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State of Knowledge on Measurement and Modeling of Coastal Overwash

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ABSTRACT

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A critical review is presented on the state of knowledge and calculation capability for coastal overwash. Overwash and overwash deposits (washover) accompanying hurricanes and severe storms can devastate coastal communities and habitat, but in many areas these processes are essential for maintaining the integrity of barrier islands while creating new habitat. This review covers general studies of overwash processes, studies from a geological perspective, physical modeling, field studies including measurements of washovers and related hydraulics, and the state of numerical modeling capability to predict overwash. Although significant literature exists describing individual overwash events and locations experiencing frequent overwash, complete hydrodynamic and morphologic documentation of an overwash event is lacking. A limited number of algorithms or models exist to quantify overwash occurrence, deposited sand volume, and upper beach profile evolution. Existing models of overwash occurrence and one-dimensional beach profile evolution have been shown to perform successfully against available data, and areas of improvement are identified. Models must be made capable of simulating the various washover morphologies that have been produced by different hydrodynamics, overwash spreading based on dune topography, friction and percolation, and interaction between swash bores. Comprehensive laboratory and field data sets to achieve these aims are still lacking.

ADDITIONAL INDEX WORDS: *Washover, barrier island morphology, hurricanes, runup, inundation, breaching.*

INTRODUCTION

The capability to predict the occurrence and consequences of storm damage is an important responsibility of coastal engineering. Coastal overwash occurs frequently around the world, but it is most evident following hurricanes and winter storms on the Atlantic and Gulf Coasts of the United States. The capability to quantitatively predict and simulate overwash and overwash deposits (washover) is just beginning to emerge. This paper reviews the state of knowledge of coastal overwash and modeling capability with the intent of stimulating research in this area. The review updates and extends information presented in a collection of papers entitled *Overwash Processes,* compiled and edited by LEATHERMAN (1981).

Overwash is the flow of water and sediment over the crest of the beach that does not directly return to the water body (ocean, sea, bay, or lake; hereafter, ocean) where it originated. Overwash occurs if either wave runup level or storm surge level (water level in excess of predicted tide) exceeds beach crest height. If the storm surge coincides with high tide, the surge level and hence potential for overwash is greater. For moderate storms, it is possible for overwash to start near high tide and stop during lower stages of the tide, depending on the storm surge and the elevation and width of the beach. Figure 1 shows an example of large-scale landward overwash of Assateague Island, Maryland/Virginia, United States, following successive northeasters on 24 January and 5 February 1998. The overwash reached Sinepuxent Bay, located to the west (left side of picture), at several locations. Vegetated washover deposits from previous storms are evident on the bay side of this barrier island.

Hydrodynamic and morphologic conditions promoting overwash are most common on sandy barrier islands, but overwash can also occur on lakes, on low-profile mainland coasts, on spits, and on gravel or shingle beaches. This review found documentation of overwash on the coasts of Australia, Canada, Denmark, Ireland, Portugal, Spain, the U.K., the United States, on the Baltic Sea, on the Black sea and on the Great Lakes of Canada and the United States. The majority of the literature pertains to overwash on the barrier islands of the Atlantic and Gulf coasts of the United States.

Washover is the sediment deposited inland of a beach by overwash. Washover can be deposited onto the berm crest or as far as the back barrier bay, estuary, or lagoon. Overwash of the mainland deposits sediment landward of the local beach crest. The quantity and shape of washover depends on the relative levels of the beach crest, water level, and wave height, and the duration of the storm, together with the back beach morphology, vegetation, and wind strength and direction.

On barriers, seaward overwash may also occur, the result

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Figure 1. Large-scale overwash on Assateague Island, Maryland/Virginia, following northeasters in late January and early February 1998. (View looking northwest; picture taken 8 February 1998.) **For color version of this figure, see page 888.**

of high bay water level and strong wind creating wind setup and waves incident toward the back barrier shoreline. Severe overwash occurs primarily in association with a major storm or a hurricane, although large morphological change by nonstorm washover is also possible, for example as observed on the Colombian Pacific coast by elevated sea level most likely caused by El Nino and spring tides (MORTON *et al.,* 2000).

Overwash is a natural process, and new washover areas sustain unique ecosystems, such as salt marshes that support various species of salt-resistant plants (*e.g.,* halophytes) (GODFREY and GODFREY, 1974) and the habitat necessary for piping plover (*Charadrius meloduso*), an endangered species along the Atlantic and Gulf coasts of the United States. On a pristine coast, overwash and windblown sand are the mechanisms by which the barrier islands migrate, and possibly how the barrier islands respond to sea-level rise (*e.g.,* BYRNES and GINGERICH, 1987; DOLAN and GODFREY, 1973; SCHWARTZ, 1975).

In developed areas, overwash can be a hazard, because erosion of the beach face allows upland areas and development on these areas to become vulnerable to storm damage. If dunes are lowered or destroyed, the storm-protection function of the beach is degraded and overwash can occur. In the extreme, overwash can be a precursor to breaching by initiating erosion of the beach face, lowering the crest elevation of the beach profile, and transporting sediment from the beach and back beach into the bay (KRAUS, MILITELLO, and TODOROFF, 2002; KRAUS and WAMSLEY, 2003). The formation of Chatham Inlet, Massachusetts, through Nauset Spit is an example of such breach development (STAUBLE, 2001).

In developed areas, overwash can damage coastal property and infrastructure, and washover in the backbarrier bay may hinder navigation. Washover that reaches the backbarrier bay also alters the inshore coastline of a barrier. In these developed areas, it may be desirable to prevent or limit overwash to preserve infrastructure and private or public property. However, experience has shown that preventing overwash entirely may also lead to increased beach erosion (DOLAN and GODFREY, 1973). Where large dunes (or seawalls) prevent overwash, beach sediment fronting the dunes can be transported offshore during a storm, causing the barrier island to narrow. Where overwash is allowed to occur, the net

volume of sand is often maintained, but the ocean and bay shoreline and dune crest positions translate shoreward. This is called barrier island rollover and is a natural process by which barrier islands maintain width and volume during rising sea level conditions. From a coastal management perspective, the landward transport of sediment by overwash must be accounted for as a sink term in a littoral sediment budget.

One of the earliest descriptions of overwash was given by JOHNSON (1919), who described "wave deltas" deposited into Laguna Madre, Texas, by storm waves that "dashed" over the barrier crest. Other early studies on overwash include that of LOBECK (1939), who described the deposits left by storm waves breaking over the barrier crest as "washover" and considered washover as the cause for the irregular inland coastlines of barriers. PRICE (1947) suggested that washover was a more suitable term than wave delta because of the disassociation with a singular wave event. He suggested "washover fan" to be a more complete description of the deposits. PRICE (1947) also suggested that washovers might be deposited by elevated water (tidal) levels rather than wave runup alone. Study and understanding of overwash and overwash processes increased rapidly in the late 1960s through the end of the 1970s, and most of this work is reported in the geological literature. Several botanists also contributed to the physical understanding of overwash. There has been a resurgence of interest in overwash and overwash processes with development of the coast and requirements of beach and dune design for storm protection.

Recently, varied overwash impacts were well documented in 2004, when three hurricanes and one tropical storm crossed the United States Gulf and Atlantic coasts within the state of Florida. Hurricane Charley made landfall on the west coast of Florida on 13 August 2004, inundating and breaching large sections of North Captiva Island. Hurricanes Frances and Jeanne crossed the central east Coast of Florida on 5 September and 26 September, respectively, causing mostly runup overwash at isolated locations along the coast. Hurricane Ivan crossed the Gulf of Mexico coast on 16 September, just east of the city of Mobile, Alabama, as a Category 3 (Saffir-Simpson scale) hurricane and with a maximum storm surge of 4.9 m. Damage attributed to just this storm encompassed 23 counties of three states and exceeded $5 billion (erosion, flooding, wave, and wind damage). Large-scale overwash by inundation occurred, and in some places, the Gulf Island National Seashore (GINS) was inundated with coupling between the ocean and the sound water levels. Along many stretches of the GINS, the road was either buried by sand or washed away by scour. On developed parts of Santa Rosa Island, Florida, 1.2–1.5 m of washover sand was deposited on property, over roads, and through buildings. Channel formation and temporary and permanent breaching were also observed (BUREAU OF BEACHES AND COASTAL SYSTEMS, 2004). The hurricane, although still of Category 5 strength, also caused large-scale overwash by inundation on Grand Cayman Island.

This critical review of the literature begins with field and laboratory studies. Then, existing procedures for calculating and modeling overwash hydraulics and morphology are discussed. The role of overwash in barrier migration and response to sea-level rise is also covered. Commonalities and differences in findings are compiled. Based on the review, recommendations are made for field data collection and laboratory studies that would provide needed basic information on overwash and washover processes and contribute to improved predictive modeling of beach profile and barrier island change.

