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Quantitative Evaluation of Coastal Geomorphological Changes in South Carolina After Hurricane Hugo

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ABSTRACT

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Pre- and post-storm aerial videotape surveys were made along 51 km of the barrier island coast of South Carolina from Garden City to Folly Beach. Before Hugo the shoreline from the beach landward to, and including the first row of development, was classified as dune field (45%), bulldozed dune ridge (25%), revetment (14%), bulkhead (12%), vegetated washover terrace (3%), and beach only (1%). After the storm, 80% of the shoreline was classified as washover sheet, and 5% as washover fan. The only areas that were not overwashed were sections of very high dune field (13%) and large bulldozed dune ridge (2%).

Our most important observations can be summarized as follows. (1) Provided the dune field was not submerged, the minimum width of dune field required to survive Hurricane Hugo, and thereby protect buildings, was 30 m. (2) Two types of dunes survived the storm: those high enough to prevent being overwashed and wide enough to prevent being completely eroded (*e.g.*, forested dunes on Pawleys Island; massive bulldozed dune at Litchfield), and those low and well-vegetated enough to be rapidly submerged without significant erosion (*e.g.*, Sullivans Island; Isle of Palms). The latter, of course, provided much less protection to buildings behind them. (3) All bulkheads and revetments were overtopped, and wave activity was carried inland to the first and succeeding rows of development. The only man-made "shoreline structure" not overtopped was a nearly 7 m high bulldozed dune ridge at Litchfield. (4) Fifty percent of all buildings completely destroyed or removed from their foundations were fronted by a "deadly" combination of dry beaches less than 3 m wide and dune fields less than 15 m wide. Eighty-four percent of all buildings completely destroyed or removed from their foundations were fronted by dune fields less than 15 m wide. Our results concerning the protective effects of dunes also provide a basis for predicting damage in other developed coastal areas in future storms.

ADDITIONAL INDEX WORDS: *Beach erosion, dune erosion, shoreline mapping, storm processes, washover.*

INTRODUCTION

The use of low altitude, oblique aerial videotape surveys in coastal areas has become an important and useful method for obtaining data on long reaches of shoreline. This method has been used extensively to map spatial and temporal changes along the barrier island shoreline in Louisiana (*e.g.*, PENLAND *et al.*, 1989).

This paper maps and interprets the storm-induced changes in shoreline morphology along two reaches of the barrier island coast of South Carolina, including the communities of Garden City, Litchfield Beach, Pawleys Island, Debidue Beach, Isle of Palms, Sullivans Island and Folly Beach. These areas were selected for two reasons. First, these islands were significantly affected by Hurricane Hugo. Second, there is a distinct change in geomorphology north of the study area; mainland beach fronts much of Surfside Beach and Myrtle Beach, providing a convenient morphological break to constrain this study.

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STUDY AREA

The South Carolina coast is composed predominantly of barrier islands and barrier spits; those included in this paper are shown in Figure 1. The tidal range is mesotidal (2-4 m). Nat-

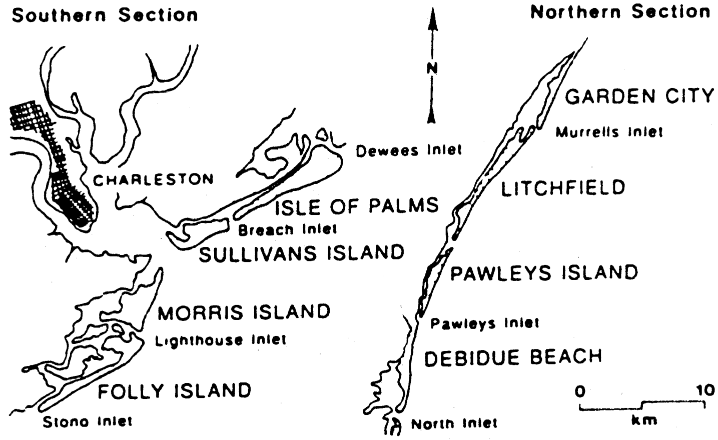

Figure 1. Location map of the South Carolina barrier islands and barrier spits used in this study. Morris Island was not mapped.

ural dunes have largely been removed for development. Artificially constructed (by bulldozing or the use of sand fences) dunes with varying degrees of vegetation are present along much of the developed shoreline, nearly all of which were constructed following the "Northeaster" storm of January 1987. A variety of sloping and vertical revetments and bulkheads front much of the developed shoreline, particularly at Folly Beach. High tide dry beach width along the coast is variable, between 0-30 m (WRIGHT and PILKEY, 1989).

The tropical depression that became Hugo reached hurricane intensity on 13 September 1989, about 1770 km E of the Leeward Islands. Hugo's track passed over the islands of Gaudeloupe, St. Thomas and St. Croix, reaching Puerto Rico on the 18th. By the 21st Hugo was several hundred km E of Florida, moving NW at about 38 kph. Landfall along the South Carolina coast at Sullivans Island occurred just before midnight on the 21st, near the time of local high tide. Hugo was a Category 4 hurricane (SIMPSON, 1974) at landfall; wind speed was 217 kph, central pressure was 934 mb. The storm continued inland after landfall and weakened, passing just west of Charlotte, North Carolina by 0800 on the 22nd. Storm surge heights ranged from approximately 2-6 m in the study area, with the highest levels recorded in Bulls Bay (U.S. DEPARTMENT OF COMMERCE, 1990).

