Factors Controlling Storm Impacts on Coastal Barriers and Beaches—A Preliminary Basis for Near Real-Time Forecasting

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ABSTRACT


Analysis of ground conditions and meteorological and oceanographic parameters for some of the most severe Atlantic and Gulf Coast storms in the U.S. reveals the primary factors affecting morphological storm responses of beaches and barrier islands. The principal controlling factors are storm characteristics, geographic position relative to storm path, timing of storm events, duration of wave exposure, wind stress, degree of flow confinement, antecedent topography and geologic framework, sediment textures, vegetative cover, and type and density of coastal development.

A classification of commonly observed storm responses demonstrates the sequential interrelations among (1) land elevations, (2) water elevations in the ocean and adjacent lagoon (if present), and (3) stages of rising water during the storm. The predictable coastal responses, in relative order from high frequency beach erosion to low frequency barrier inundation, include: beach erosion, berm migration, dune erosion, washover terrace construction, perched fan deposition, sheetwash, washover channel incision, washout formation, and forced and unforced ebb flow.

Near real-time forecasting of expected storm impacts is possible if the following information is available for the coast: a detailed morphological and topographic characterization, accurate storm-surge and wave-runup models, the real-time reporting of storm parameters, accurate forecasts of the storm position relative to a particular coastal segment, and a conceptual model of geological processes that encompasses observed morphological changes caused by extreme storms.

ADDITIONAL INDEX WORDS: Coastal morphology, storm impacts, predictive models, near real-time forecasting.

INTRODUCTION

The destructive forces of oceanic storms and their ability to rapidly and permanently alter the landscape on human time scales have been known since coastal inhabitants began making post-storm observations. Despite millennia of observed storm impacts, our scientific understanding of storm meteorological and oceanographic processes and attendant predictive capabilities have advanced significantly only during the past few decades. Recent scientific progress has been aided by the deliberate acquisition of pre- and post-storm data (images, ground surveys) by government agencies and academic institutions, and implementation of systematic monitoring programs that provide a temporal scale to post-storm processes and coastal adjustment.

The 1938 hurricane that devastated the northeastern coast of the U.S. (Brown, 1939) was perhaps the first coastal storm that resulted in multiple geological studies of morphological change. Since then, there have been many additional studies of morphological responses to major storms (Hayes, 1967; Wright *et al.*, 1970; Schwartz, 1975; Morton, 1976; 1978; 1979; Nummedal *et al.*, 1980; Kahn and Roberts, 1982; Morton and Paine, 1985; Penland *et al.*, 1989; Gayes, 1991; Stauble *et al.*, 1991; Thieker and Young, 1991; Tedesco *et al.*, 1995; Stone *et al.*, 1996; Stone and Wang, 1999). These and many other studies illustrate the wide range of coastal responses to storm processes and provide a wealth of data to develop generic coastal impact forecasts.

The primary purposes of this study are to summarize the physical factors that influence the subaerial impacts of storm processes on coasts composed of mobile sediments, to present a systematic classification of coastal responses based primarily on relations among rising water levels and land elevations, and to place the historical/empirical post-storm observations in the context of a near real-time forecasting program. This study focuses on the sandy beaches and barriers of the western Atlantic and Gulf of Mexico seas because the adjacent, densely populated coastal regions annually experience extratropical and tropical cyclones and there are abundant records of storm parameters and field data to characterize the resulting morphological changes.

PRINCIPAL FACTORS INFLUENCING STORM IMPACTS

Post-storm ground and aerial observations (see previous list of references) provide a basis for developing a conceptual...
model of storm-surge inundation and deposition (Figure 1). Washover sediments eroded from the shoreface, beaches, and dunes during extreme oceanic storms typically are deposited within 200 m of the shore and at elevations less than 2 m above normal wave runup unless onshore flow velocities are greatly accelerated by wind stress (Morton et al., 2000b). The zone of active storm deposition, which is controlled by antecedent topography, coincides with the zone of breaking waves and runup near the shore and commonly is well below and seaward of the maximum storm-surge drift line (Figure 1). Although maximum storm surges typically are 4 to 8 m above normal for intense hurricanes, and 1.5 to 2.5 m for major northeasters, elastic storm deposits do not form at the maximum water elevation where the surge and superimposed wave runup intersect the land surface. Instead, the maximum surge constructs wrack lines, which are an accumulation of organic debris, trash and other fine-grained sediment.