DEFINITION OF OVERWASH PROCESSES AND MORPHOLOGIES

Much of the literature on overwash concerns singular regional or temporal events. A coast may overwash by either: (1) excessive wave runup, a lower-magnitude event that causes washover fans and terraces; or (2) mean water level exceeding the beach crest, generally a larger-magnitude event causing sheetflow and even barrier rollover. These processes may occur together, varying either spatially along a coast or at one location during different phases of a storm. Recent publications (MORTON *et al.,* 2000; SALLENGER, 2000) have clearly defined the differences between overwash occurring from wave runup and overwash occurring when the water level (including surge and wave setup) exceeds the beach crest. SALLENGER (2000) called the latter "inundation regime" in his Storm Impact Scale, and it is often called storm surge flooding or coastal flooding in the media. Most authors (*e.g.,* BYRNES and GINGERICH, 1987; DOLAN and GODFREY, 1973; LEADON, 1999; WEIR, 1977) have referred to water level exceeding the beach crest as overwash. In this paper, the two different processes are referred to as (1) runup overwash and (2) inundation overwash. These classifications are developed in DONNELLY, KRAUS, and LARSON (2004) and within the scope of this review.

Overwash of various magnitudes results in different morphological deposits. Below, four different overwash regimes and the resulting washover morphologies described in DONNELLY, KRAUS, and LARSON (2004) are further defined. Any of the regimes may occur within one storm, varying both spatially and temporally. Figure 2 is a schematic plan view over a typical dune line (or beach crest) subject to overwash with three common overwash deposit types.

Runup Overwash

The first two overwash regimes are caused by wave runup overtopping the beach crest or local discontinuities in the dune crest. Figure 3 is a schematic cross-sectional depiction of a sand dune or berm crest subject to high surge level and overtopping by waves. Runup overwash can be categorized in terms of the relative elevations of water level and the barrier beach, the frequency of overtopping waves, and the excess wave runup, ΔR. The quantity ΔR is the difference between the wave runup height, R, added to the storm surge height, S, and the dune or beach crest height, d_c; ($\Delta R = R + S - d_c$), where d_c is the elevation to the dune crest from the mean water level (or from some common datum).

Regimes 1 and 2, caused by runup overwash, can be classified according to the relative magnitudes of $R + S$ and d_c.

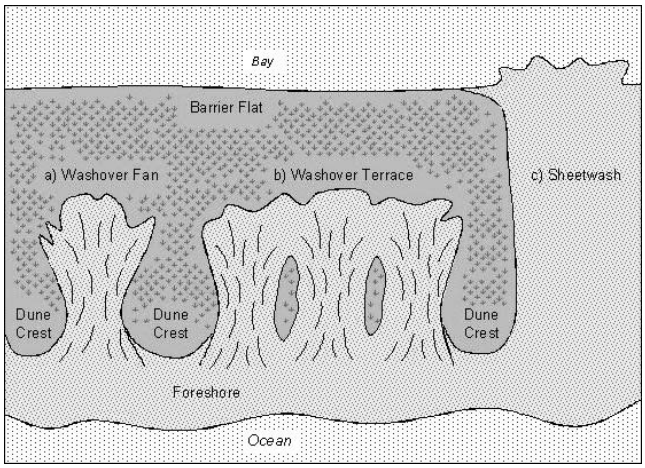

Figure 2. Definition sketch of common morphological deposits occurring during overwash of dunes or beach crests such as (a) a washover fan, (b) a washover terrace, and (c) sheet wash deposit.

1. $R + S \approx d_c$ (crest accumulation): If $R + S$ is just slightly larger than d_c, few waves overtop the dune, and for those that do ΔR is small. Sediment is deposited on the dune crest or in the throat of an existing washover (CARTER and ORFORD, 1981; FISHER, LEATHERMAN, and PERRY, 1974; LEATHERMAN, 1976a; ORFORD, JENNINGS, and PETHICK, 2003) and hence the crest of the throat or berm is raised, which may eventually halt further overwash. The term crest accumulation was first used to define overwash processes by ORFORD, JENNINGS, and PETHICK (2003).
2. $R + S > d_c$ (crest lowering): S is still less than d_c, but many waves have sufficient excess runup, ΔR, to overtop the dune. Sediment is eroded from the face of the dune or beach crest and transported to be deposited on the backshore.

The resulting deposits vary according to local barrier topography and ΔR. Where dunes are relatively high, but uneven, overwash usually exploits existing gaps or lower areas

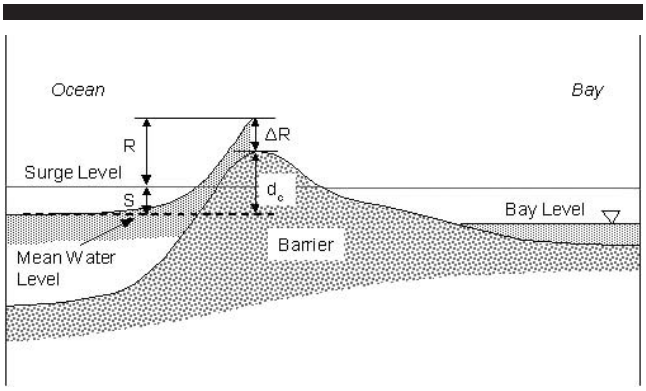

Figure 3. Definition sketch showing the cross-section of a barrier beach subject to overwash by wave runup.

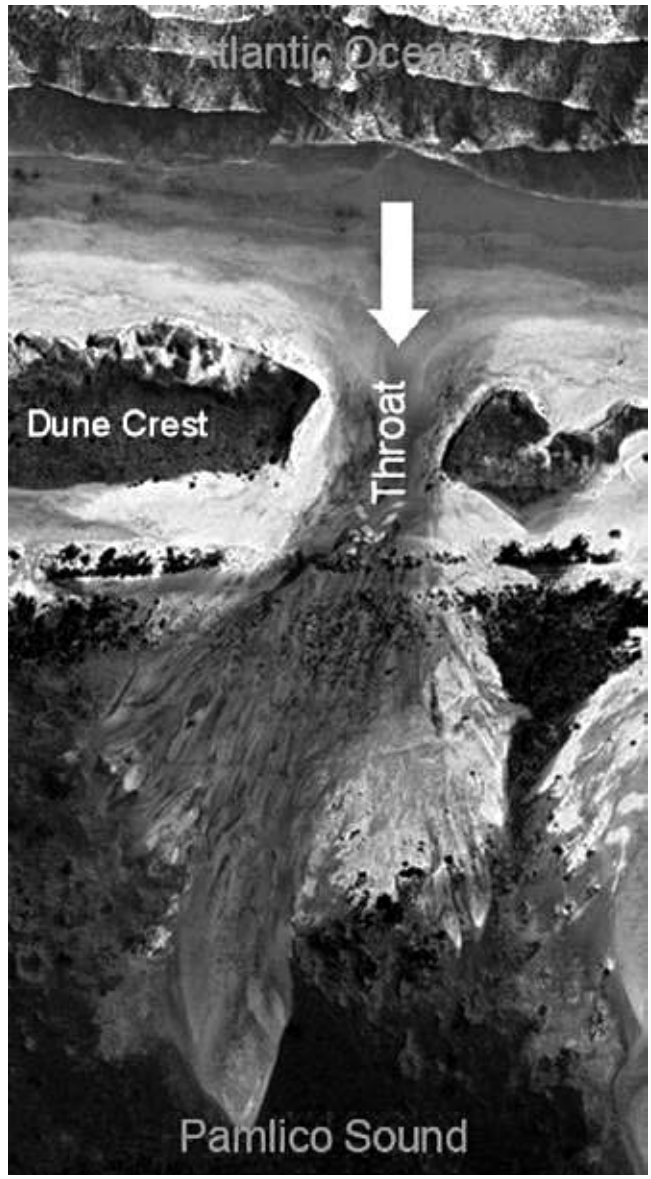

Figure 4. Washover fan deposited on Ocracoke Island, North Carolina, during Hurricane Isabel, September 2003. **For color version of this figure, see page 889.**

in the foredune line, funneling through the gap of the breach and spreading laterally on the back barrier. The gap is often called the "throat" of the overwash. As the water mass spreads laterally on the back barrier and friction and percolation take effect, the velocity of the bore decreases, and the entrained sediment is deposited. This may be called "fanning overwash" because the resulting depositional feature is called a "washover fan." Such fans can reach the barrier lagoon. Figure 4 shows a washover fan on Ocracoke Island, North Carolina, deposited during Hurricane Isabel that made landfall on 18 September 2003. Note the fanning out of the deposit on the back barrier and sand deposited into Pamlico

Figure 5. Washover fan deposited on Ocracoke Island, North Carolina, during Hurricane Isabel, September 2003. **For color version of this figure, see page 889.**

Sound. Fanning of overwash can be restricted by local topography. Figure 5 shows another washover at Ocracoke Island where the overwash was funneled along a beach access path and spreading was restricted by the flanking topography until the overwash bore reached the road.