METHODOLOGY

Videotape surveys prior to the storm were conducted on 27 May 1988 and 9 September 1989. A post-storm survey was conducted on 23 September 1989. All flights used a single-engine high-wing aircraft flying at a speed of approximately 75 knots at an altitude of 60 m, about 70 m from the shoreline. Videotaping was done using an RCA Super-VHS high-resolution video camera.

A multi-tiered classification system was developed to map both the coastal geomorphology as well as the type of development along the shoreline. The shoreline is here defined as the area from the beach landward to, and including, the first row of development. The elements of the classification system are shown in Figure 2. Features noted on the aerial videotape were mapped onto 1:1200 orthophotographs prepared by the South Carolina Coastal Council. The minimum mappable unit was 3 m. Once mapped, the linear alongshore distance occupied by each feature was measured and entered into a database for quantitative analysis.

The shoreline was first classified as developed or undeveloped. The type of development was classified as either single-family homes, or multi-family structures, including condominiums and hotels. Areas lacking dunes or shoreline structures were classified as beach only. A house sited on the pre-storm high tide line, for

Developed (D)	Undeveloped (U)
Single-family (s) or Multi-family (m)	Dune Field (df) Bulldozed Dune Ridge (db) Washover Terrace (wt) Washover Sheet (ws) Washover Fan (wf)
Dune Field (df) Bulldozed Dune Ridge (db) No Dune/Beach Only (b) Bulkhead (bh) Revetment (r) Washover Sheet (ws) Washover Fan (wf) Gap (g)	

Figure 2. Elements of the coastal classification used in this study. See text for explanations of each category.

example, would be classified as beach only. A category termed "gap" was utilized to map undeveloped areas between buildings greater than 15 m (approximately one single-family building lot width). "New gap" was used to describe areas where houses were completely destroyed and/or removed from their foundations after the storm.

Morphologic features common to both developed and undeveloped reaches include dune field, bulldozed dune ridge, washover sheet and washover fan. A dune field is defined as one or more continuous, well-vegetated dune ridges. A bulldozed dune is one that has been built artificially (typically by bulldozing sand up from the beach), and can have any amount of vegetative cover. These features were usually comprised of a single sand ridge. The width of dune field and bulldozed dune was classified as shown in Figure 3. A washover sheet is a large, laterally continuous (generally > 20 m), storm-generated overwash feature characterized by a significant amount of sediment deposition. Field observations indicated that washover sheets are on the order of several cm to nearly 2 m thick. Washover fans occur between breaks in dune ridges and are similar in thickness to washover sheets. An additional pre-storm category, washover terrace, was used to describe low, sparsely vegetated undeveloped reaches lacking any significant dunes that we interpret as old washover sheets.

Dune field and dry beach widths were measured and placed into broad width classes because of the limits on video resolution. Post-storm dry beach width was not mapped due to the obvious difficulty in defining the landward boundary of the beach. It is important to note the distinction we have made between the morphological classification of dune field and the assignment of dune field widths in the study area. In order for a reach of shoreline to be classified as dune field, the dune field must not be fronted by another morphological type (*e.g.*, bulldozed dune, bulkhead, revetment). Dune field widths, however, were assigned to the entire length of shoreline in the study area to recognize the presence (or absence) of both nat-

Dune Field Width (m)	Dry Beach Width (m)	Structure Performance
<1 1-15 15-30 >30	<3 3-15 >15	Undamaged Damaged Destroyed

Figure 3. Dune field width, dry beach width, and structure performance categories used in this study. See text for explanations of each category.

ural and man-made dunes that were landward, seaward, or physically situated on top of other morphological types.

Shoreline engineering structures were classified as bulkhead or revetment. For purposes of this paper, the following definitions of shoreline structures apply: a bulkhead is any vertical structure built of wood or concrete; a revetment is a sloping structure composed of rocks and/or construction debris, which may also be backed by a bulkhead. Structure performance was divided into three broad categories (Figure 3): undamaged, damaged or destroyed. To be classified as undamaged, a bulkhead or revetment must have appeared intact after the storm. Damaged bulkheads suffered obvious failure (such as missing sheets or piles and collapse/removal of backfill), but were still largely in place. A damaged revetment had up to approximately half of its volume removed, but more typically, damage was indicated by large amounts of revetment material scattered across the beach and backshore. In areas of destroyed bulkheads and revetments, only a few pilings or rocks remained in place.

RESULTS

Shoreline Classification

The total length of mapped shoreline was 51 km. The general classification (Table 1) shows that before Hugo the shoreline was dune field (45%), bulldozed dune ridge (25%), revetment (14%), bulkhead (12%), vegetated washover terrace (3%), and beach only (1%). After the storm, 78% of the shoreline was classified as washover sheet, 5% as washover fan, and 2% as beach only. The only areas that were not overwashed were sections of very high dune field (13%) and large bulldozed dune ridge (2%).

Dry Beach Width

Before the storm, dry beach widths were split nearly evenly among the three categories (Figure 4). Isle of Palms had the longest length of wide dry beach (88% of its shoreline had a width > 15 m). The longest length of narrow dry beaches fronted Pawleys Island and Folly Beach. Each had 67 and 66 percent of its beach, respectively, in the < 3 m category.

Dune Field Width

Sand dune, including both natural dune field and bulldozed dune, comprised 36 km (70%) of the shoreline before the storm (Table 1). Twenty-three km were natural dune field; 13 km were bulldozed. Nearly half (25.0 km; 49%) of the total dune field had a pre-storm width > 30 m (Table 2). Only 6.6 km (13%) had a width of 15-30 m. There was 10.7 km (21%) with a width of 1-15 m, and 8.7 km (17%) of width < 1 m (essentially nonexistent).