Several physical factors can influence the type and magnitude of storm impacts. Those factors include the alongshore variability of storm processes, geographic location relative to the storm center, prior storm history, duration of beach inundation by waves, high wind speeds, flow regime of washover currents, morphology and elevations of the ground surface, grain sizes of transported material, density of vegetative cover, and human modifications. Only a few of these variables are totally independent and several of them are closely linked, such as pre-existing topography and washover flow regime. The following synoposes explain how the major factors influence subaerial storm impacts. The references cited include supporting data, expanded explanations, and additional examples.

Storm Characteristics

Historically significant storms are unique in their individual characteristics and the roles that storm surge, winds, and rainfall play in causing coastal damage (Brown et al., 1974). Some storms are known for their high surge (March 1962 northeaster, Hurricanes Carla, Camille, and Hugo), others are noted for their high winds and associated damage (Hurricanes Celia and Andrew), and still others are memorable for their extensive aftermath rainfall and flooding (Hurricanes Beulah, Agnes, and Floyd). For assessing potential coastal impacts, the most important storm parameters are radius of maximum winds, sustained wind speeds, alongshore storm-surge profile, forward speed, and orientation of the storm path relative to orientation of the coastline (Simpson and Riehl, 1981). Storms that cause the greatest morphological changes and the most destruction are systems with high sustained wind speeds, large radii of maximum winds, and high storm surges that remain stationary for several days (northeasters), or move slowly onshore before making landfall (hurricanes).

The coupling between wind and water, and the control exerted by water depth largely determine the storm wave heights and current velocities that alter coastal morphologies. Clearly high wind speeds and relatively deep nearshore water enhance the destructive forces of storms by increasing the erosional forces of waves. Also storm surge impacts are related to the normal tidal range because the storm surge represents water levels above that expected by the astronomical tide. Therefore, storm surge impacts typically are greater on microtidal coasts and the resulting damage can exceed that on mesotidal coasts because on microtidal coasts there is greater disequilibrium between storm generated water levels and wave-adjusted land elevations.

Location Relative to Storm Path

The patterns and magnitudes of storm impacts also depend partly on the storm path relative to a particular coastal location (Simpson and Riehl, 1981). In the Northern Hemisphere, strong cycloonic winds rotate counterclockwise, which causes onshore transport of water to the right of the storm center (looking onshore). At the same time, to the left of the storm center, water is either blown away from the coast or the maximum height of the storm surge is greatly reduced by winds blowing offshore. For hurricanes, the dome of water around the storm eye (inverted barometric pressure effect) decreases with distance away from the storm center. These conditions cause substantially different erosional and depositional responses alongshore even during the same storm. This concept is illustrated by comparing the different simultaneous storm-surge impacts of Hurricane Alicia. To the right of the storm path the response was primarily deposition of washover terraces whereas washout was the response to the left of the storm path (Morton and Paine, 1985).

The storm effect of shoreline orientation on coastal morphological responses has been demonstrated for all large storms that have impacted long coastal segments including Carla (Hayes, 1967), Camille (Wright et al., 1970), Danny (Penland et al., 1989), Hugo (Stauble et al., 1991), and Andrew (Tedesco et al., 1995). Being near the storm center is not a prerequisite for extensive damage to beaches and nearby development. Even the swell of distant storms can erode beaches, flood adjacent coastal property, and deposit washover sand inland of the beach. Hurricanes tracking through the Gulf of Mexico on a westerly course frequently cause damage on Gulf and Caribbean beaches far from the storm paths. In 1988, Hurricane Gilbert, which tracked westward from Cuba to Mexico, caused prolonged flooding of northern Gulf Coast beaches (Morton et al., 1994). Furthermore, high water levels and swell generated in the Caribbean by Hurricane Lenny (1999) caused beach erosion and washover that
damaged homes and other facilities in northern Colombia, more than 500 km from the storm center.

**Timing of Storm Events**

Successive storm impacts in the same coastal region are common, but their cumulative impacts are poorly understood. Both increased damage from subsequent storms and no significant change after the first storm have been reported. For example, CHUTE (1946) reported that two Atlantic winter storms produced only minor additional erosion after the 1944 hurricane. In contrast, morphological changes and economic losses on Galveston Island during Hurricane Alicia were accentuated because the protective foredunes, which were destroyed 3 years earlier by Hurricane Allen, had not rebuilt (Morton and Paine, 1985). Repeated inundation of the central coast of North Carolina by Hurricanes Bertha and Fran in 1996, Bonnie in 1998, and Floyd in 1999 promoted greater erosion and washover construction than would be expected by any single storm of equivalent magnitude (http://coastal.er.usgs.gov/hurricanes).