If the longshore rate of expansion at which fanning overwash occurs is high, the borders between individual fans become less well defined, and the deposits form a washover terrace (also washover apron) (Figures 1 and 2). Washover terraces can also form where the beach crest is low and uniform. Washover that extends into the back-barrier lagoon appears as a subaqueous washover delta (LEATHERMAN, 1976a). Even where a washover does not reach the back barrier, water may run off from the fan to the bay via "sluiceways" or "guts" (Figure 6). According to LEATHERMAN (1976a), sluiceways are small vegetated channels at the water table that convey the water down to the bay, whereas guts are deeper, wet channels that usually form where the fan is nonvegetated or

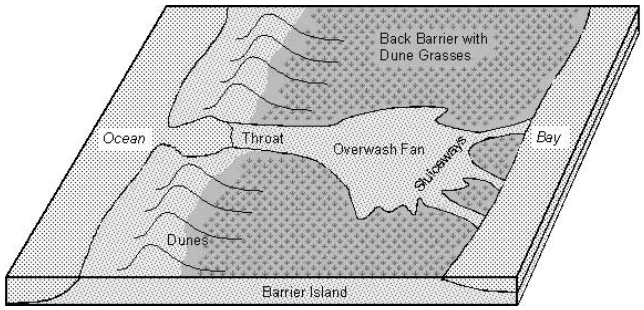

Figure 6. Schematic showing typical overwash fan morphology.

where overwash has been frequent enough to remove or lay back the vegetation.

Inundation Overwash

The third and fourth overwash regimes occur where $S > d_c$. The consequences of overwash by inundation vary depending on the extent of beach inundation and the beach topography. The water and sediment transported landward as a result of a water level raised above the general dune crest height was called "sluicing overwash" by ORFORD, JENNINGS, and PETHICK (2003), but is also known as sheet wash or sheet overwash. Sheet overwash covers a wide lateral extent of the beach.

3. $S \approx d_c$ (minor inundation): During extreme storms or on low-profile barriers or beaches, where S exceeds d_c, water flows constantly over the beach crest during the time of higher water level. Sediment is eroded from the beach face and/or the back barrier, but because of either a large barrier width, beach topography, low S, porosity, or friction (*e.g.,* vegetation), the overwash does not reach the bay, and washover is deposited as the bore slows. Where the dune crest height is uniform, a sheet of water and sediment flows over the crest and the deposition is usually caused by porosity and friction losses. If S exceeds d_c locally, for example at a gap in the dune line, fanning overwash occurs, and, as observed for runup overwash, the deposit may first be accelerated by funneling and then slowed by lateral spreading, depending on the topography. Because of the constant flow of water through a gap in the dune line, overwash fans caused by minor inundation often have channels eroded in the throat.
4. $S > d_c$ (complete inundation): Where the submergence of the crest is sufficient, an entire barrier or spit can become inundated. If coupling between the ocean and bay occurs, it is the magnitude of the water level gradient between ocean and bay, $S - d_b$, that drives the net flow and hence the amount of sediment transported (Figure 7). The quantity $S - d_b$ is defined as the difference between the water level in the bay and the mean water level in the ocean (surge not included). Complete inundation overwash erodes the shoreline, and deposits large amounts of sediment inland

of the beach (*e.g.,* 1–2 m were deposited on Santa Rosa Island during Hurricane Ivan).

Sometimes during complete inundation overwash, a length of beach is subject to a continuous flow of water over the entire crest, but localized inundation through a gap in the beach crest may also occur. Such overwash causes channeling and even temporary breaching. A temporary breach closes after the water level returns to normal, as opposed to a full breach, which may remain open for a long time. Inundation along the shore causes sheet overwash (Figure 2). Sheet overwash is more common on barrier spits and where coastal dunes are low, but it may also occur after persistent wave attack or overwash has reduced the existing dunes to a sufficiently low level. An example of sheet overwash on the Texas mainland is shown in Figure 8. Where sheet overwash occurs, lateral spreading is negligible, and sediment is often carried over hundreds of meters and deposited in the back barrier lagoon. Complete inundation overwash can either lead to net erosion or deposition depending on $S - d_b$, wind and wave currents, and the tide strength and direction. This type of overwash also initiates the breaching process, and the action of tide can temporarily generate ebb and flood flow, similar to that at an inlet.

FIELD STUDIES

Nearly all of the literature regarding overwash is based on qualitative field observations. Overwash is a phenomenon of interest in disciplines as varied as botany, ecology, engineering, geology, geography, and planning, so the objectives and nature of these field observations vary significantly. Field studies of overwash can be divided into four types: (1) poststorm studies, (2) regional studies, (3) monitoring and site-specific measurements, and (4) sedimentologic studies. The first three are discussed in detail here, whereas only the most morphologically or hydrodynamically pertinent of the sedimentologic studies are reviewed.

Poststorm Studies and Reports

Poststorm studies and reports provide valuable insight into overwash processes (*e.g.,* BYRNES and GINGERICH, 1987; EISER and BIRKEMEIER, 1991; LEADON, NGUYEN, and CLARK, 1998; MORTON *et al.,* 2003; SUTER *et al.,* 1982). Nearly all of these studies provide pre- and poststorm cross-shore profile surveys of overwashed areas, together with qualitative observations of the processes. Such surveys give information on overwash processes and washover morphologies, and some studies also contain data sets useful for modeling beach profile change. This section reviews selected poststorm studies and reports that made interesting or new observations, or that drew new conclusions regarding overwash.

SUTER *et al.* (1982) presented new descriptions of washover morphologies and provided further interpretation of overwash processes based on a study of aerial photographs taken after Hurricane Allen, 1980, on South Padre Island, Texas. Lower parts of South Padre Island were inundated by the hurricane surge, and a time lag in surge level between ocean and bay of 14 hours generated a 1.5-m high water gradient across the island. This study was the first to impress the importance of and quantify water level gradients across barrier islands. Using Manning's equation, the gravity-driven current across the island was calculated to reach a maximum of 0.55 m/s. Where coastal dunes existed, the surge penetrated gaps in the dune line forming channels below the surge level (*i.e.,* inundation overwash), through which overwash flowed and deposited sediment fans on the back barrier. Currents generated by the water level gradient and funneling through these channels were calculated to reach about 2 m/s. SUTER *et al.* described the resulting washover morphology as "heart shaped" fans. The gaps may have been formed by the event or may have been preexisting gaps lowered by this event. Aerial photographs of an area with frequent overwash fans indicate a regularity of channel formation that may be related to surf zone processes. SUTER *et al.* (1982) also described the reactivation of closed tidal inlets by overwash caused by low beach elevations. Large gaps in the foredune ridge existed at the closed-off tidal inlet between Mustang and Padre islands, and the area was therefore vulnerable to high wave runup and storm surge causing extensive washovers (the largest resulting from Hurricane Allen).

BYRNES and GINGERICH (1987) studied overwash on Metompkin Island, Virginia, following Hurricane Gloria (27 September 1985). Metompkin Island is a low-profile duneless barrier on the Atlantic Coast of the United States. By analyzing cross-shore beach profiles surveyed before and after the hurricane, they showed that the seaward volume losses from shoreline recession were approximately balanced by the addition of sediment volume landward of the beach crest caused by overwash. Pre- and poststorm beach profile shapes were shown to have a similar shape, with the poststorm profile translated landwards. Therefore, the island migrated landward, while maintaining its general shape, a process known as rollover. The rate at which this occurred varied along the barrier island. The northern end, which had a lower prehurricane elevation, migrated 4.5 times faster than the southern end, which was higher. Additionally, the southern end lacks the marsh surfaces seen on the back beach of the northern part of the island, so overwash carried to the other side of the island was deposited directly into the bay.

STAUBLE (1991) and EISER and BIRKEMEIER (1991) report on overwash caused by Hurricane Hugo, which crossed the Atlantic Coast of the United States in September 1989. Surge levels reached 6.1 m during this Category 4 hurricane, bringing widespread inundation overwash of barriers by sheet overwash, and also inundation overwash of the mainland. Notable observations from STAUBLE (1991) include the removal of dunes up to 5 m high and the transport of sediment and other material (debris) across a spit and marsh onto the mainland, demonstrating the power of type 4 overwash (complete inundation), even where coupling between the ocean and bay does not occur. Also, overwash was observed between gaps in longshore protection structures such as seawalls. Overwash in these locations caused scour at the edges of structures and damage to their landward sides.