Overall, dune field width narrowed considerably due to the storm (Table 2). Only 21% of the natural dune field > 30 m remained in this size class, and only 1.0 km (8%) of bulldozed dune remained, all of it at Litchfield. Very few dunes with a width of 15-30 m survived. All dunes < 15 m wide were completely eroded away. Dunes wider than 30 m were eroded to varying extents, resulting in the "redistribution" of much of the wide dunes into the smaller width classes (Figure 5).

Table 1. *Shoreline classification before and after Hurricane Hugo expressed as percent of shoreline length for each island and as percent of total shoreline length.*

	Shoreline length (km)	Before (%)						After (%)					
		df	db	b	wt	bh	r	df	db	b	ws	wf	ng
Garden City	7.8	24	23	5	0	42	6	0	0	0	100	0	14
Litchfield	6.6	53	27	0	16	4	0	12	8	1	71	8	0
Pawleys Island	5.9	9	68	1	7	15	0	9	12	14	65	0	12
Debidue Beach	6.0	31	47	0	0	22	0	60	0	0	38	2	2
Isle of Palms	10.0	90	1	0	0	0	0	0	0	0	100	0	4
Sullivans Island	4.8	94	0	0	0	1	5	0	0	0	65	35	4
Folly Beach	9.9	18	20	1	0	2	59	14	0	0	85	1	11
Total	51.0	45	25	1	3	12	14	13	2	2	78	5	7

df = dune field db = bulldozed dune b = no dune/beach only wt = washover terrace bh = bulkhead r = revetment ws = washover sheet wf = washover fan ng = new gap

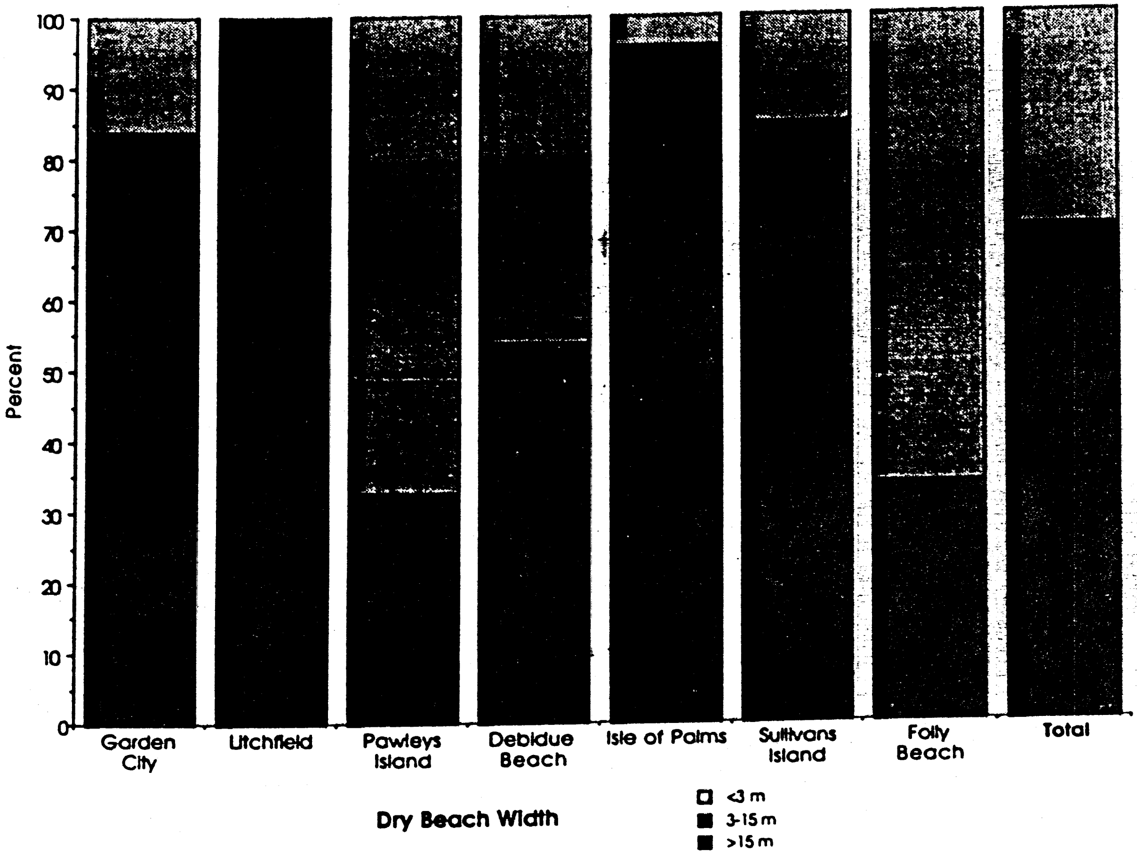

Figure 4. Stacked column graph showing dry beach widths mapped before the storm. Isle of Palms had the longest length of wide beach; the longest length of narrow dry beaches fronted Pawleys Island and Folly Beach.

Table 2: *Dune field width classification before and after Hurricane Hugo expressed as percent of shoreline length for each island and as percent of total shoreline length.*

	Shoreline length (km)	Before (%)				After (%)			
		A	B	C	D	A	B	C	D
Garden City	7.8	45	25	13	17	100	0	0	0
Litchfield	6.6	4	31	16	49	79	21	0	0
Pawleys Island	5.9	24	25	20	31	78	6	3	13
Debidue Beach	6.0	0	12	4	84	14	7	2	77
Isle of Palms	10.0	0	5	17	78	33	15	23	29
Sullivans Island	4.8	4	6	1	89	19	30	8	43
Folly Beach	9.9	34	37	14	15	71	15	7	7
Total	51.0	17	21	13	49	59	13	7	21

A = < 1 m B = 1-15 m C = 15-30 m D = > 30 m.

