and standard deviation of feature centroids by group. Square indicates average location of centroid along the study area, and line is one standard deviation in length from average centroid. Also provided are kurtosis and skewness values for each group.
Figure 4.11: Feature distributions for all groups by km-long division
Figure 4.12: Group 1 feature distribution by km-long division.
Group 1 features reappear, and in several of the western km-long divisions, Group 1 features outnumber all other features combined. Group 1 features make up an average of ~39% of the features when present between divisions 25 and 39.

**Group 2**

Group 2 features are more numerous in the center of the study area and less so at the edges (Figure 4.10); however, they appear in all but 7 of the km-long divisions. Figure 4.13 shows the distribution of Group 2 features. They make up about 9% of the features in the kilometer divisions 0-7 when present. There are two large concentrations of features in the middle, the first is in divisions 8-18, where Group 2 constitutes approximately 41% of the features, and then the second concentration is in divisions 20-33, with approximately 43% of the features. The bimodal distribution of Group 2 has high spots in the middle of their respective blocks, and then a tapering off to the edges and a blank kilometer division in between. Group 2 features make up ~14% of the features in divisions 37-40 and thus are dwarfed there by Group 1 features.

**Group 3**

Group 3 features are distributed mainly in 3 groups with several gaps: divisions 10-13, 15-16, and 23-25 are devoid of features (Figure 4.14). The main concentrations of features include a strong and rather narrow concentration in the east, a narrow (6 km long) concentration in the middle, and a wide concentration in the west (15 km long). There is one feature in division 14. In the easternmost block, Group 3 features are the
Figure 4.13: Group 2 feature distribution by km-long division.
Figure 4.14: Group 3 feature distribution by km-long division.
most dominant when compared to the other groups as they comprise ~38% of the features in divisions 0-9 (Figure 4.11). In the middle concentration, they are slightly less dominant, comprising ~35% of the features between divisions 17 and 22, and ~29% in the westernmost block (divisions 26-40). Their standard deviation is large compared to the other groups, and they are centered about 3 km west of Rollover Pass.

**Group 4**

Features in Group 4 are more commonly distributed in the northeastern reach of the study area (divisions 0-23) and less so in the west, where only one appears in any km-long division (Figures 4.10, 4.11, and 4.15). Their centroid in Figure 4.10 is the most easterly of all the groups, with a low standard deviation for dispersion, thus are closely spaced. From Figure 4.11: in the wide-spanning concentration from divisions 0-23, there are several gaps at divisions 8, 10, 14, 16, and 22. In divisions 0-23, Group 4 features comprise ~20% of the features in the divisions in which they are present. The western portion of the study area (divisions 24-40) has just 5 of the Group 4 features, and those are essentially scattered randomly at divisions 27, 29, 30, 34, and 36. In those divisions, Group 4 features are less numerous than other groups, as they comprise only 13% of the features in the divisions in which they are present.

**Group 5**

Group 5 features have their highest concentrations in the eastern portion (divisions 0-20), where they comprise ~31% of the features in the divisions in which
Figure 4.15: Group 4 feature distribution by km-long division.
they are present. Figure 4.10 shows that Group 5’s centroid is far east, and it has a standard deviation similar to Group 4. See Figures 4.11 and 4.16 for the distribution patterns of Group 4 features. There is a gap with no Group 5 features at division 3, which is dominated by a small number (4) of large features from Group 3 and one feature from Group 4. The rest of the western divisions (23-39) are peppered with Group 5 features, though Group 5 features dominate division 34 as they comprise ~43% of the features in that division. Within divisions 23-39, Group 5 features comprise 16% of the features in the divisions in which they are present.
Figure: 4.16: Group 5 feature distribution by km-long division.
CHAPTER V

SUMMARY AND CONCLUSIONS

In this chapter, a discussion is made about the different flow environments on Bolivar Peninsula and the differences between group morphologies as well as the likely reasons for those differences. The distributions, shapes, and sizes of the groups of features are iterated, as well as a discussion of the limitations of cluster analysis is also covered. Issues experienced when digitizing the features are discussed, as well as backflow erosion. Finally, the summary and conclusions of this research are given.