A comprehensive poststorm report for Hurricane Opal is provided in LEADON, NGUYEN, and CLARK (1998). On 4 October 1995, Hurricane Opal made landfall on the Florida Pan-

handle coast, United States. The storm surge height, including wind and wave setup, was estimated from nearshore water level measurement to vary between 3.6 and 4.9 m along the coast. Poststorm surveys show erosion or complete removal of dunes, even where the prestorm dune crest appears to be higher than the storm surge level. This suggests that runup overwash may be sufficient to remove dunes, perhaps by dune scarping and offshore erosion prior to overwashing. Although the profile data presented in LEADON *et al.* (1998) are useful for qualitative analysis, they do not extend sufficiently shoreward to evaluate the full extent of overwash deposition.

MORTON *et al.* (2003) presented a retrospective study of overwash impacts of the Ash Wednesday storm of March 1962 on the mid-Atlantic Coast, United States. The Ash Wednesday storm is well known because of its long duration, which caused significant damage along the U.S. Atlantic Coast. The storm, a northeaster, was almost stationary for five high tides, creating favorable conditions for overwash. Dune heights that were originally sufficiently high to prevent overwash were eroded by the high water levels and waves, eventually allowing overwash. MORTON *et al.* (2003) categorized the morphologic response between New Jersey and North Carolina into four categories. Twenty-three percent of the coast had high dunes that were eroded but maintained a dune shape and formed dune scarps. Such dunes blocked or minimized overwash. Seventy-eight percent of the coast consisted of washover terraces, 5% sheet overwash, and 4% channel or inlet incision. Note that the numbers exceed 100% because some parts of the coastline responded in more than one way. MORTON *et al.* (2003) also studied the washover penetration distances from high-quality poststorm aerial photography. Maximum washover penetration was 700 m, and highest penetrations occurred as sheet overwash or where channels or inlets were incised. The average washover penetration distance along the coast was about 290 m. Developed shores, with hard coastal structures, showed less washover penetration of the shoreline than nondeveloped shorelines. Where roads intercepted coastal sand dunes or in developed areas where dune heights were reduced, washover penetration increased. The average depth of deposited washover was estimated to be between 0.5 and 0.7 m. It is interesting to note that some of the overwash impacts of this storm can still be seen more than 40 years later.

Regional Studies

Many studies of overwash have made use of aerial photography to examine longshore variations in existing overwash morphologies. These are summarized in this section.

Some of the first known studies to explicitly describe overwash processes were those of PIERCE (1969, 1970). PIERCE (1970) compared and contrasted existing tidal inlets and washover fans, suggesting that the formation of one or the other is a function of the barrier configuration, the lagoon depth, and the direction of overwash (landward or seaward, where seaward overwash is caused by bay water levels exceeding the bay beach crest height). Inlet formation was described as a consequence of seaward overwash channeled along tidal creeks and, to a lesser extent, landward overwash and breaching on a narrow barrier with no tidal flats. On a wide barrier, landward overwash deposited washover fans on the tidal flat. PIERCE conjectured in this case that a washover fan is a more likely occurrence than breaching, because a wide barrier usually has a milder back barrier slope, resulting in lower flow velocities and hence less erosion.

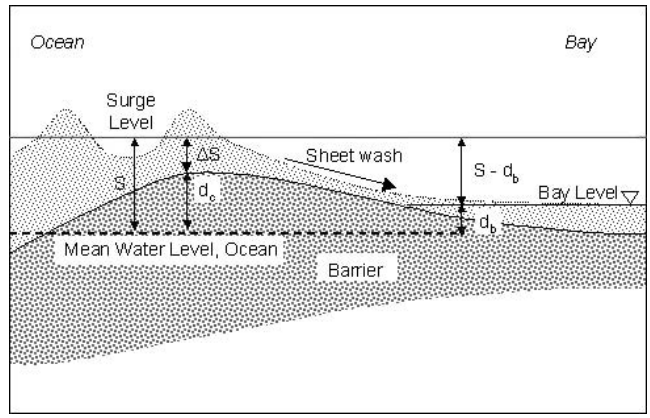

Figure 7. Definition sketch showing the cross-section of a barrier beach subject to overwash by inundation where the barrier is fully inundated.

CLEARY and HOSIER (1979) studied a series of aerial photographs from 1938 to 1977 of the southeast North Carolina Coast, United States. They selected vegetation destruction lines (the landward limit of vegetation damage after an event) and foredune removal as washover indicators, and remarked that even where dunes had revegetated, a washover penetration line was still evident behind the new dune. They distinguished between coastal sections of intact dunes, isolated washover fans, washover terraces, and foredune recovery. Using these categories and the large temporal range of data, they suggested that beaches subject to overwash in fine-grained sediment areas recovered faster after an event than beaches subject to overwash in coarse-grained sediment areas, because the fine-grained washovers can then be redistributed by the poststorm wind climate into dunes, hence making them less susceptible to repeated overwash.

DOLAN and HAYDEN (1981) analyzed 40 years of historical shoreline position data and overwash penetration measurements for the Outer Banks, North Carolina, and Fenwick Island, Maryland, to quantify change in shoreline position and overwash penetration rate. They also analyzed the shoreline erosion and overwash penetration positions resulting from the 1962 Ash Wednesday storm to quantify poststorm conditions. For the 1962 Ash Wednesday storm, visual observation indicated that overwash penetration was at a maximum where the rate of overwash penetration prior to the storm was at maximum. A significant correlation was calculated between these two signals. This is probably because beach or dune crest heights are lower where overwashing had occurred previously, making such areas more susceptible to future overwash. A similar trend was observed for shoreline recession, although there was no statistically significant correlation be-

Figure 8. Beach at Jefferson County, Texas. (View looking south.)

tween the shoreline recession and the 1962 storm overwash penetration. DOLAN and HAYDEN (1981) also analyzed longshore shoreline erosion rates and overwash penetration positions for longshore periodicities. Their analysis indicated periodicities of 15.5 km and 13.3 km for the two barrier islands.

ORFORD and CARTER (1984) compared overwash throat spacing on sections of beach with and without dunes on a coarse clastic barrier in southeast Ireland. The spacing of overwash throats was determined by land survey techniques, as opposed to the method of DOLAN and HAYDEN (1981), who analyzed aerial photography. Where dunes were present, their analysis indicated that the throat spacing was random, but on the duneless section of barrier, their analysis showed that the throat spacing had a periodicity ranging between 30 and 40 m. The authors hypothesized that the regular throat spacing may be related to a zero-mode, subharmonic edge wave whose longshore wavelength matches the overwash spacing given that long period waves (9–11 s) are dominant in Celtic Sea storms. This hypothesis is covered in the discussion section on overwash occurrence.

By analyzing the washover deposits produced by 17 hurricanes on the Gulf Coast, PENLAND and SUTER (1984) demonstrated that the angle at which a hurricane crosses a barrier island exerts some control on the location of peak overwash occurrence. A hurricane that approaches normal to the shore has the highest peak surge and strongest onshore winds ahead of the eye of the storm and to the right of the eye because of the direction of wind and forward momentum of the storm. Thus, the greatest overwash occurs to the right-hand side of the storm. Occasionally, the weaker offshore winds on the left of the hurricane can cause some seaward overwash, but this is usually followed by landward overwash as the storm passes and onshore winds resume. PENLAND and SUTER (1984) define hurricanes approaching the shore obliquely as either left-oblique impact or right-oblique impact, depending on the side the storm approached from (facing the shore). A right-oblique impact is similar to a shore-normal impact, but a left-oblique impact can cause significant seaward overwash to the left of the storm because the peak storm surge is lagged behind the storm impact and the strong hurricane winds are directed offshore. These factors combine to give an elevated water level in the back-barrier lagoon and a lower water level on the open coast, and hence seaward overwash may occur. As the storm passes inland and the storm surge reaches the coast, the direction of overwash can reverse. Further observations supporting overwash reversal were made by PENLAND *et al.* (1989), who observed the impacts of three hurricanes that crossed the Gulf Coast, United States, during 1985. Observations included strong seaward overwash, fluidized mud overwash of the Louisiana Chenier plains, and varying degrees of coastal overwash.