Astronomical tides can constructively or destructively interfere with the maximum surge elevation depending on the timing of storm influence relative to the local tidal cycle. Storms that strike the coast at spring high tide tend to cause more damage because the storm surge superimposed on the high tide causes greater flooding and overwash. A well-known example is the March 1962 northeast, the most destructive Atlantic winter storm in terms of land loss and number of homes damaged or destroyed (U.S. Army Corps of Engineers, 1963). The storm, which coincided with abnormally high spring tides, remained stationary for almost 36 hrs so that beach and barrier flooding lasted over 5 consecutive spring high tides (O'Brien and Johnson, 1963). The strong northeast winds, broad fetch, and high angle of wave approach caused record flooding and beach retreat from New England to Florida.

**Duration of Backbeach Flooding**

The duration of breaking waves partly determines the volume of sand eroded from the beach. If beach flooding persists through only one high tide, then excavation of sand from the beaches and dunes is minimized. However, if beach flooding lasts for several days, then beach and dune erosion normally will be severe and large volumes of sand will be liberated from the beach-dune system (Brown, 1939; Hayes, 1967). The implications of this principle of total energy dissipation are important because a slow moving low intensity storm can cause just as much beach and nearshore change as a fast moving high intensity storm (Figure 2).

The long exposure time (36 hrs) for backbeach flooding during the March 1962 northeast was a principal reason that beach and dune erosion was so severe (U.S. Army Corps of Engineers, 1963). In 1999, Hurricane Dennis tracked slowly along the East Coast of the U.S. and stalled offshore for more than a week. Even though it weakened to tropical storm status before moving ashore, it caused extensive beach erosion and wave runup along the coast of North Carolina because waves attacked the beaches and dunes for a prolonged period (Bales et al., 2000).

**Wind Stress**

Extreme storms with high wind speeds transfer additional energy to the oceans, bays, and lagoons, and increase the turbulence and velocities of these coastal water bodies. The turbulence augments the ability of waves and currents to erode sediment, and the increased velocities allow the currents to transfer more sediment, farther inland and faster (Morton, 1979). Consequently, high-velocity wind-driven currents influence the morphology of the deposits, and their maximum distance of inland penetration (Figure 3).

Moderately turbulent washover of barrier islands without the influence of wind stress is uncommon, but it can occur when water levels are significantly increased by non-storm conditions. In 1997, barrier islands along the Pacific coast of Colombia were repeatedly inundated (Figure 4) when onshore wind was blowing and there were no large waves in the eastern Pacific. Tide gauge records and sea-level anomalies interpreted from Topex-Poseidon altimeter data showed that non-storm washover of the barriers was caused by the coincidence of spring high tides with an El Niño event that elevated water levels in the eastern Pacific Ocean near the equator about 30 cm (Morton et al., 2000a).

**Flow Confinement**

Erosional and depositional patterns and inland extents of storm-surge impacts are partly controlled by the confinement (lateral restriction) of storm surge (Morton, 1978). If the washover flow is unconfined, then the land surface is inundated by sheetwash (Figure 5). However, if the washover flow is confined to interdune lows or incised channels (Figure 3), then the energy of onshore flow is concentrated, flow velocities accelerate, and washover sediments are transported and deposited much farther inland. Leathemian (1977) examined sediment transport and deposition in a confined washover channel during a moderate winter storm. Although this study advanced quantification of washover hydraulics, the field conditions represented shallow flow depths (0.3 to 0.6 m) and washover produced by successive individual surges generated by breaking waves rather than total barrier inundation. More recent attempts to quantify washover flow has relied on video surveys (Holland et al., 1991) because of the difficulty of operating current meters in the zone of breaking waves and strong currents during a severe storm.

**Antecedent Topography and Framework Geology**

The topographies of beaches and barrier islands commonly control the extent of storm-surge impact by preventing washover in some areas and promoting washover in others. For example, high vegetated dunes can preclude the penetration of storm surge, and simultaneously divert the high-velocity flow into adjacent low-lying areas that become washover conduits (Wright et al., 1970, and Kain and Roberts, 1982). Once formed, strong washover currents can repeatedly occupy these channels, and they predictably are extremely haz-
ardous areas for coastal construction. On the Atlantic coast of the U.S., perched washover fans are commonly constructed at different interdune sites by different storms rather than being frequently reoccupied (Deery and Howard, 1977).

Thieler and Young (1991) showed that in South Carolina, dunes more than 30 m wide and 4.5 m high were the only ones that were not breached by the storm waves of Hurricane Hugo. Bulkheads and revetments constructed in place of the natural dunes as storm protection were all overtopped and many failed as a result of Hugo’s high storm surge.