Shoreline Structures

Of the 51 km of shoreline in the study area, 13.3 km (26%) are fronted by "hard" shoreline structures. Of this, 6.1 km (12%) is classified as bulkhead and 7.2 km (14%) as revetment. Post-storm structure performance is shown in Figure 6. Fifty-eight percent of the bulkhead was destroyed, 16% damaged, and 26% undamaged. Twenty-four percent of the revetment was

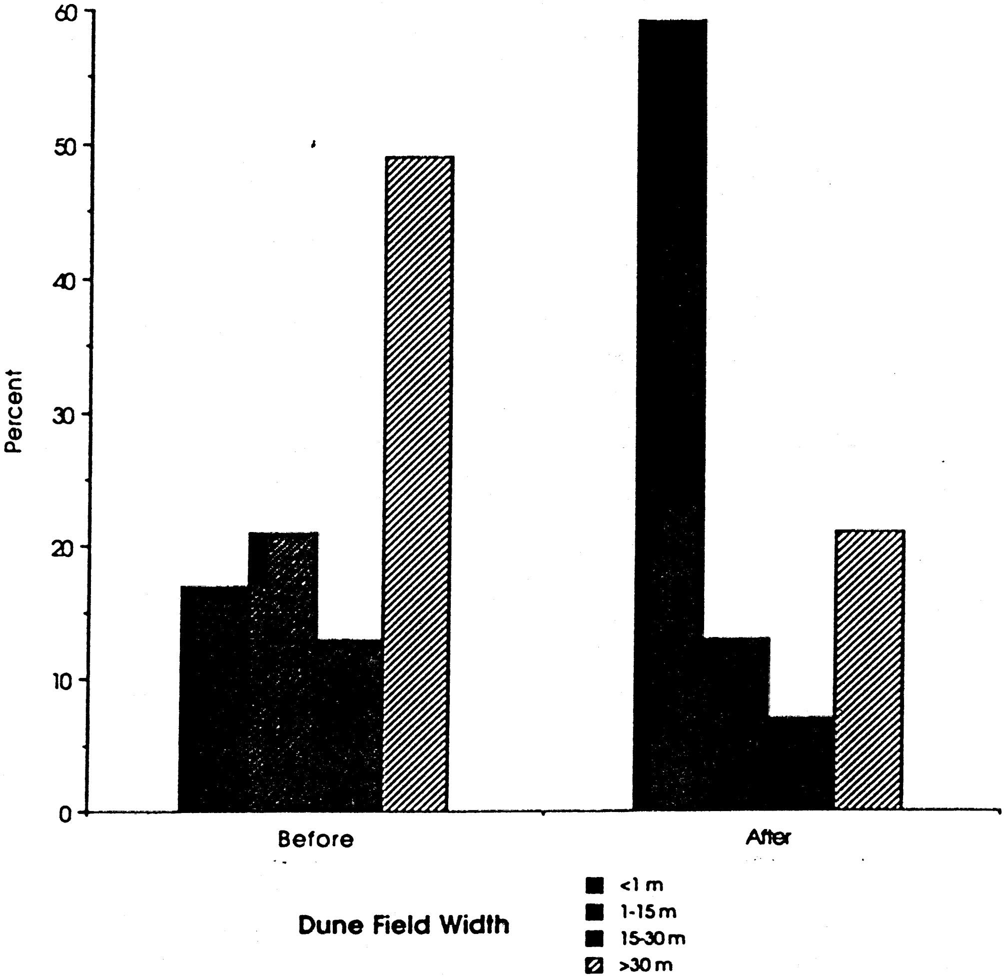

Figure 5. Column graph showing the distribution of dune field width classes before and after Hurricane Hugo. All dunes less than 15 m wide before the storm were completely eroded, along with nearly all of the dunes in the 15-30 m category. Very few dunes in the 15-30 m category survived. Nearly all of the dunes > 30 m survived, but were eroded to differing extents, contributing to the "redistribution" of dunes in the intermediate width classes.

destroyed, 68% damaged, and 8% undamaged. In addition, all of the bulkheads and revetments in the study area were overtopped by storm surge and waves.

DISCUSSION

Dry Beach Width

All of the shoreline had essentially no post-storm dry beach. Hence, this study quantifies only the pre-storm dry beach width. For Garden City, Isle of Palms and Sullivans Island, the wide pre-storm beach is attributable, at least in part, to local inlet processes and the impoundment of sand updrift from jetties (KANA, 1988). It is difficult to isolate the effect of pre-storm dry beach width on shoreline structure damage; however, the data in Table 3 show that areas with *both* a narrow dry beach and a narrow or nonexistent dune field had by far the most "new gaps" (buildings completely destroyed and/or removed from their foundations). Clearly, this