Flow Environments

Several flow environments can be seen on Bolivar Peninsula. The processes and conditions differed between the flow environments, and these differences led to characteristic forms produced within each flow environment. The first flow environment (piano key section) occurs in the northeast from km division 0 through 7, which is low and backed by Hwy 87; there is no bay landward of this area. This area likely experienced flow separation and a hydraulic jump during the backflow stage as water was flowing seaward, crossing Hwy 87 onto the beach, with sediments being nearly completely eroded. Groups 3 and 4 are greatly produced in this flow environment. The second flow environment was fronted by the geotube, from km division 8 through 17. This is a narrow and low part of the peninsula; it was one of the most developed areas of Bolivar Peninsula (though most of the pre-existing homes were felled by the storm). In
this area, breaches channelized flow through the geotube, leading to characteristic scour forms seen in Groups 2 and 5. The third flow environment is from km division 23 through 26; it is marked by large dendritic channels. This area has a high elevation, with cross-shore oriented roads and houses near the beach. The large dendritic channels formed at some of the roads as well as houses; this flow environment is best represented by Group 2 features. The fourth sub-environment is from km division 26 through 40; this area is mostly low, with wide beaches backed by a vegetated dune. There were shore-parallel troughs between eroded dune and the vegetation line (Groups 3 and 4) as well as small pools formed on the beach (Group 1).

**Group 1**

Table 5.1 contains summarized shape and size qualities about all the groups of features. The distribution of Group 1 features over the study area can be seen in Figure 5.1. There are some features concentrated in the northeast, a lone one at km division 14, and a bloc of them in the southwest. Most of Group 1 features occur in the southwest reach of the study area, which is sparsely populated, has low-lying vegetation, and has a wide, shallow beach.

The first group of features (Figure 5.1) is in the northeast part of the study area, within km divisions 0-9. Appendix A depicts the features in detail. In this area, piano key features are quite common; the Group 1 features occurring here are likely formed in the same fashion: water draining back after the surge stripped off most of the beach,
Table 5.1: Summary table of shape and size qualities by group.

<table>
<thead>
<tr>
<th>Group #</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Small, compact</td>
</tr>
<tr>
<td>2</td>
<td>Large, dendritic</td>
</tr>
<tr>
<td>3</td>
<td>Longshore orientation, piano key or trough shaped</td>
</tr>
<tr>
<td>4</td>
<td>Ornate, piano key shaped or small and dendritic</td>
</tr>
<tr>
<td>5</td>
<td>Cross-shore orientation, elongated, non branching</td>
</tr>
</tbody>
</table>
Figure 5.1: Group 1 feature concentration: vertical bars represent number of features per km division.
leaving small shore-perpendicular bars and other formations. The Group 1 features here are just small piano key features.

Before the storm, a large dune was present in both the central and southwest reaches of the study area. However, the dune was at a variable distance from the coast: in the southwest reach, the dune was at a distance of 2.2 km from the shoreline, and in the central reach, it terminates into the coastline. The geotube ran from the termination of the dune to the northeast, on the other side of Rollover Pass. A narrow beach backed by a large dune or a geotube seems to inhibit Group 1 feature formation. A single Group 1 feature appears in the central part of the study area, at km division 14. There are also several Group 1 features at km division 9; these formed where houses once stood, and in the aerial photos (Appendix A), pilings can be seen.

Group 1 features are most numerous in the southwest, starting at km division 25 and then going through division 39. There is a small concentration of Group 1 features between km divisions 25-28. At this small area (Figure 5.2), the beach is slightly wider, likely giving more favorable conditions for Group 1 feature formation. The rest of the features in the south, from divisions 30-39, occur where the foreshore is wide and low. These features are typically small pools which formed where a low sand dune was nearly completely obliterated during a storm. Likely, backflowing water cut scoured out the features due to local perturbations in water flow. A narrow beach backed by a large dune or a geotube thus seems to limit Group 1 feature formation.
Figure 5.2: Group 1 features are more common at this wide beach. Vertical bars represent number of features per km division.
Group 2

Group 2 features formed mainly around Crystal Beach and Gilchrist. Figure 5.3 displays their distribution throughout the study area. Group 2 features appear to be associated with narrow parts of the peninsula as well as urbanized areas. The features are also associated with a narrow beach backed by a dune or geotube. In the northeast reach, where there was no geotube, the features are rare. In this area, they are related to piano key features.