Where the shore is composed of a thin veneer of sand over stiff mud, or outcrops of older strata (hardgrounds), the storm response is controlled largely by the erosional characteristics of the firm substrate (Riggs et al., 1995). In marshes fronting the ocean, sand can be stripped from the subaerial beach and deposited in the adjacent marsh grasses leaving mud exposed on the beach. This response is common in the Mississippi delta (Weight et al., 1970, and Kahn and Roberts, 1982; Dingler and Reiss, 1995; Sallenger et al., in press b) and on other mud-dominated coastal regions or transgressive barriers such as along the Eastern Shore of Virginia. The presence of hardgrounds or coral reefs near the shore can also influence the impacts of storm processes by acting as breakwaters that reduce the wave energy reaching the shore (McIntire and Walker, 1964).

Sediment Textures

Most beaches and barrier islands of the world are composed of sand that is easily eroded and transported by waves and currents of extreme storms. In fact, powerful storms have so much energy they can move boulders and large blocks of con-
cretes (Brown, 1939; Chute, 1946; Fitzgerald, et al., 1994). At high latitudes, many storm beaches and washover terraces consist primarily of gravel (Figure 6, Orford and Carter, 1982; Forbes et al., 1995) instead of sand (Figure 5). These former glacial sediments are transported and deposited by wave-current interactions generated by strong extratropical storms (northeasters).

Storm waves can erode fine beach sand more easily than coarse sand or gravel (Nelson, 1991), and washover currents can transport sand farther inland because it is much finer than gravel. An example of this latter phenomenon (Fitzgerald et al., 1994) was attributed to an intense Atlantic north-easter that generated high waves for more than five days (Gill and Deitmeyer, 1992) and caused widespread beach retreat and washover (Davis and Dolan, 1992). The storm constructed washover deposits of cobbles and boulders up to 1 m thick (Figure 6), and gravel overwash damaged many expensive seaside homes. Field observations in southern Maine and the work of Fitzgerald et al. (1994) suggest that rapid inland dissipation of wave and current energy commonly causes cobble-boulder washover ridges to aggrade within 10 to 15 m of the source material.

The storm surge of Hurricane Camille created its own coarse sediment load by destroying large motels and apartment complexes. Post-storm field reports (U.S. Army Corps of Engineers, 1970) and aerial photographs show that the storm surge reduced these buildings to cinder blocks and bricks that were swept from their foundations by the wave and wind-driven currents, and transported inland as bed load.

**Type and Density of Vegetation**

Vegetative cover can influence storm response by (1) reducing wind speed (Powell and Houston, 1996), washover currents (Morton and Paine, 1985), and storm surge (Hald, 1988) crossing the shore; (2) encouraging the accumulation of organic and inorganic sediments (Cahoon et al., 1995); and (3) acting as a sediment binder that resists erosion (Stoddart, 1964). Some common coastal vegetation habitats are maritime forests, scrub thickets, grassy uplands, grassy or forested dunes, fresh-water swamps, mangrove swamps, fresh-water marshes, and salt-water marshes. Each type of coastal vegetation has its own unique features that can retard erosion. For example, dense stands of salt marsh and mangroves trap sediment or offer resistance to waves and currents so that land loss is prevented or mitigated. However,
the roots of grasses and trees are generally too shallow to reduce erosion from large storm waves that lower the backbeach and undercut the dunes or uplands.

Vegetative cover in the storm impact zone can vary from sparse to dense (Chute, 1946; Morton and Paine, 1985) and it can range from short grasses to dense stands of mangroves with extensive prop roots or pneumatophors (Tedesco et al., 1995; Morton et al., 2000a). The density of coastal vegetation is inversely related to washover impacts because the roots act as binding agents that stabilize the soil, and the exposed vegetation increases friction that decreases velocities of overwash currents and breaking waves. Consequently, dense vegetation tends to reduce the magnitude of erosion and decrease the inland penetration of washover.

Type and Density of Development

Storm impacts on coastal regions also locally depend on the type and density of coastal construction because artificial structures and topographic modifications tend to complicate
Figure 7. The inland penetration of washover currents by the 3 m surge of Hurricane Carla on Bolivar Peninsula, Texas was greatly magnified after developers removed the protective foredunes. Photograph taken by the National Ocean Service.

wave and current interactions, and they can accentuate the destructive forces of the storm (Figure 7, Morton and Paine, 1985). When high-velocity currents encounter rigid structures, the currents typically are deflected or focussed, turbulence increases, and deep local scouring augments the beach and dune erosion (Morton, 1976). In Hurricane Hugo, shore-parallel structures typically increased beach and dune erosion (Birkemeier et al., 1991), whereas some shore-normal structures contributed to localized nearshore erosion by either trapping sand that would normally move alongshore, or directing the strong, sand-laden currents offshore causing permanent losses of beach sand (Gayes, 1991).