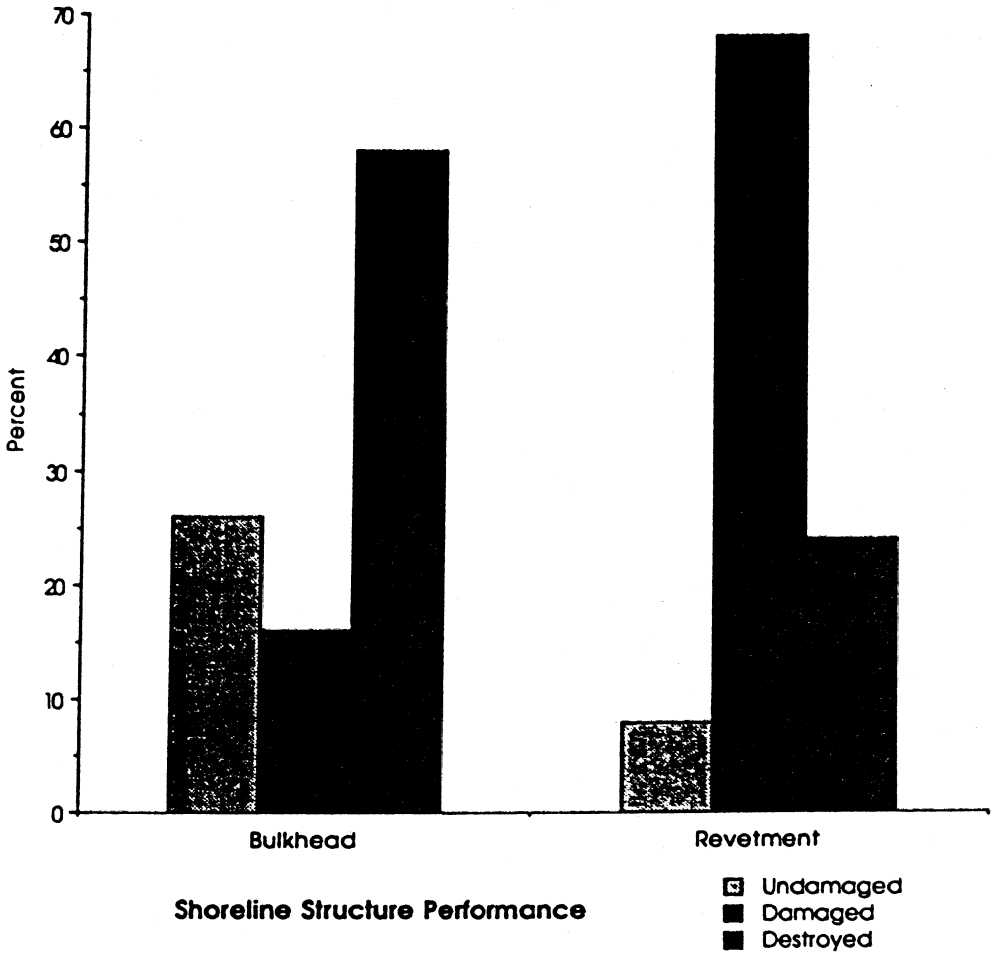

Figure 6. Column graph showing post-storm shoreline structure performance. Hard structures fronted 13.3 km of shoreline in the study area before the storm, of which 6.1 km was bulkhead, and 7.2 km revetment. See text for explanations of each category.

Table 3. *Pre-storm dry beach and dune field widths fronting the 3.6 km of "new gap" in the study area, expressed as a percent.*

Dry Beach Width (m)	Dune Field 0-15	Width (m) > 15
< 3	50	4
3-15	31	4
> 15	3	8

is a strong endorsement for maintaining wide beaches and dune fields for storm protection.

Dune Field Width

There were two very different modes of dune survival. First, dunes survived when high enough to prevent being overwashed, yet wide enough to prevent being completely eroded. The large, forested dunes on Pawleys Island and a bulldozed dune at Litchfield offer excellent examples of this type of dune (Figures 7 and 8). In fact, these large dunes were the only shoreline features not overtopped by storm surge and