The features are numerous in km divisions 8-16, backed by the geotube. This area is also where the peninsula is narrow. In this area, the features were carved in washover deposits leftover from the storm surge stage. The two right-most features on the top row of Figure 4.6 are caused by breaks in the geotube. In these cases, water flowed along the geotube to a breach and exited. The linear edges at the landward extent of some of the features are due to Highway 87, which survived the storm with minimal damage.

The features are not common in km divisions 17-21, where Bolivar Peninsula is wide. There are no features in the km-long division number 19, which is the widest part of Bolivar Peninsula; additionally, no homes were in this division, and the only objects on the ground were low-lying vegetation and oil installations. The features are common around the populated Crystal Beach, where there was a large dune abutting the shore, causing higher elevations, and the peninsula is narrow. The features are uncommon in the southwest; however, in several divisions, like 37 and 38 (Appendix A), the features formed in small washover deposits. The bodies of water behind these two divisions
Figure 5.3: Group 2 feature concentration: vertical bars represent number of features per km division.
likely decreased the flow velocity during the surge stage, allowing for an enhanced rate of sedimentation. This extra sediment provided a substrate into which the features could form during the backflow stage.

The features are more common in narrow parts of the peninsula, where water could quickly and freely flow back over the land when the storm surge receded. Additionally, Group 2 features are rare in lower elevations. The features displaced many homes in Crystal Beach, undermining foundations and often completely removing all evidence of preexisting buildings. These features are also commonly associated with roads leading up to the beach. The flow likely was channelized in the road and thus was able to cut it down to form a feature.

**Group 3**

Group 3 features are at the highest frequency in the northeastern part of the study area, where there is no geotube, the peninsula is widest, and there is no bay behind the barrier (Figure 5.4). They also occur where the peninsula is wide in the center of the study area and the southwest portion. There are few of these features around Rollover Pass, where the peninsula is narrowest, and also few around Crystal Beach, where the peninsula is narrow. However, there are a few of these features in the mostly unpopulated southwest. The features are most commonly associated with a wide, low-lying peninsula, and with less urbanization.

The erosive power of the long-running backflowing currents at the piano key section (divisions 0-7) were likely amplified by the road, which may have caused a flow
Figure 5.4: Group 3 feature concentration: vertical bars represent number of features per km division.
separation transverse to flow. Here, the road probably acted as a weir. This allowed the water to denude the beach (during the \(~17\) hours of backflow in this area) by forming a hydraulic jump and strong gradient in transport, leaving only small mounds of littoral material, which form the barriers between the separate features. There are very few of these features over the extent of the geotube, as the geotube was more likely to produce channelized flow through its breaches.

There is a concentration of these features from divisions 17-22, where there was no geotube, and the peninsula is wide. In this area, they tend to be small and confined to the beach (whereas Group 2 features tend to extend past the beach). There is also a concentration in the southwest. Here, the features are shore-parallel troughs which formed just behind a preexisting sand dune. Likely, water was flowing back across the peninsula, which was mostly vegetated (see Appendix A); when the water came off the vegetation onto the sand, a flow separation would have formed and formed these shore-parallel formations. Additionally, the water coming off the vegetation would not have been carrying much sediment, so when it reached the beach, its transport potential would have been very great, thus eroding the beach.

As they are wide, shore-parallel features more likely formed by even overland flow instead of channelized flow, they are more common in low and wide parts of the peninsula. They are common in low-lying non-urbanized areas because there are no features on the ground to disrupt sheet flow and cause channelization.
Group 4

Group 4 features occur mostly in the northeast and central reaches (Figure 5.5). In the northeast, they appear as piano key features (most of which were grouped in Group 3). Further to the west, the features occur alongside Group 2 features and resemble those features in that area. When formed in the piano key section, Group 4 features have very complex, delicate shapes, indicating a difference in their formation from the formation of other piano key features. They also tend to be more shore-perpendicular and smaller than Group 3 piano key features. Figure 5.6 shows the three km divisions where Group 4 features are the most numerous. In this area, the beach is wider, with a narrow pre-storm back dune seaward of Hwy 87. This hints that these features are more likely to form on a wider beach backed by a road and a low pre-storm dune.

At Rollover Pass, where Group 4 features are more common in a stretch about 3 km long, the features are smaller than Group 2 features but are likely related in their formative processes. Figure 5.7 shows this area. The features here are typically shorter than the Group 2 features, with the Group 2 features starting at the road. At divisions 21 and 23 (see Appendix), the features are boxier or more angular than the other features present.