Widely spaced and elevated wooden buildings with small footprints cause minimal interactions with storm processes (Figure 2). In contrast, closely spaced concrete pilings or massive foundations of large buildings, swimming pools, and coastal defense structures locally increase the erosion by focussing the flow between buildings and preventing the wave dissipating transfer of sand from the dunes to the beach and bars (Morton, 1976). Because hard structures do not store and release sand like dunes, more sand erodes from the beach to satisfy the capacity of the strong waves and currents. Photographs before and immediately after Hurricane Carla (Figure 8) illustrate this concept. Carla removed all of the sand from the beach and transported it alongshore and offshore. Although some of the sand returned to the beach months and years after the storm, the beach never fully recovered and the storm represented a significant net erosion event for the beach along the seawall.

CONTINUUM OF STORM RESPONSES

Coastal responses can evolve during storms depending on storm intensity and duration. As a first approximation, beach and dune responses can be predicted on the basis of storm surge and superimposed wave runup relative to the land elevation (Sallenger, 2000). Although this relationship is of primary importance, there are other variables that also affect coastal responses. The responses presented in Table 1 are organized on the basis of the relations among (1) land elevations, (2) water elevations in the ocean and adjacent lagoon (if present), and (3) stages of rising and falling water. The discussion also is organized progressively from the high-frequency beach erosion events that result several times a year from only slightly elevated water levels, to low-frequency total inundation events that occur only during late stage impacts of extreme storms.

Beach Erosion

When elevations of the ocean are lower than the sandy backbeach or adjacent coastal headland (Table 1), then minor storm waves typically erode low scarps in the backbeach or headland (Figure 9). Scarps in the backbeach are common, but they are temporary features that eventually are obliterated by seasonal beach changes. Scarps of an eroded headland, however, may represent the new shore position that will not advance seaward even long after the storm. The latter case applies particularly to mud-rich headlands that are eroding because they are promontories that focus waves and
of water from the beach to the ocean allows preservation of the sand deposited in the backbeach. McIntire and Walker (1964) observed storm-induced forebeach erosion and backbeach aggradation when the storm surge was only about 0.7 m above normal mean high tide. Keen and Stone (2000) also reported onshore sand transport and beach aggradation of a mainland shore associated with two hurricanes of moderate intensity in Florida.

Dune Erosion

Coastal erosion will be severe if the storm surge and wave runup is substantially higher than the backbeach, but lower than the height of the dunes or bluff (Figure 11). Extensive beach and dune or bluff erosion is the most common morphological response reported for intense storms. Severe storm erosion typically produces beach profiles that are planar and seaward dipping or slightly concave upward (Brown, 1939; Hayes, 1967; Morton, 1976; Leatherman, 1979; Morton and Paine, 1985; Penland et al., 1989; Birkemier et al., 1991; Fitzgerald et al., 1994; Stone et al., 1996).

When the height of the storm surge and breaking waves are about equal to the height of the dunes, then the inland extent of washover is minor, but washover greatly increases where dunes are absent. Post-Hurricane Carla photographs show that the washover penetration was 3 times greater (from 100 m to 300 m) where developers lowered or eliminated the dunes (Figure 7). Constructing artificial sand dunes and stabilizing them with native plants are popular activities associated with many shoreline protection and beach nourishment projects. However, artificial dunes do not necessarily respond the same way to storm processes as natural dunes. Even when indigenous species are planted on artificial dunes, the roots may remain shallow because the plants did not grow while the dunes aggraded. Consequently, artificial dunes can be less resistant to wave attack and erosion than natural dunes, and as a result they may erode more rapidly than natural dunes (Morton et al., 1994).