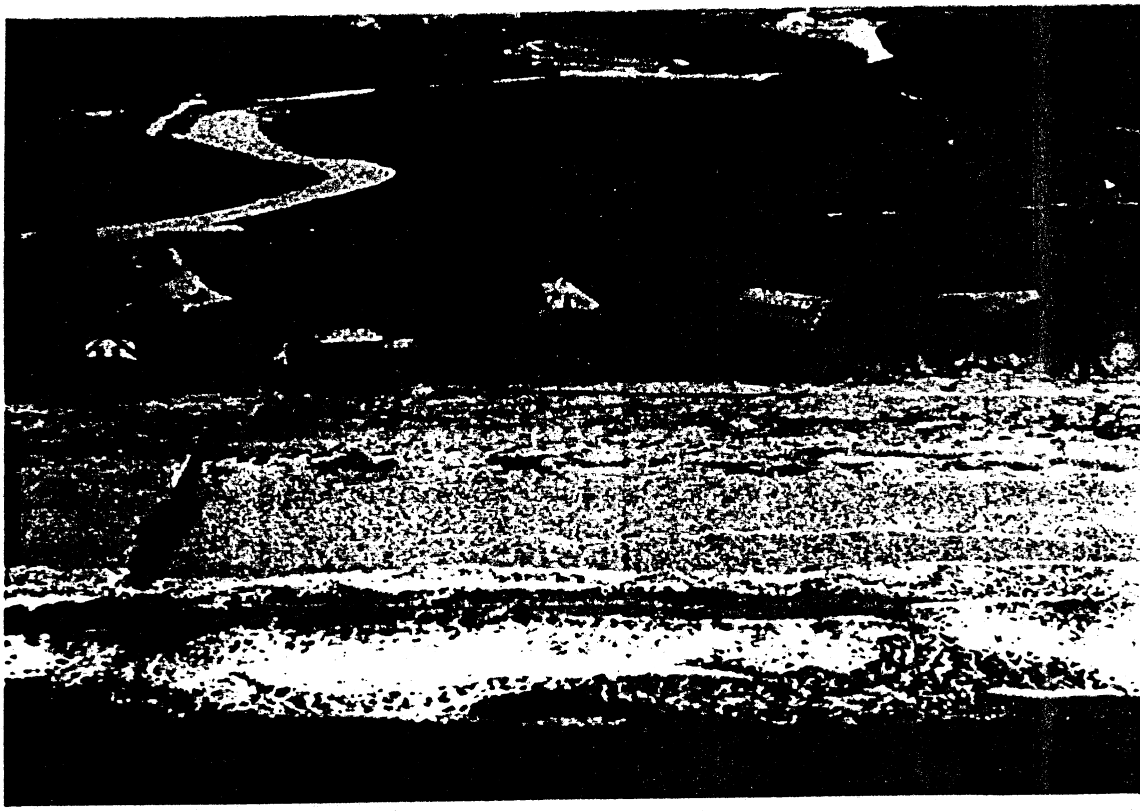

Figure 7. Large, forested dunes on Pawleys Island that survived the storm. These dunes were not overtopped by storm surge and waves, and protected development behind them. Houses sited well back in the dunes suffered little damage, while extensive damage occurred to poorly set back buildings that were left out on the beach as a result of beach and dune retreat.

waves. Second, dunes survived when low enough to be rapidly submerged by the storm surge without extensive scarping, yet were well enough vegetated to prevent serious erosion. Rapid submergence and dune survival is best shown on Isle of Palms and Sullivans Island (Figure 9). Although the dunes survived, they provided minimal protection to structures behind them.

The most important point to make regarding changes in dune field width is that very few dunes less than 30 m wide before the storm survived, and all dunes less than 15 m wide were completely eroded away. Dunes wider than 30 m were eroded to varying extents, resulting in the "redistribution" of much of the wide dunes into the smaller width classes (see Figure 5).

Dune field width, or lack thereof, had a significant effect on the formation of "new gaps." This relationship is shown in Table 3; 84% of the "new gaps" were found in areas with dunes less than 15 m wide before the storm.

Shoreline Structures

The data for hard structures (see Figure 6) show clearly that bulkheads and revetments responded differently to Hurricane Hugo. Because of the nature of the structure, a bulkhead is more likely to fail completely under storm-induced stress rather than sustaining limited damage; 58% of the bulkheads were destroyed. Many undamaged bulkheads survived because they were buried under a bulldozed dune prior to the storm, which provided at least partial protection during the storm.

In the case of revetments, far more were damaged than destroyed (68% and 24%, respec-

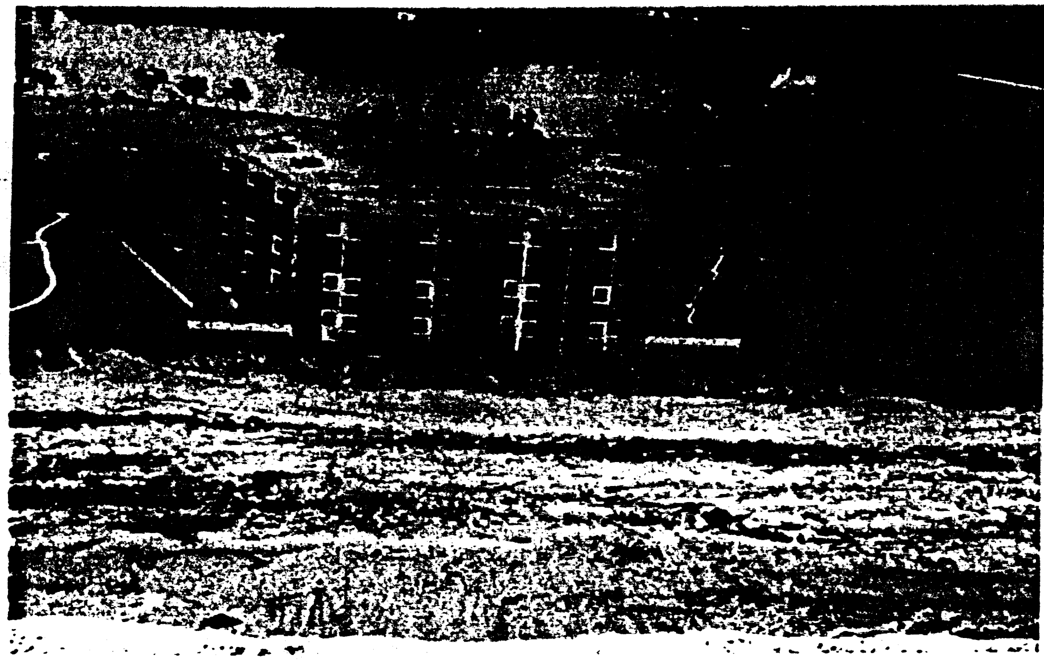

Figure 8. A well-vegetated, bulldozed dune ridge fronting condominiums at Litchfield was not overtopped during the storm. This dune was the only man-made "shoreline structure" not overtopped (all bulkheads and revetments in the study area were overtopped).

Figure 9. Low, well-vegetated dunes on Isle of Palms were rapidly submerged by storm surge, and were not extensively scarped. These dunes, however, provided little protection to development behind them.

tively). This indicates that wave activity was sufficient to move the revetment material (typically quarry stone up to 1 m in diameter), but not necessarily cause the complete destruction of the structure. Only two revetments, one on Sullivans Island and the other on Folly Beach, were classified as undamaged. It is important to emphasize that we do not take into account all outside conditions in this evaluation; rather, the data are offered as an impetus for further study.