Group 2 features form a small transitional group, as these features are too dissimilar (based on cluster analysis results) to be classified in other groups. From Figure 4.3, Group 4 features have a low coefficient of variation for most of the statistics
Figure 5.5: Group 4 feature concentration: vertical bars represent number of features per km division.
Figure 5.6: Group 4 features are more common at this wide beach. Vertical bars represent number of features per km division.
considered. This means they share many form attributes in common, but that does not mean they necessarily are related formationally.

**Group 5**

Group 5 features occur mostly in the eastern part of the study area (Figure 5.8). There is also a small concentration around Crystal Beach. They seem to be more common in narrow and populated parts of the peninsula. Group 5 features are typically simple, elongated channels. In the northeast reach of the study area, at divisions 1 and 2, there is a concentration of Group 5 features. Highway 87 is further from the shore than it is in divisions 3-7 (where Group 5 features are not numerous), and there is a layer (revealed to be coarse shell by a ground examination) at the seaward side of the road visible in the satellite imagery (see Appendix A). This layer seems to have channelized flow which cut Group 5 features. The resistant layer and the distance of the road to the beach seem to have limited the ability for piano key features to form.

Along the length of the geotube, many Group 5 features formed alongside Group 2 features. The Group 5 features differ from Group 2 features by being less complex, typically a single straight channel. The Group 2 features also commonly extend from the road. They differ from Group 4 features in this area by being larger and simpler. The features in this area seem to have formed over at least 2 stages: 1) the storm surge overwashed the geotube and deposited large amounts of sediment. 2) The storm surge then drained back through the washover deposits, cutting channels as it went. Resulting breaches in the geotube are apparent in the aerial photos in Appendix A. It is unknown
Figure 5.8: Group 5 feature concentration: vertical bars represent number of features per km division.
whether these breaches in the geotube occurred during the overwash stage, backflow stage, or both. Around divisions 9 and 10 in Appendix A, the carpet which served as the foundation for the geotube can be seen oriented with offshore flow, though this would likely occur despite what stage the geotube was breached.

Group 5 features seem to be weakly correlated with the width of the peninsula, being more common around narrow parts of the peninsula. At Crystal Beach, there is a small concentration of features. They are possibly positively correlated with the level of urbanization; however, the eastern part of the study area is virtually unpopulated, and that is where the highest concentration of Group 5 features (in division 2) occurs.

**Cluster Analysis**

When selecting the number of groups used in cluster analysis, it became apparent that, to the eye, there are more than 5 types of shapes. Clustering with the statistics produced by Liu et al.’s (2008) algorithm did not produce unambiguous cluster groups, and when the dendrogram (Figure 4.1) is viewed, it is apparent that some groups have large subgroups within them. The higher up the highest branch is made, the more dissimilar the features are within that group. For instance, Group 4 has the lowest top branch as well as many of the lowest measures of dissimilarity (coefficient of variation: Figure 4.4). Because of the dendritic nature of the dendrogram, it is difficult to quantify how many subgroups are within each group, as a subgroup cutoff would need to be defined at a vertical distance on the y scale. However, groups 1, 2, 3, and 5 all have at least two subgroups above a distance of 800 (unknown units).
It may be concluded that different shape statistics are needed to adequately group the features to the satisfaction of the eye, or another clustering method produced in the future might help delineate the groups better. However, there is no ideal measure to describe shapes and no perfect way of clustering. The other statistics produced by the software (for example, ellipticity and asymmetry) but not used in analysis were so closely correlated with the ones used in cluster analysis that they were unusable for cluster analysis as they only caused greater weighting of certain measures by acting as proxies for those measures. For example, rectangularity and ellipticity correlated too highly to consider them unique descriptive statistics; they have an $r^2$ value that rounds to 1.

Another aspect to consider is that grouping the features by shape and size characteristics does not take into account formative processes. It would then be possible for two features to be grouped together based on shape and size characteristics though they were formed by different processes or grouped differently even though they were formed by the same processes.