Botanists have also made contributions to the understanding of overwash deposits. GODFREY and GODFREY (1974) studied aerial photographs, old maps, and records of ephemeral inlets on Core Banks, a low barrier island on the North

Carolina coast, for the period 1939 to 1974. They surveyed an overwash fan and the surrounding dunes and marshes, and took sediment plugs to examine the sediment history of the island. GODFREY and GODFREY (1974) related overwash with salt marsh formation on barrier islands. Vegetated washovers soon develop a layer of peat on their surface. Vegetated washovers extending into the backbarrier lagoon or tidal creeks provided a ramp for tidal runup that flushes detrital nutrients. They acknowledged the role of salt-resistant plants in maintaining dunes and slowing overwash, and they suggested that overwash processes, beach preservation, dune vegetation, and barrier island migrations were interrelated. DAHL *et al.* (1983) analyzed pre- and posthurricane surveys to quantify the effects of vegetation on dune change following an overwash. Similar to the observations of GODFREY and GODFREY (1974), a greater quantity of sand was transported inland for the unplanted dune. Between overwash events, vegetated dunes were shown to accumulate more sand (during eolian transport), increasing their resistance to overwash.

Monitoring and Site-Specific Measurements

Detailed field studies have been conducted, usually involving monitoring of sites known to overwash regularly. The placement of data collection equipment and presence of researchers at an expected overwash during a large storm is potentially dangerous and hence not typically feasible, so most such studies pertain to low profile barriers and spits that overwash under nonstorm conditions. Exceptions to this are the experiments carried out at Assateague Island during northeaster storms and a Category 1 hurricane (*e.g.,* FISHER, LEATHERMAN, and PERRY, 1974; FISHER and STAUBLE, 1977, 1978; LEATHERMAN, 1976). This section summarizes field studies according to (1) field measurements at Assateague Island, and (2) field measurements elsewhere.

1. Field Measurements at Assateague Island

Because of the low profile and accessibility of its northern end, Assateague Island, Maryland, United States is a convenient location at which to measure overwash, even during storms and offshore hurricanes. Results from the earliest and most comprehensive of these studies, a 26-month intensive study on five overwash sites on Assateague Island, were published by FISHER, LEATHERMAN, and PERRY (1974), LEATHERMAN (1976a, 1976b, 1976c, 1977, 1979a, 1979b, 1979c), LEATHERMAN, WILLIAMS, and FISHER (1977), and FISHER and STAUBLE (1977, 1978). Their overwash measurements included profile change volume from pre- and poststorm surveys and visually observed depths of overwash, velocities from bidirectional current meters (and visual observations), and approximate suspended sediment volumes during northeasters and a Category 1 hurricane positioned offshore.

Five sites with washover fans and broad washover flats were surveyed regularly along cross-shore transects (LEATHERMAN, 1976a). Additionally, a grid was established at Site 1, a distinct washover fan, and surveyed monthly and immediately prior to and following storms. Land-based photography of the sites supplemented the qualitative morphological change data. For the earliest experiments, velocity in the washover throat was measured with a Gurley current meter during events. Frequency of overwash bores was also interpreted from the current meter record (FISHER, LEATHERMAN, and PERRY, 1974). Later experiments employed a Marsh McBirney bidirectional electromagnetic current meter and a Hydro Products pressure transducer to continuously measure velocities and depths in the washover throat (LEATHERMAN, 1976a; FISHER and STAUBLE, 1977). The current meter functioned well, but the flow depths were insufficient for the successful functioning of the pressure transducer. Suspended sediment was measured on the beach with a custom-built sampler (LEATHERMAN, 1976a). Flow depths in the washover throat were too small for the sampler, but suspended sediment in the throat was collected using vials during the earlier experiments described in FISHER *et al*. (1974).

The following describes a typical event. The dune was subject to overwash by runup during a northeaster in March 1973. Approximately one surge per minute overwashed the dune, in some cases reaching the bay. Given an offshore wave period of 8–12 seconds, approximately one in six waves overwashed. Instantaneous velocities in the throat reached a maximum of 2.4 m/s. Colored sand plugs were inserted to reveal erosion depth. The study showed that erosion was concentrated in the throat of the washover, but the net result of the two overwash events was deposition in the fan, which thinned toward the bay. As a result of this deposition, particularly at the end of the storm, the width of the throat reduced (LEATHERMAN, 1976a). As can be seen, the monitoring of actual overwash events contributed significantly to the type of data available to analyze overwash hydrodynamics.

The sites at Assateague Island were also monitored during Hurricane Belle, a Category 1 hurricane that traversed 82 km offshore, parallel to Assateague Island (FISHER and STAUBLE, 1977). During this event, the island overwashed for 2.5 hours, coinciding with the peak storm surge and high tide. Similar to the 1973 northeaster, the surges occurred on average 1 per minute. The deepest surge measured 0.7 m above the throat surface, and the most powerful surges registered velocities in the throat exceeding 3.5 m/s. Profiles were surveyed after the storm to determine the morphology change resulting from these conditions. The barrier crest rolled landwards and increased slightly in height. Some sand was deposited in the back barrier bay. A small beach berm on the beach face was removed. The net sand deposition on the back barrier resulting from this overwash event was very similar to the net sand deposition resulting from a large northeaster storm in this area.

FISHER, LEATHERMAN, and PERRY (1974) presented a four-step conceptual model for overwash processes based on their observations from the earlier experiments:

1. Erosion in the throat.
2. Deposition of sand on the fan and in the bay.
3. As storm intensity decreases, overwash bore velocities decrease and sand is deposited on the throat and in the fan.
4. The washover is reworked by the abating storm winds.

Although each of the defined processes occurs, it is now known that the order of the first three can interchange depending on surge hydrograph and storm development.

Results from the first two storms encountered during the study were used to quantify the role of overwash in the sediment budgets of barrier islands (FISHER *et al.*, 1974). Both LEATHERMAN (1976a, 1976c, 1979a, 1979b) and FISHER and STAUBLE (1977, 1978) discuss overwash sediment budgets and the relative role of overwash sedimentation and eolian deflation concluding, for the study period, that eolian deflation was the dominant process, and thus the contribution of overwash is limited. Although this may have been true for the study period and location, KOCHEL and DOLAN (1986) and KOCHEL and WAMPFLER (1989) showed a greater contribution by washover to the sediment budget if studied over a longer period.

LEATHERMAN (1976a, 1976c, 1977) made pioneering contributions to the understanding of overwash hydrodynamics. Reynolds and Froude numbers calculated for several events showed that flow in the overwash is generally turbulent and subcritical but that the front of the surge may be supercritical (LEATHERMAN, 1977). Sediment sampling showed that a large surge often left a distinct sedimentation unit, and smaller surges sometime had entirely insignificant transport rates, but may involve *in situ* grain sorting (LEATHERMAN, 1976a). There are four suspended sediment measurements that can be compared with the instantaneous velocity measurements in the throat for the corresponding surge. Although all of the measured surges reached a maximum instantaneous velocity of 2.4 m/s, there were large variations in the amount of suspended sediment measured. Two of the overwash surges were short, involving one velocity peak and a small volume of overwash. These two overwashes carried almost no suspended load. The other two overwash surges were deeper and involved larger volumes of water and two or three velocity peaks. The measured sediment concentrations in these bores were 106 and 107 g/L. Even for the larger surges, the suspended load was calculated to be approximately 16% of the total sediment load, and bed load was therefore deduced to be the dominant transporting process (LEATHERMAN, 1977). As a result of that event, LEATHERMAN (1976c) concluded that the volume of accretion depends mostly on the surge height. For these experiments, wave height was found to be less important than storm surge level in causing overwash.

A decade later, four washover fans on Assateague Island were monitored by KOCHEL and DOLAN (1986) for 1 year to determine sediment budgets. Geological rather than geographical techniques, *i.e.,* deposit stratigraphy, were applied to measure overwash deposit thicknesses throughout the fans. The sediment budgets revealed that large infrequent deposits, *e.g.,* for a 15-year return interval storm, based on surge level contribute more to the sediment budget than several smaller storms of much smaller return interval. It was proposed that the larger deposit from the 15-year storm provided shielding from eolian deflation, whereas the smaller deposits were more easily and rapidly removed.

The washover fans on Assateague Island were further monitored for 4 years, and the results of this monitoring are reported in KOCHEL and WAMPFLER (1989). They proposed that the extended period of monitoring enabled them to draw more convincing conclusions on the relative roles of overwash deposition and eolian deflation. The 4-year period represented 2 average years, 1 particularly stormy year, and 1 particularly calm year for the region. Although, as observed by LEATHERMAN (1979b), eolian transport dominated in the calm year, the normal and stormy years demonstrated the overall contribution of overwash accretion on the sediment budget.