Washover Terrace Construction

When the ocean is higher than the barrier or coastal-plain headland (Table 1), and land elevations near the shore are vegetated and relatively uniform (low dunes or no dunes), then the waves and currents construct washover terraces

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**Table 1.** Classification of erosional and depositional storm responses depending on the coastal setting and differences in elevations of the sea and adjacent land.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Ocean Level &lt; Dune or Berm Elevation</th>
<th>Ocean Level ≥ Dune or Berm Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier Island</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mainland Coast or Barrier</td>
<td>Beach Erosion or Berm Migration</td>
<td>Washover Terrace</td>
</tr>
<tr>
<td>Ocean Level ≥ Lagoon Level</td>
<td>Dune Erosion</td>
<td>Perched Fans or Washover Terrace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sheetwash</td>
</tr>
<tr>
<td>Ocean Level &lt; Lagoon Level</td>
<td>Washout Ebb flow</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

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**Figure 8.** Immediate A. pre-storm and B. post-storm photographs of the Galveston, Texas seawall. Severe beach erosion was caused by the 3 m surge of a category 4 hurricane (Carla in 1961). Photographs by Marcus Milling.

**Figure 7.** Post-Hurricane Carla photographs show that the washover penetration was 3 times greater (from 100 m to 300 m) where developers lowered or eliminated the dunes (Figure 7). Constructing artificial sand dunes and stabilizing them with native plants are popular activities associated with many shoreline protection and beach nourishment projects. However, artificial dunes do not necessarily respond the same way to storm processes as natural dunes. Even when indigenous species are planted on artificial dunes, the roots may remain shallow because the plants did not grow while the dunes aggraded. Consequently, artificial dunes can be less resistant to wave attack and erosion than natural dunes, and as a result they may erode more rapidly than natural dunes (Morton et al., 1994).

They lack high dunes because the sand supply is limited (Morton, 1996).

**Berm Migration**

The forebeach can be the source of sand for backbeach aggradation during some storm conditions (Figure 10). As ocean waters rise, waves eventually break on the berm crest and flood the backbeach (Table 1). Sand eroded from the berm crest and forebeach is transported across the backbeach by shallow sheetwash produced by wave runup. The sand subsequently is deposited near the base of the dunes because water levels are well below the dune crests, and the current velocities rapidly decrease as energy is dissipated. If the maximum depth of flooding is only slightly greater than the backbeach elevation, then the weak, low-turbulence return flow

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Figure 9. Minor flooding and moderate waves are capable of eroding beaches and forming low ephemeral scarps such as this one on Caladesi Island, Florida.

(Figure 12, Schwartz, 1975; Morton and Paine, 1985). More energetic waves and higher surges will increase the inland distance of sediment transport within limits, but the washover-terrace response remains the same, and it does not change to some other constructive or destructive phase. The frictional drag created by the vegetation rapidly decelerates the washover currents and inhibits long-distance inland transport of storm deposits. Terraces are typically narrow (<100 m wide), but long and continuous parallel to the shore (Figure 5).

Perched Fan Deposition

If a barrier island is relatively wide and the storm-surge is lower than some of the dunes, then the typical response is deposition of isolated interdune fans that are perched on top of but do not cross the island (Table 1). Perched fans (Figure 13) are deposited landward of the foredunes, but the shallow depths of flooding and vegetative friction prevent washover currents from transporting sand into the lagoon. These small isolated fans primarily fill in the interdune swales and ag-

Figure 10. A wedge of sand about 50 cm thick was deposited in the backbeach near the dunes of Bolivar Peninsula, Texas by the 1 m surge of a distant category 4 hurricane (Gilbert in 1988).
grade the barrier surface (Deery and Howard, 1977). Eolian processes may subsequently modify the fan surfaces and form low eolian mounds (Leatherman, 1979). Because the perched fans are not normally associated with scour channels, subsequent washover currents do not necessarily reoccupy them.

Sheetwash and Channel Incision

If storm surge and superimposed wave heights exceed heights of the primary dunes, then the entire headland or barrier island is inundated and the response is commonly sheetwash, or for barrier islands, incision of washover channels through the barrier core (Table 1). Barrier breaching and new inlet formation are enhanced when water levels in the open ocean rise rapidly, when the ocean is substantially higher than the lagoon as the storm approaches the shore, and where the barrier islands are long and narrow. Examples are the numerous wide channels cut through Matagorda Peninsula, Texas (Figure 3) and the Chandelier Islands of Louisiana by Hurricanes Camille, Frederic, and Georges (Wright et al., 1970; Stone et al., 1999).

Washout Formation

Minor beach washout is common when water from heavy rain is ponded by marshes or intradune lows, and the runoff drains across the beach. In contrast, storm related washout of barrier islands (Table 1, Figure 14) is infrequent because it requires unique water level and topographic conditions (Morton and Paine, 1985). Washout processes are opposite to washover considering the direction that water initially flows through breaches in the dunes and across the barrier. Where wind simultaneously elevates water in bays or lagoons and lowers water in the adjacent ocean, the setup and set-down across the barrier results in the lagoon being higher than the ocean. Initial washout incision occurs near the dunes because there the difference in hydrostatic head between the ocean and bay is greatest and water levels actively equilibrate. As lagoon waters flow seaward across the barrier, the incised channels extend landward by excavation, similar to headward eroding streams (Morton and Paine, 1985). Late-stage draining of water from the surface and from the saturated sand is by sapping that results in dendritic drainage patterns at the heads of the channels (Figure 14, Chute, 1946).