**Issues in Digitizing Features**

There were problems when delineating the features, especially in the piano-key section. One problem was when to decide if two adjacent features were one or more than one separate features as the separation between any two was sometimes indefinite. The various data sources were consulted when delineating the boundaries, and a best-guess was made on the boundary. Additionally, the object-oriented software was sensitive to
the way the feature boundaries were delineated because fractal dimension was one of the attributes used in analysis. Therefore, if a feature was more generalized than specific (as in had fewer vertices in the shapefile), it would have affected the cluster analysis results. Great care was taken to ensure all features were of the same level of generalization, though errors may have occurred. In some cases, features changed between the datasets as the bulk of aerial photos were taken several days before the Lidar while the rest of the aerial photos were taken after the Lidar. This was the case in the Piano Key section where a shore-parallel sand bar formed at the shoreline. In these instances, more weight was given to the earlier dataset.

**Backflow Erosion**

Even the slowest calculated velocities for the backflow stage would have been sufficient to entrain beach sediment. Additionally, the water flowing over the peninsula would not have encountered any sizable sediment sources until reaching the beach, and therefore was able to denude the beaches on Bolivar more effectively than if the backflow was heavily sediment-laden. The reason why the northeastern reach of the study area was so much more heavily denuded than the rest of the peninsula is due to the fact that for around 19 hours, there was offshore flow of a sufficient speed to entrain and move sediment. The central and southwest reaches would have experienced offshore flow for around 5-6 hours of a lower predicted velocity than the northeast reach, thus they are not as heavily denuded as the northeast reach.
Conclusions

Analysis of post-Hurricane Ike aerial photography and Lidar data revealed the development of scour and backflow features in the beach and dune environments along Bolivar Peninsula, Texas. The forms and distributions of these features vary widely within the study area. Using Ward’s cluster analysis, 454 features were grouped according to shape and size characteristics generated with an object-oriented shape analysis program. Five distinct groups of features emerged from the cluster analysis. Group 1 features tended to be small and compact; Group 2 features were very large and typically dendritic in nature. Group 3 features had a longshore orientation, and many of them resembled piano keys. Group 4 features were ornate and were sometimes piano key shaped; many of them were similar in shape to Group 2 or 3 features though statistically different enough to be grouped alone. Group 5 features tended to be very elongated, oriented cross-shore, and mostly non-branching.

As the scour features have a wide variety of shapes and distributions, the processes which formed them likely varied as well. At least 4 distinct flow environments have been identified along the peninsula, corresponding to characteristic forms of scour features. The first flow environment involved a hydraulic jump and flow separation caused by water flowing transverse to Hwy 87 and denuding the beach with characteristic forms like Groups 3 and 4. The second flow environment was due to the geotube, which was breached during the storm and caused characteristic scour patterns in Groups 2 and 5. The third flow environment combined comparatively high elevation with cross-shore oriented roads and houses and is typified by Group 2 features. The
fourth flow environment occurred on wide beaches, where the foredune was eroded, leaving flat vegetation behind the old dune. Backflowing water coming off the vegetation onto the beach scoured many shore-parallel troughs in this flow environment with characteristic forms from Groups 1, 3, and 4.

The objective of identifying scour features caused by Hurricane Ike was successful. However, since the data sources used (the 2008 Lidar and aerial photographs) to identify them were temporally separated by a few days, and even the earliest data (aerial photographs taken one day after the storm) allowed for some post-storm recovery, the boundaries of the fresh scour features produced by the storm and storm backflow cannot be known exactly, as the features began changing as soon as they were formed. Additionally, the resolution of the Lidar and clarity of some parts of the aerial photographs were not always high enough to pinpoint the locations of the boundaries. Due to this, the edges of the scour features are generally correct approximations. The objective of categorizing the features using statistical methods was successful. However, new ways of quantifying and categorizing shapes must be invented to achieve a more reliable clustering of features. Researchers involved in studies of shape analysis have been unsuccessful at developing methods which can classify shapes to the satisfaction of the human eye; humans can better categorize and classify shapes than even the most advanced techniques to date. The objective of examining the patterns of size, shape, and distribution of the features was successful. The patterns seen are generally explainable and logical based upon the environments in which the features formed and the predicted backflow patterns after the storm. The northeast reach had
around 19 hours of backflow capable of entraining sediment, which removed nearly all of the sand on the beaches in the piano key section down to the resistant mud layer. Overwash was deposited behind the geotube, which was breached during and/or after the storm, and then backflow was channelized through the geotube breaches and overwash, resulting in characteristic scour forms. In the central reach of the study area, where backflow was around 5-6 hours long, large dendritic channels were able to form in the backbeach area and extend down to the shoreline. Average elevation of the pre-storm dune was higher in the central reach than in the northeast, and the dune was close to the shoreline; water flowing seaward over the dune was channelized and formed characteristic scour shapes. The southwest reach had offshore flow for about 5-6 hours which created troughs seaward of the surviving vegetation and landward of the pre-existing beach dunes.