2. Field Measurements Elsewhere

Lacustrine overwash and inlet formation was studied on barrier islands and spits bordering the North Pond on Lake Ontario, United States (WEIR, 1977). In a lacustrine environment, short-term elevated water levels or storm surge are caused by moving atmospheric low pressures, wind and wave setup, and wind-induced seiching, and tidal variation is nonexistent. Seasonal variations in lake level caused by snow melt runoff in the catchment and even longer-term (decadal) variations in water level may be linked to variations in precipitation in the catchment caused by climatic variations. When WEIR (1977) monitored changes to overwash fans in the region for two summer months in 1976, the lake water levels were near the peak of such a long-period cycle. Inundation overwash caused by a storm event was described, and observed processes included the removal of a 3-m-high foredune and 9 m of shoreline recession. The greatest shoreline recession was observed where washover activity and inlet formation activity were highest. At the same time, though, maximum fan extension into the bay was 55 m, and area calculations reveal that the net result was widening of the barrier. In other areas of the barrier, washover was observed to add to the growth of recurved spits. Although overwash caused shoreline recession, it helped maintain the integrity of the barrier island. Lacustrine overwash was also observed on Long Point, a large barrier spit on the north shore of Lake Erie, Canada (DAVIDSON-ARNOTT and FISHER, 1992). The authors presented a six-stage overwash and overwash recovery qualitative model, related to a long period (decadal) cycle of water elevations. During times of highest lake level, overwash formation is at its peak, the beach is comparatively narrow, and older washovers are easily reactivated.

Although most observations of overwash have been made on sandy beaches, studies have also been conducted on gravel and shingle barriers. CARTER and ORFORD (1981) and ORFORD and CARTER (1982) made many observations of overwash processes resulting from topographic surveys of a gravel beach and more detailed sedimentary surveys of an overwash fan and other structures in southeast Ireland. The shoreline was surveyed by automatic quickset level. One washover fan was monitored in detail and was trenched in various locations to determine deposit stratigraphy. The longshore distribution of wave height was calculated from a wave refraction program with input of offshore wave measurements. The region of greatest overwash occurrence corresponded with the region of highest breaking waves. Two processes that differ significantly from those observed on sandy barriers are the development of swash ramps, which facilitate crest accumulation (low-magnitude runup overwash), and deposition of coarse sediments in the throat of a washover that conglomerate to

form a throat plug. Swash ramps build onto dune scarps and consist of a distinguishing sedimentation pattern in comparison to the adjoining dunes. They are often observed to occur between overwash fan positions and are observed built onto dunes up to 6 m above mean high water. On a washover fan, a throat plug acts to filter the grain size and hence reduce the amount of sediment carried to the backbeach by ensuing overwashes. An increase in wave energy, however, may remove the plug (ORFORD and CARTER, 1982).

CARTER and ORFORD (1981) described several stages of an overwash event. Swashes converge on gaps in the dune line (the throat) where reflection from the dunes on either side contributes to the formation of a three-dimensional turbulent flow. This flow through the throat scours a hole on the seaward side of the dune. As the water or runup level increases, such that some smaller wave events overwash the throat, sediment is deposited in the throat, creating a plug. Rising surge levels saturate the throat, eroding the plug and overwash spreads onto the back barrier.

Further information on the overwash response of gravel barriers, and in particular the long-term effects, can be found in ORFORD, JENNINGS, and PETHICK (2003). These authors observed the effects of the remnants of Hurricane Lilli as it passed by the Porlock and Blakeney barriers, U.K. Overwash was observed to extend into the back barrier bay and at one location lead to a breach, which subsequently widened because of tidal action. Where overwash occurred, the old beach ridge was entirely removed, and the lateral variation in overwash was minimal, suggesting that inundation overwash (referred to as "sluicing overwash") occurred. Crest accumulation was described by ORFORD, JENNINGS, and PETHICK (2003) as negative feedback because the increase in crest height decreases the excess runup, ΔR, and hence the magnitude of overwash. Crest lowering was described as positive feedback because the decrease in crest height increases ΔR, and hence the rate of overwash increases. ORFORD, JENNINGS, and PETHICK (2003) suggested that the variations in maximum water level during a tidal cycle might initially cause negative feedback as crest accumulation overwash begins to occur. If this negative feedback is insufficient to protect the barrier as the water level increases, crest lowering (positive feedback) begins as high tide approaches and the beach crest is both lowered and translated landward. Eventually the tide level drops sufficiently such that negative feedback again occurs and the crest height increases and moves back offshore. In conclusion, ORFORD, JENNINGS, and PETHICK (2003) surmised that overwash caused by extreme storms is unlikely to cause the complete breakdown of a gravel barrier.

BRADBURY and POWELL (1992) conducted a field study at Hurst Spit, a shingle beach on the south coast of the U.K. Quarterly and poststorm profiles were surveyed at 20 sites alongshore (100-m spacing) between 1987 and 1992, and waves and tide were also monitored. The monitoring period includes the large storm of winter 1989 which, in association with overwash, moved the toe of the dune line 60 m landward. This storm was characterized by high surge levels and moderate storm wave heights, but similar responses were observed for storms with low surge levels and extreme wave heights, indicating the variability in parameters controlling overwash occurrence and magnitude. Longshore variability in breaking wave height is manifested in longshore variability in profile response.

A novel video technique was applied by HOLLAND, HOLMAN, and SALLENGER (1991) on Trinity Island (part of the Isles Dernieres barrier island chain), Louisiana, United States, to measure overwash bore celerity. The area monitored is a generally two-dimensional low-lying barrier subject to sheet overwash during extreme storms. Nearshore ocean and bay water levels were measured using pressure transducers, and water level and wave height across the island were measured with capacitance-type wave staffs. Results show both wave velocity and depth decreasing landward of the crest. The celerity vector fields show generally cross-shore (landward) flow, but with frequent direction variations of greater than 30° from normal. It may be surmised from the data presented that the barrier was overwashed by wave runup rather than surge level because overwashes were observed to occur at a periodicity of around 6 minutes. For calculating the overwash velocity, on the landward slope of the barrier HOLLAND, HOLMAN, and SALLENGER (1991) found that the celerity of the bore front can be computed from:

$$C_{\text{bore}} = 2.6\sqrt{gh} \tag{1}$$

where g is the acceleration of gravity and h is the flow depth at the beach crest. This equation resembles that of the celerity from shallow water linear wave theory. The proportionality coefficient by linear regression was calculated to be 2.6 with an R^2 value of 0.77, which is slightly larger than the coefficient describing the bore speed in dam break wave theory (LE MEHAUTE, 1976), also involving a solitary wave phenomenon. Initial bore velocity, beach slope, and bed permeability and roughness are also expected to control bore celerity. A method to calculate bore celerity on the back slope, and hence velocities within the overwashing flow, makes it possible to calculate sediment transport over the crest using conventional sediment transport formulas. The method relies on knowledge of the overwash depth at the dune or beach crest.

A recent contribution to field studies on overwash was carried out in the Ria Formosa Barrier system, Portugal. MATIAS *et al.* (2003) monitored changes in surface elevation on the washover terrace of a broad flat barrier island during high tide for 4 hours under medium wave conditions. Washover evolution was determined using a 10 × 10 m grid of rods at which the surface elevation was measured at 30-minute intervals. The nearshore significant breaking wave height was around 1.0 m. Overwashing into the lagoon occurred only during the peak of the tide (MATIAS *et al.,* 2003). Accretion was observed on the berm and crest, indicating a net shoreward transport of sand. Changes in depth inferred from colored sand plugs were determined to range between 5 and 30 cm, increasing toward the seaward end of the washover. The authors suggest that the large variation in mixing depth over the study area indicates preferential flow channels, a response to minor topography variations. During a follow up field experiment, high-resolution X-band radar and a time-stacking technique gave the numbers of runups and over-

Table 1. *Summary of wind-affected washover features (compiled according to Morton, 1979)*

Morphology Type	Description	Cause
Curved overwash channel	Deep, narrow channel leading to washover fan. Channel begins perpendicular to beach but curves in direction of wind.	Overwash by overflow confined to gap in beach crest/dune line. Curving may be caused by wind stress or bay circulation.
Flame-shaped fans	Elongated washover fan deposits. May be asymmetrical with greater sand volume on leeward side of channel. Bedforms may be observed on the deposit (in Morton 1979a, wavelength ranged from 5 to 8 m).	Overwash by overflow through a channel can result in higher velocities because of funneling. Where the flow is no longer confined, it continues landward because of the high flow velocities in the channel. Asymmetry of the deposit may be caused by wind stress.
Striations	Long grooves of sand removed on the back barrier.	Caused by strong currents which cause erosion while the barrier is overwashed. Direction contrary to surge direction may indicate wind-driven currents or other strong currents.
Transverse sand waves	Sand waves created at the bay margin perpendicular to the coastline (in Morton 1979a, wavelength exceeded 85 m and amplitude was less than 0.5 m).	Formed by currents parallel to the barrier while the barrier was overwashed (storm surge is perpendicular to the barrier).
Rhomboid bedforms	Criss-cross pattern (rhomboid shape) observed outside of the washover channel.	Formed by supercritical flow that is induced by wind currents.

washes, the velocity of the runup, and the velocity of the return flow (MORRIS *et al.,* 2004).