Hurricane Emily generated high waves and a surge of 2–3 m in Pamlico Sound that exceeded water levels in the Atlantic Ocean (Bush et al., 1996). Despite extensive flooding of the soundside of the North Carolina barriers, the dune heights exceeded the storm surge and prevented washout. Although washout is an uncommon morphological storm response, it is still capable of undermining and destroying coastal highways, houses, and utilities (Morton and Paine, 1985).

Forced and Unforced Ebb Flow

Most of the beach and dune erosion, channel excavation, and washover construction occurs during the flooding phase of the storm. Because the late-stage ebb-flow bedforms and other surficial modifications are preferentially exhibited on post-storm aerial photographs, they may be misinterpreted as evidence for initial channel excavation from the lagoon side, or the predominant process that caused large-scale morphological changes and sediment redistribution.

Strong offshore winds of Hurricanes Camille and Frederic focused ebb flow through incised channels of the Chandelier Islands of Louisiana (Wright et al., 1970; Kain and Roberts, 1982). Penland et al. (1989) described the elongate washover fans constructed by forced ebb flow across the eastern chenier plain beaches during Hurricane Danny. Forced return flow can construct deposits with associated large-scale sediment-
Figure 12. Laterally extensive washover terrace near Cozumel Mexico constructed by the 5.5 m surge of a category 4 hurricane (Gilbert in 1988).

Figure 13. A series of perched fans were deposited along Smith Island, North Carolina by the 1.5 m surge of a category 3 hurricane (Fran in 1996).

Tertiary structures superimposed on the oceanic overwash features, or it can obliterate the depositional features formed during initial overwash of the barrier. Multiple depositional events associated with diverse or opposing flow directions and multiple surge events from the same storm are common (Wright et al., 1970; Morton, 1979). Changing wind conditions, such as rapid accelerations, decelerations, or rotation, and fluctuating water heights associated with the tides and breaking waves can cause multiple surge events.

In the aftermath of an extreme storm, water levels in coastal bays, marshes, and lagoons commonly exceed those in the adjacent ocean, and water levels may remain abnormally high for days or weeks (Brown et al., 1974). High water inshore of the barriers can be caused either by floodwater runoff from the mainland or remnants of the storm surge. Where there are no high dunes to impede the flow, a typical post-storm response is return flow from the lagoon side of the beach (Hayes, 1967) that transports sand eroded from the barrier and deposits it nearshore to broaden the zone of breakers. When post-storm lagoon water flows seaward through a barrier, it is under the influence of gravity, but not wind stress. The ebb flow reworks the washover fans and terraces, and deposits sandbars at the mouths of the drainage channels (Wright et al., 1970; Tedesco et al., 1995) that are analogous to minor ebb-tidal deltas (Figures 3 and 15A). Where sand transport rates in the littoral drift system are high, the channels typically close within a few months or years (Figure 15B).

**IMPLICATIONS FOR NEAR REAL-TIME FORECASTING**

The preceding discussion demonstrates that near real-time predictions of storm impacts on beaches and barrier islands are possible if there is sufficient supporting information.
Storm Hazard Vulnerability Maps

Lidar instruments have promoted major advances in rapid, cost-effective, large-scale mapping of beach and dune topography (Sallenger et al., in press a). This laser technology provides dense spatial topographic coverage with centimeter scale accuracy. Extant lidar coverage of the southeast Atlantic and Gulf Coasts of the U.S. are swaths about 0.5 km wide centered on the beaches and dunes. Expanding the lidar surveys landward and incorporating other spatial data, such as recent orthophotos, video surveys, and topographic maps, allows morphological characterization of the coast and generation of storm hazard vulnerability maps. Combining photographic and topographic layers in a GIS provides a basis for mapping the detailed pre-storm topography, calculating the threshold elevations for washover and inundation using a wave runup model (Sallenger, 2000), and locating potential breaches in the dunes based on lidar elevations and dune widths.