It was observed by Nichols and Marston (1939) that the changes caused by the hurricane of September 21, 1938 (Great Hurricane of 1938) would be likely erased within a few years (qtd. in Wolman and Miller, 1960). This is because beach systems are dynamic and forever changing. However, through restoration works like dredging and groin emplacement, the damage has healed (Nersessian, 1993). If the basic proposition that a constant set of processes results in a characteristic landform, Bolivar will return it to its previous state as equilibrium is reestablished, though this new equilibrium state could be further landward if transgression takes place (Brunsden and Thornes, 1979). Intense changes (natural and anthropogenic) have been made to the Bolivar coastal zone since the storm. In early 2010, most of the scour features had been completely reworked.
by shore processes, obliterated by machinery, or were covered with too much vegetation
to be easily recognizable. The beaches have been nourished in the central and
southwestern reaches of the study area, a barricade has been installed on the seaward
side of Hwy 87 in the northeastern reach, much of the rubble has been cleaned up
(including the defunct geotube), and new houses are in various states of completion. “Let
the hurricane tear up its thousand huge fragments; yet what will that tell against the
accumulated labour of myriads of architects at work night and day, month after month?”
(Darwin, 1839, 548).
REFERENCES


Darwin, C. 1839. Journal and Reasearches 1832-1836. In *Narrative of the surveying voyages of His Majesty’s Ships Adventure and Beagle, Between the years 1826 and 1836, Volume 3*. London.


NOAA. 2006. Lidar Metadata File.


APPENDIX A

The study area was broken into 41 km-long divisions (0-41) for ease of reference. Each km-long division has three panes showing a) the post-storm aerial photos, b) the post-storm Lidar, and c) the scour feature shapes classified by group. The shoreline (pink) is shown in panes a and b, and the numbered km-long divisions are shown in pane c.
Appendix A, Division 0: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline
- Features Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 1: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 2: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 3: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5
Appendix A, Division 4: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 5: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 6: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 7: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 8: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 9: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 10: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline
- Features

Group
1
2
3
4
5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 11: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features Group
1
2
3
4
5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 12: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  1
  2
  3
  4
  5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 13: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5
Appendix A, Division 14: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 15: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
Group
1
2
3
4
5
Appendix A, Division 16: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 17: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 18: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84: USGS/NOAA
Appendix A, Division 19: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5
Appendix A, Division 20: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline
- Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84, USGS, NOAA
Appendix A, Division 21: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
Geotube
2006 Shoreline

Features
Group
1
2
3
4
5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 22: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group:
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 23: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 24: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 25: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 26: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 27: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 28: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- **Geotube**
- 2006 Shoreline

Features
- **Group**
  - 1
  - 2
  - 3
  - 4
  - 5
Appendix A, Division 29: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend

- Geotube
- 2006 Shoreline

Features

- Group
  - 1
  - 2
  - 3
  - 4
  - 5
Appendix A, Division 30: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84; USGS; NOAA
Appendix A, Division 31: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- **Geotube**
- 2006 Shoreline

| Features |
|----------|----------|
| Group    |          |
| 1        |          |
| 2        |          |
| 3        |          |
| 4        |          |
| 5        |          |

UTM Zone 15N WGS 84; USGS; NOAA
Appendix A, Division 32: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline
- Features
  - Group 1
  - Group 2
  - Group 3
  - Group 4
  - Group 5

UTM Zone 15N WGS 84; USGS, NOAA
Appendix A, Division 33: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 34: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 35: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend

- Geotube
- 2006 Shoreline

Features

- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
Appendix A, Division 36: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
Geotube
2006 Shoreline
Features
Group
1
2
3
4
5
Appendix A, Division 37: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 38: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.
Appendix A, Division 39: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline
- Features
  - Group:
    - 1
    - 2
    - 3
    - 4
    - 5
Appendix A, Division 40: Post-Ike (a) aerial photos, (b) Lidar, and (c) scour feature shapes classified by group, km-long divisions numbered and represented by thick alternating lines.