All hard structures in the study area were overtopped by storm surge and waves, including a dune-on-top-of-bulkhead configuration at Debidue Beach (Figure 10). Furthermore, of the 3.6 km of "new gaps," 48% were fronted by hard structures.

Case Studies: Litchfield and Pawleys Island

Litchfield and Pawleys Island represent the spectrum of storm responses we mapped. With the exception of revetments, all of the pre- and post-storm features in the classification are present on these two barriers. In addition, their proximity to one another meant that they were subjected to nearly identical tide, storm surge, wind speed and wind field conditions.

Litchfield

Before the storm, the 6.6 km of mapped shoreline at Litchfield was classified as follows (see Table 1): 53% dune field, 27% bulldozed dune, 16% washover terrace, and 4% bulkhead. There are no revetments present at Litchfield. After the storm, only 12% of the Litchfield shoreline was classified as having a dune field, 8% bulldozed dune, 1% beach only, 71% washover sheet and 8% washover fans. No "new gaps" formed. This is primarily due to building setbacks that left wide dunes between the beach and the first row of development, as well as extensive dune-building projects. Dry beach width may also have played a role in protecting development;

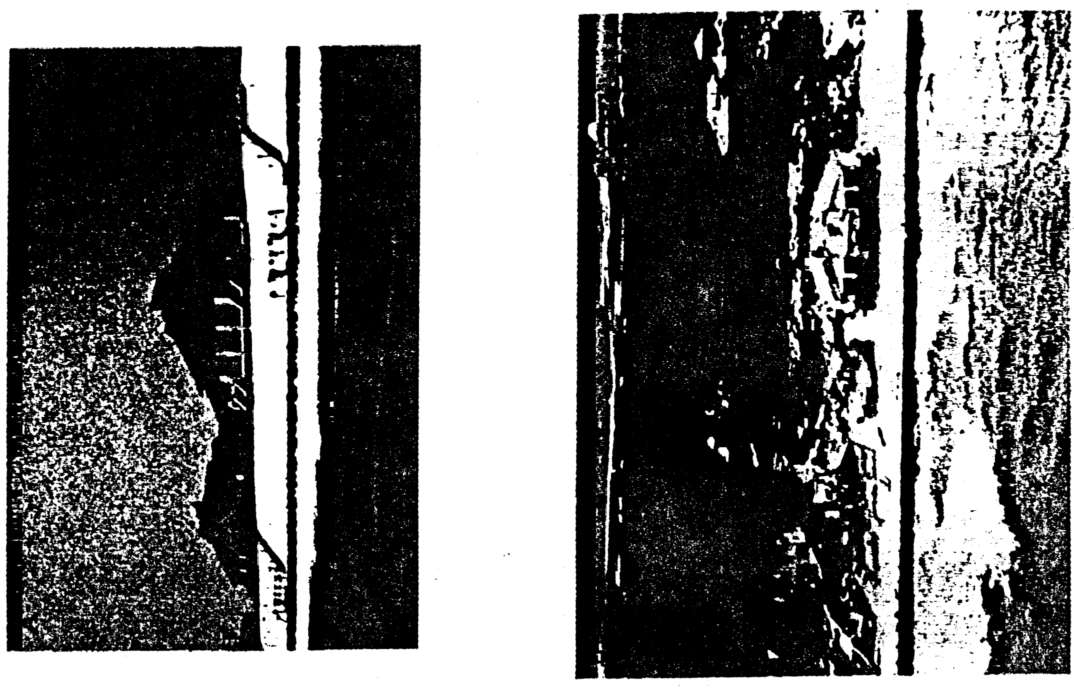

Figure 10. A: Dune-on-top-of-bulkhead at Debidue Beach in the summer of 1987. B: Storm surge and waves overtopped the bulkhead and dune at Debidue Beach, carrying destructive wave activity inland. Note that the bulkhead was left intact, as it was underwater for much of the storm.

all of the shoreline at Litchfield had pre-storm dry beach widths of greater than 3 m.

Dune field widths changed dramatically. Prior to the storm, nearly half (49%) of the area had dunes more than 30 m wide (see Table 2). After the hurricane, no dunes wider than 15 m remained. All of the dunes less than 15 m wide were removed, along with nearly all of the dunes between 15-30 m. Of the dunes remaining, all now less than 15 m in width, only 13% were 15-30 m wide before the storm. The remainder represents what was left of the dunes that were more than 30 m wide before the storm.

The extensive dune removal also contributed to significant changes in the morphological classification. Specifically, 71% of the reach was classified as washover sheet, 8% as washover fan, and 1% as beach only.

The primary mode of dune survival on Litchfield was height and width sufficient to withstand overwash and erosion. Both the large natural dunes and a large (nearly 7 m high) bulldozed dune fronting a stretch of condominium development were not overwashed, and were of sufficient width that they were not completely eroded by the storm. Indeed, this bulldozed dune was the only man-made "shoreline structure" in the entire study area that was not overtopped by storm surge (see Figure 8).

One hundred percent of the 264 m of bulkhead along the Litchfield shoreline was classified as damaged (*i.e.*, none was considered either undamaged or destroyed). It is important to note that much of this bulkhead was deeply buried under dunes prior to the storm, and thus protected from wave attack until exhumed by beach retreat.

Pawleys Island

Of the 5.9 km of shoreline on Pawleys Island, only 9% was classified as dune field prior to the storm. Sixty-eight percent of the reach was comprised of bulldozed dune, with 1% beach only, 7% washover terrace, and 15% bulkhead. There are no revetments on Pawleys Island. In contrast to Litchfield, however, there is a timber/stone groin field present along much of the shoreline. Although the groins appeared to be trapping sediment, any offset present was generally insufficient to affect classification of pre-storm beach widths on either side of a given groin.