The storm vulnerability GIS layers should also include the projected impacts of storms with specific design characteristics, and the spatial classification of prior extreme storm impacts, such as maximum beach/dune erosion and washover penetration. The maximum impact layer should also identify the storm of record and important characteristics, such as surge heights. This same approach was used successfully for statewide coastal hazards mapping in Texas before the development of a GIS (Brown et al., 1974).

Historical/Empirical Record of Storm Impacts and Storm Parameters

Federal and state agencies typically conduct post-storm ground surveys of still-water flood elevations and obtain aerial photographs and video surveys of the areas that experienced the greatest impact. Impact photographs for major storms since the 1960s are available for most populated coastal segments of the southeast Atlantic and Gulf Coasts of the U.S. The photographs can be used to map and classify the alongshore patterns of storm impacts.

In the U.S., the National Weather Service (NWS) is responsible for archiving past storm records and providing real-time weather forecasts of both extratropical and tropical cyclones. The National Hurricane Center (NHC), which is an office of the NWS, monitors tropical disturbances in the Atlantic, Caribbean, and Gulf Coast regions. The NWS provides timely information and data about the storm parameters, and forecasts the expected regions of storm impact.

Contingency and Response Plans

For Federal and state agencies responsible for disaster preparedness and management, there are two temporally sepa-
Predicting potential storm impacts is critical to both the contingency and response plans. The response plan is initiated as the storm approaches the coastal community and continues through the storm aftermath and relief efforts. In a near real-time forecasting mode the disaster management response plan is partly triggered by the predicted storm impact. This critical step requires dedicated cooperation and close coordination between disaster management agencies and the storm-impact forecasting team. Near real-time forecasting involves assembling all the pertinent GIS layers, linking with the real-time forecasts of storm parameters, and calculating the expected history of wave runup superimposed on the storm surge (Sallenger, 2000) as a storm approaches the coast.

The National Oceanic and Atmospheric Administration (NOAA) operates the National Data Buoy Center and is collaborating with selected coastal states to operate real-time coastal oceanographic observation networks of instrumented monitoring stations. Most of the monitoring stations are located in the bays, but some are placed at nearshore ocean...
Figure 16: Principal data and information components necessary for near real-time forecasting of beach and barrier island responses to storm processes. Following are the abbreviations for U.S. federal agencies identified as sources of input data: USGS = U.S. Geological Survey, USACE = U.S. Army Corps of Engineers, NHC-HRD = National Hurricane Center-Hurricane Research Division, NOAA = National Oceanic and Atmospheric Administration, NWS = National Weather Service.

**DISCUSSION AND CONCLUSIONS**

Morphological changes on beaches and barriers during extratropical storms and hurricanes are controlled primarily by (1) differences in elevations between the wave runup and adjacent land surface, (2) differences in hydrostatic head between the ocean and adjacent lagoon, and (3) duration of backbeach flooding. Other controlling factors include storm path, timing of storm events, magnitude of wind stress, antecedent topography, type and density of vegetation, and sediment textures. These factors largely determine the morphologies, textures, and spatial ranges of deposits and the durability of storm-induced coastal changes.

A historical-empirical classification is proposed to forecast storm impacts as a complement to physics-based numerical models. The classification can be used to initially anticipate storm responses. For example, if beach or barrier topography exceeds storm surge height, high waves and strong nearshore currents degrade the beaches and dunes and transport the eroded sediments alongshore and offshore. Both landward and seaward sediment transport can occur if beach or barrier topography is less than storm-surge height. Prolonged backbeach flooding increases the volume of sand excavated from the beaches and dunes. Consequently, slow moving or stalled storms of moderate intensity can cause as much change as fast moving, intense storms.

Rapidly rising ocean levels and long distances to the nearest inlet produce relatively steep water level gradients between the ocean and lagoon. The gradients cause disequilibrium conditions across barriers that promote breaching of barrier islands and scouring of deep, narrow washover channels or new inlets. Confined washover flow through discrete channels generally favors channel incision, scour, and construction of discrete fans and greater inland penetration compared to unconfined sheetwash flow. When wind circulation patterns increase lagoon levels above ocean levels, then channel incision and seaward flow can cause beach washout and dune breaching. However, the convergence of conditions that optimize washout is rare compared to the frequency of washover.

Forecasting of storm impacts on sandy beaches and barriers may be possible if the following information is available: (1) an integrated geomorphic and topographic map that depicts extant ground conditions and storm vulnerability, (2) a coastal response model that incorporates the impacts of previous extreme storms, (3) a compilation of historical storm parameters linked to the coastal response model, and (4) near-real-time surge and wave runup predictions for storms expected to influence a particular coastal sector.

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**LITERATURE CITED**