Legend
- Geotube
- 2006 Shoreline

Features
- Group
  - 1
  - 2
  - 3
  - 4
  - 5

UTM Zone 15N WGS 84; USGS, NOAA
APPENDIX B

Python Code Used on 2006 Lidar to *Float Grid* and *Project*.

```python
# FloatToRaster_sample.py
# Description:
#   Converts a file of binary floating point values
#   representing raster data to a raster. Also projects the data.
# Requirements: None
# Author: MKP
# Date: 7 December 2008

# Import system modules
import arcgisscripting, glob, os

# Create the Geoprocessor object
gp = arcgisscripting.create()

dircomp = "tx2m"    ### Must be changed each run, and is part of the specific folder
                    ### name for each
                    ### group of lidar data

dir = "C:/ike_thesis/2006_lidar/" + dircomp + "/"
flt_dir = "C:/ike_thesis/2006_lidar/" + dircomp + "/float/"

## Directories need to be changed for each state, and a float folder needs to be added
## manually
## to each directory

# Get the full path for all files with extension '.flt' in directory
# After running this line, inlist will contain the full paths for all such files
# for example, "c:/data/rhode island/001_001.flt"
inlist = glob.glob(dir + "*.flt")

# Process all the .flt files found in the directory
for pathname in inlist:
    # Separate the filename (eg. 001_001.flt) from the full path (eg. c:/data/001_001.flt)
    (filepath, filename) = os.path.split(pathname)
    
    # Get the file name without the extension. If the variable 'filename' contained
    "001_001.flt"
```

# then after running the following line, 'shortname' will be "001_001" and 'extension'
will be ".flt"

(shortname, extension) = os.path.splitext(filename)

# Set the variable item = shortname

item = shortname
print dircomp + item + ".flt" + " is being processed..."
try:
    # Set local variables
    InFloatFile = dir + item + ".flt"
    OutRaster = flt_dir + dircomp + item

    # Process: FloatToRaster_conversion
    gp.FloatToRaster_conversion(InFloatFile, OutRaster)
    print dircomp + item + ".flt" + " is finished."

except:
    # Print error message if an error occurs
    print gp.GetMessages()

gp.workspace = flt_dir
gp.toolbox = "management"
coordsys = "Coordinate Systems/Projected Coordinate Systems/Utm/Nad 1983/NAD1983 UTM Zone 15N.prj"
##Coordinate system must be verified, especially about the zones as they change between states...
    gp.defineprojection(flt_dir + dircomp + item, coordsys)

    print dircomp + item + " is now processed and projected."
print dircomp + " float and projection are complete."
Appendix C, Map 1: Change detection calculated by subtracting pre-storm Lidar from post-storm Lidar. Note the depositional areas (black) landward of the beach. The beach was the site of extensive erosion (light grey) along the entire coast. The area of no change (medium grey) corresponds to the elevation difference between -0.2 and 0.2.
Appendix C, Map 2: Change detection calculated by subtracting pre-storm Lidar from post-storm Lidar. Scour feature shapes (colored) are overlayed onto change detection map, light grey is erosion, medium grey is no change, and deposition is black. Note differences in feature and erosion/deposition patterns between beach backed by geotube and not.
Appendix C, Map 3: Change detection (2006-2008) calculated by subtracting pre-storm Lidar from post-storm Lidar. Light grey squares represent homes lost in the storm. The linear depositional zone behind the features is a water-filled ditch. Note washover lobes in northeast corner of figure.
Appendix C, Map 4: Change detection (2006-2008) calculated by subtracting pre-storm Lidar from post-storm Lidar. Note the washover deposits behind the scour features.
Appendix C, Map 5: Change detection (2006-2008) calculated by subtracting pre-storm Lidar from post-storm Lidar. Note the erosion of the dunes behind the beach. Also note areas of deposition behind areas of erosion. Serrated forms in top right corner of map are water-filled ponds.
VITA

Name: Michael Killgore Potts

Address: Dept of Geography
        MS 3147 TAMU
        College Station TX 77843

Email Address: michaelpotts@gmail.com

Education: B.S., Geography, Texas A&M University, 2005
            M.S., Geography, Texas A&M University, 2010