Sedimentologic Studies

Many studies of overwash can be found in the geological literature. Although the focus of this review is on overwash modeling, geologists have made many contributions to the understanding of overwash processes, often by studying washovers and their sedimentary units. In areas where overwash occurs, historical washovers can be detected by coring. HAYES (1967) presented the first evidence that washover sediments are recognizable in the stratigraphic record. Subsequent washovers are often separated by a layer of dark organic material and occasionally by grass that is buried, aligned at the angle of flow direction (SCHWARTZ, 1975). Many of the earlier studies are reprinted and summarized in LEATHERMAN (1981) or are briefly summarized in SCHWARTZ (1975) and LEATHERMAN (1976a).

HAYES (1967) studied the response of the Texas coast, United States, to Hurricanes Carla (September 1961) and Cindy (September 1963). By examining pre- and poststorm beach and back-beach sediments, he discovered horizontal laminations of coarse shell and sand on the barrier flat. The ebb tide superimposed on storm surge was observed to have deposited a significant amount of cross-bedded sediment and, in some places, a thin clay layer, usually where scour had occurred. Beach macroinvertebrates were also observed to have been carried inland as washover sediment. These observations were presented as evidence that previous storms are recorded as layers in the stratigraphic record and to emphasize the role that large storms play in moving sediment inland.

SCHWARTZ (1975) examined washover sediment texture and textural grading following a northeaster on an Assateague Island overwash fan to understand overwash processes. The fan was subject to runup overwash. On the back-beach, deposits were horizontally stratified, indicating a layer deposited after each surge. Toward the bay, the deposits dip in the direction of the bay, typically extending outwards with each surge with further horizontal layering on top. This is known as a delta foreset stratification and is associated with the landward terminus of the washover, allowing historical identification of the washover penetration. According to SCHWARTZ, textural grading of sediments suggested that bed load was dominant, which is in agreement with LEATHERMAN (1977), who also hypothesized bed load dominance after taking suspended sediment measurements in a similarly sized storm on Assateague Island.

MORTON (1979) describes five washover morphologies on the Texas Gulf Coast barriers following three hurricanes that formed by wind stress during overwash or by wind stress modifying a newly deposited washover. The morphologies are summarized in Table 1. He remarks that the driving forces are difficult to quantify because of the uncertainty in wind stress coefficients, and that the additional transfer of momentum because of the horizontal component of wind-driven rain, sea spray, and wind gusts may increase the wind stress significantly during a hurricane or large storm.

LABORATORY STUDIES

Relatively few laboratory studies on overwash have been conducted through which the transport processes and morphology change can be quantified. The usual difficulties in reproducing a scaled moveable bed model may apply, unless the work is conducted in a large-scale facility such as done for beach profile change at SUPERTANK (KRAUS, SMITH, and SOLLITT, 1992). WILLIAMS (1978) conducted the first set of laboratory experiments aimed directly at overwash and also suggested one of the earliest predictive models. At around the same time, STAUBLE (1979) conducted experiments examining the effects of uprush and backwash on sediment transport, including the case where overwash occurs. Apart from the experiments by WILLIAMS (1978) and STAUBLE (1979), overwash was not simulated in the laboratory until 1992. Since then, results from several studies and associated analyses have been published for various different

types of overwash (BRADBURY and POWELL, 1992; HANCOCK, 1994; PARCHURE, DEAN, and SRINIVAS, 1991; PIRRELLO, 1992) (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data), discussed below.

Runup Overwash

WILLIAMS (1978) simulated overwash by runup of monochromatic waves generated in a 30-m-long by 2.5-m-wide tank. The waves were created by a piston-type wave generator driven by a hydraulic actuator and measured offshore with a capacitance wave probe. A cart-mounted profiling device measured vertical variation in profile using a linear variable differential transducer, and horizontal variation in profile using a rotational potentiometer. The average sediment grain size was 0.21 mm.

Typically, sediment was deposited at and behind the dune crest such that the test was terminated when the buildup of the dune crest prevented overwash. Therefore, this experiment involved crest accumulation, as defined above. WILLIAMS (1978) identified three types of profile response. Williams' Normal Response 1 results in an increase in dune crest height and accretion on the back beach. Normal Response 2 results in an increase in dune crest height and some erosion on the back beach. The third type, Erosive Response, results in a decrease in dune crest height and, generally, accretion on the back beach. Finally, two of the tests were terminated when the overwash eroded the dune to below the water level such that overwash by inundation was initiated; thus, this response can be described as crest lowering caused by overwash by runup. Williams' results pointed to some relationship between wave steepness, profile response, and overwash response. It appeared that overwash response is affected by the nearshore response to the incipient wave conditions.

STAUBLE (1979) examined the effect of single uprush bores and the subsequent backwash for both normal runup conditions and overwash conditions. A single incoming bore was formed by rotating the gate of a 13-m-long, 0.75-m-wide double-gated glass flume until the bore flowed upslope. Before the backwash from the bore reached the gate again, the gate was raised to allow the backwash to flow out the tank. A beach was constructed using a 5-cm layer of natural beach sand from Assateague Island on top of a plywood base sloped at 2°. For the overwash case, the constructed beach reached a crest when the beach was 5.8 m long, and a back beach, also sloping at 2° was constructed behind the crest. This back beach terminated in a collection tank. Three capacitance gauges were used to monitor water levels on the seaward beach, and a fourth gauge monitored water levels on the backbeach. Two Marsh-McBirney bidirectional current meters and one Marsh-McBirney unidirectional current meter were positioned to monitor the flow velocity at a fixed distance above the bed. The unidirectional meter was orientated so as to only record the backwash velocities. Sampling rate for all instruments was 0.05 seconds.

In comparison to the case of an ordinary runup bore on the same beach, the overwash swash experiment showed reduced backwash, namely the flow that did not overtop the beach crest, and hence less backwash sediment transport on the foreshore and net change of the foreshore slope occurred. For the runup case, the greatest capacity to transport sediment was observed at the end of the backwash mode. For the overwash case, this capacity was obviously reduced. Morphological profile change was observed after 10 repeats of the bore. For the overwash experiment, the crest had lowered about 3 cm but migrated seaward. There was net erosion on the backbeach; however, a small bar-like accretion was formed in the middle of the backslope. It is unclear from this publication whether or not the flow at the crest was supercritical; however, the maximum uprush flow on the beach slope is subcritical. The results of this study provide data for an isolated uprush and backwash cycle, and allow comparison of the hydrodynamics and sediment transport capabilities for an ordinary runup on an infinite beach and an overtopped beach. Such data sets are useful in considering the action of excess runup, ΔR, as a measure of the overtopping flow and the sediment transport potential. The data also provide further insights into the changes in seaward profile when return flow is reduced by overtopping.

BRADBURY and POWELL (1992) simulated runup overwash on shingle beaches in a 3-D wave basin, and process observations were made. Although the experiments were conducted on a shingle beach, many of the qualitative results are applicable to sand beaches. The model spit, made of graded anthracite, represented 1 km of prototype beach onto which random waves were generated. By designing and calibrating the laboratory model to fit observed field conditions (field study is described above in the "Field Studies" section), they were able to reproduce the observed profile response at Hurst Spit on the south coast of the U.K. Adjustable parameters included wave height (1-m to 4.5-m prototype), period (6-s to 12-s prototype), static water level (freeboard ranged from 0.5-m to 6-m prototype), wave approach angle (5–15°), and crest width (2-m to 20-m prototype). Beach profiles were measured at 2-m prototype spacing before and after each test using a computer-driven incremental bed profiler. An overhead video camera recorded the evolution of the crest features. Waves and water level were measured, but the procedures are not described.