After the storm, only 9% of the shoreline was still fronted by a dune field, 12% by a bulldozed dune, while 14% was classified as beach only, and 65% as washover sheet. There were no washover fans present on Pawleys Island; dune that was not overtopped or removed was not breached. This is in part due to the type of development on the island: buildings are either well set back in the dunes, or are at the back of the beach itself, or are fronted by a bulkhead and/or small bulldozed dune with minimum setback.

Both modes of dune survival discussed above are present on Pawleys Island. The dune field at the northern tip of the island is low, wide and well-vegetated. The entire dune field was likely underwater during much of the storm, yet was not severely eroded (Figure 11). In the central part of the island, several large, forested dunes are present (see Figure 7). These dunes are over 6 m high in places, and also contain a large volume of sand. The height of the dunes prevented overwash due to storm surge; the great volume of sand available for release during the storm further contributed to the dunes' survival.

Of the 885 m of bulkhead on Pawleys Island, 91% was classified as destroyed, and the remaining 9% as damaged. The large amount destroyed can be accounted for by the fact that much of the bulkhead was at or near the high tide line prior to the storm. That is, the bulkhead was not deeply buried under bulldozed dunes as at Litchfield. Thus, the bulkhead was continuously exposed to the full brunt of the storm. Any bulkhead that survived the wave attack was also subjected to intense storm surge ebb. As shown in Figure 12, storm surge ebb channels were incised up to 25 m back into the island, frequently cutting directly through bulkheads.

In contrast to Litchfield, which had no destroyed buildings, 12% of the Pawleys Island shoreline contained "new gaps." There are several explanations for this observation. First, 49% of the shoreline was fronted by dunes less than 15 m wide before the storm. As discussed above, dunes this size provided little protection and were completely removed by Hurricane Hugo. Second, Pawleys Island is developed along almost its entire length, including areas where the island is narrow (in places less than

Figure 11. Low, well-vegetated dunes on Pawleys Island were rapidly submerged by storm surge, and were not extensively eroded. These dunes, however, provided little protection to development behind them.

150 m wide) and of low elevation. Third, much of the development on Pawleys Island is older, constructed in the years following Hurricane Hazel in 1954. Not only have the beach and dunes narrowed considerably since that time, but also the buildings were not constructed or elevated sufficiently to withstand a large storm such as Hugo. Much of Litchfield, however, has been developed only within the last 5-15 years; buildings are generally well set back from the shoreline, well-constructed and well-elevated. Furthermore, unlike Pawleys Island, many of the more hazardous building sites at Litchfield have not as yet been developed.

CONCLUSIONS

We investigated the relationship between shoreline characteristics and storm response on 51 km of the barrier island coast of South Carolina from Garden City to Folly Beach. Based on detailed mapping using pre- and post-storm high-resolution aerial videotape surveys, we have reached several conclusions concerning geomorphological changes after Hurricane Hugo as well as the impact on barrier island development.

The general classification shows that before Hugo the shoreline was dune field (45%), bulldozed dune ridge (25%), revetment (14%), bulkhead (12%), vegetated washover terrace (3%), and beach only (1%). After the storm, 80% of the shoreline had been completely overwashed and 5% was occupied by washover fans. The only areas that were not overwashed were sections of very high dune field (13%) (*e.g.*, forested dune on Pawleys Island) and a large bulldozed dune ridge (2%) at Litchfield.

Pre-storm dune field widths were < 1 m (17%), 1-15 m (21%), 15-30 m (13%), and > 30 m (49%). Just over 21 km of dune field was completely removed by Hugo, leaving widths of: < 1 m (59%), 1-15 m (13%), 15-30 m (7%), and > 30 m (21%). Most (87%) of the dune that survived was > 30 m wide before the storm. All dunes less than 15 m wide before the storm were completely eroded away.

There were two very different modes of dune survival. Dunes survived when high enough to prevent being overwashed and wide enough to prevent being completely eroded (*e.g.*, forested dunes on Pawleys Island; massive bulldozed dune at Litchfield), and when low and well-vegetated enough to be rapidly submerged without significant erosion (*e.g.*, Sullivans Island; Isle of Palms). The latter, of course, provided much less protection to buildings behind them.

All of the bulkheads and revetments in the study area were overtopped. The only man-made "shoreline structure" not overtopped was a nearly 7 m high bulldozed dune ridge at Litch-

Figure 12. On Pawleys Island, storm surge ebb channels (black arrows) were incised well into the island, frequently cutting through bulkheads, causing their ultimate failure in a seaward direction. The photo also shows an excellent example of what we defined as "new gap," where beachfront buildings were destroyed and/or removed from their foundations. Note also the three houses carried by storm surge into the backbarrier marsh (white arrows).

field. Of the 7.3 km of revetments existent before Hurricane Hugo, 24% were destroyed, 68% were damaged and 8% were undamaged. Of the 6.1 km of bulkheads, 58% were destroyed, 16% were damaged, and 26% were undamaged. Buildings were destroyed along 3.6 km of shoreline, 48% of which was fronted by bulkheads or revetments.

Eighty-four percent of all buildings completely destroyed or removed from their foundation were fronted by a "deadly" combination of beaches less than 3 m wide and dune fields less than 15 m wide.

Our results also provide a basis for predicting damage in other developed coastal areas in future storms. Much of the coast of New Jersey, for example, lacks beach and dune widths sufficient to withstand a Hugo-type onslaught. Thus, the damage potential for New Jersey is great.

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