Both crest accumulation and lowering were observed. Crest accumulation occurred for a very narrow range of hydraulic conditions, namely when the overtopping waves just reached the crest. As the wave height and/or the water level increased, crest lowering began. The rate of crest lowering was observed to be a function of the crest width and the hydraulic conditions. There was also a large spatial variation in the rate of crest lowering. Crest lowering was observed to occur by (1) formation of small washover fans, followed by (2) formation of channels within the washover fan, increasing the rate of crest lowering. As the crest lowers, the rate of lowering increases because the frequency of overtopping waves increases. Wide beach crests are slower to form channels than narrow beach crests because the overwash accelerates on the steeper backslope of a narrow crest. Waves propagating across the crest were sometimes observed to liquefy the sediment fan, rapidly extending the washover fan shoreward with each wave. Where a large overwashing wave was followed by several smaller waves, crest accumulation could be-

gin again, forming small ridges that restricted extension of subsequent overwashes. This observation illustrates the importance of modeling overwash with random waves. Characteristic to shingle beaches, percolation through the beach was observed to produce small streams and washout fans on the shoreward side of the beach.

HANCOCK (1994) and KOBAYASHI, TEGA, and HANCOCK (1996) developed a relationship for sediment concentration in overwashing runup incorporating the results of overwash by runup experiments on a dune profile (sand) under varying incident peak spectra wave periods, T_p. Moveable bed experiments were conducted in a 33-m-long, 2.44-m wide wave tank. The tank was partitioned so that the test width was 0.61 m, and random waves were generated. Sand was well sorted, with an average grain size of 0.38 mm. Three incident capacitance-type wave gauges measured water level variations at a frequency of 20 Hz. The gauge data were analyzed to separate the incident and reflected waves. A fourth capacitance wave gauge was partially buried in sand at the crest. This gauge recorded the overwash flow depths and, between overwash bores, it recorded the wetted sand surface. Beach and dune profiles were measured before and after each run using a cart-mounted Parametrics A302S-SU high sensitivity series 1.0 MHz, Accusan immersion transducer connected to a Panmetrics model 22DL precision microprocessor thickness gauge. The thickness gauge recorded the time taken for an ultrasonic pulse transmitted by the transducer to reflect off the sand water interface back to the transducer.

An average volumetric sediment concentration was calculated from the volumes of water, Q, and sand, Q_s, overwashed. The range of volumetric concentration values, c_s, for all the experiments was found to be small, between 0.023 and 0.056, and the relationship between Q and Q_s may therefore be described as linear such that

$$Q_s = c_s Q \tag{2}$$

Furthermore, the wave gauge at the crest of the initial dune showed the overwash depth, frequency of runups resulting in overwash, and the time development of the dune crest height (HANCOCK, 1994). For small T_p, initial runs were characterized by smaller, infrequent overwash events. For the experiments with larger T_p values, initial overwash rates were high, and the rate of dune crest lowering was also high. As mentioned above, for BRADBURY and POWELL (1992), these results indicate the positive feedback mechanism that overwash can initiate. Hancock also compared measured overtopping rates with the overtopping equations of DE WAAL and VAN DER MEER (1992) and VAN DER MEER and JANSSEN (1995) for structure overtopping. Results were within order of magnitude range, which indicated that structure-overtopping equations can give only a rough estimate of overwash rate. They also calculated wave reflection coefficients in the nearshore using the method of SEELIG and AHRENS (1995) and compared with measured reflection coefficients. For waves that did not overwash, the equation performed well, but not for overwashing waves.

Most recently, BALDOCK *et al.* (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data) conducted laboratory experiments of overwash by runup. The experiments were conducted in a 20-m-long by 0.9-m-wide wave flume at the University of Queensland, Australia. A planar beach consisting of a 5-mm-thick layer of 0.3-mm median grain size sand was constructed. The beach was truncated at the estimated point of maximum runup and a catchment tray placed directly under the truncation point. Overtopping flow volumes and overwashed sand volumes (dried and weighed) were therefore measured. Offshore waves were measured with an electronic wave gauge. The focus of the measurements was on overwash and washover quantities, as opposed to beach profile change. The resulting measurements were consulted to verify a numerical model of swash overtopping (M.G. HUGHES and T.E. BALDOCK, unpublished data) based on an analytical solution of the shallow-water equations (PEREGRINE and WILLIAMS, 2001). Their model is discussed in the section on modeling.

Inundation Overwash

Further conclusions related to subaqueous profile development and overwash response can be drawn from the experiments described in PARCHURE, DEAN, and SRINIVAS (1991) and SRINIVAS, DEAN, and PARCHURE (1992). A barrier island with an initial linear profile and broad flat crest was modeled using fine sand (d_{50} = 0.2 mm) in a 46-m-long and 1.8-m-wide wave tank at the University of Florida. The wave tank was divided in half so that the experiments were conducted in a 0.9-m-wide section. A wave generator with hydraulic-drive pistons at two elevations allowed the piston, flap, or combination motions to simulate both regular and irregular waves. A capacitance wave gauge, an electromagnetic current meter, and an automatic bed profiler were cart-mounted so that measurements could be taken cross-shore. An overwash collection basin was placed at the shoreward end of the horizontal beach crest. Collection efficiency was concluded to be poor because some suspended sediment was observed to bypass the bucket.

The experiments were conducted with water levels below, at, and above the beach crest, but the wave height for the experiment conducted below the beach crest was insufficient to cause observable overwash by runup profile change. The water level at the beach crest resulted in deposition on and behind the crest, and water levels above the beach crest generally resulted in translation of the crest landward. Currents across the island reached 1.1 m/s (prototype).

SRINIVAS, DEAN, and PARCHURE (1992) found that offshore bars were formed for the regular wave simulations, but were indistinct or nonexistent for the irregular wave simulations. Additionally, the magnitude and peakedness of the bar were reduced as surge level increased. The authors suggested that this was because of the lack of return mass transport as the island became inundated. As expected, the location of the bar shifted landward as the surge level increased because the location of breaking waves moved landward. For the simulation of the rising and falling surge level, a small bar appeared initially, but was flattened as the water level increased, indicating that the bar did not have time to form and stabilize in between increases in water level. The simulations of PARCHURE, DEAN, and SRINIVAS (1991) are only

applicable to field conditions where ocean and bay water levels are not coupled. Nevertheless, conclusions drawn from comparing regular and irregular waves and unsteady water level will be useful for design of future laboratory experiments on overwash.

PIRRELLO (1992) continued the work of PARCHURE, DEAN, and SRINIVAS (1991) and SRINIVAS, DEAN, and PARCHURE (1992) by simulating overwash by inundation with varying wave height and period and surge level in the same facility. Superimposed water level gradients were also modeled to simulate cross-island currents induced by the flow of water from ocean to bay where the ocean level is higher than the bay level. These currents were created by pumping water into the shoreward end of the tank with a 7.5-hp pump. The results of Pirrello's first experiments (those without an imposed water gradient) are similar to those of PARCHURE, DEAN, and SRINIVAS (1991) and SRINIVAS, DEAN, and PARCHURE (1992), but contain the effects of varying wave steepness. Again, there is inconsistency in the results. Although the breakpoint and bar moved further offshore for increasing wave steepness while the overwashing surge level was low, the opposite occurred for the higher surge level. It is not known why this occurred. PIRRELLO (1992) also measured currents and wave height across the island. After breaking, wave height reduced gradually, and then remained constant across the island. Wave height decay was shown to occur more steeply for low surge level than for high, and current measurements showed greater negative velocities for the low surge level than for the high surge level, indicating greater amounts of return flow at low surge levels.

The addition of a cross-island current was significant. The position of wave breaking shifted shoreward, and wave decay occurred steeply after breaking with a gradual residual decay across the island. Additionally, current measurements indicate a lack of return flow in the surf zone. Deposition across the island was slightly larger, but, more importantly, the volume of sediment collected at the shoreward end of the crest was one to two orders of magnitude greater than that collected in the previous experiments. This is, therefore, considered a more realistic representation of inundation overwash.

OVERWASH MODELING

Prediction of Overwash Occurrence and Magnitude

Prediction of overwash occurrence can provide valuable planning information for local authorities, emergency services, and coastal residents. The extent and magnitude of overwash deposits are dependent on:

1. Storm surge magnitude and duration (which depend on the storm severity and location of the storm eye relative to the beach).
2. Direction from which the storm approaches the coastline.
3. Wave height and period.
4. Tidal phase during peak storm surge.
5. Nearshore bathymetry.
6. Beach topography, in particular barrier width and elevation.
7. Wind direction and velocity.
8. Presence or absence of dune vegetation.

CLEARY and HOSIER (1979) presented what is probably the first quantitative overwash prediction methodology. By reference to cross-shore beach transects placed every 1 km on the southeast North Carolina coastline, they standardized and summed the total island width, the herbaceous and the arborescent vegetation widths (which are related to the dune recovery), and the erosion rate. This sum was then shown to have a high negative correlation ($r = -0.9597$) with the frequency of overwash history at each transect. Based on these results, overwash susceptibility levels (severe, moderate, or low) were assigned along the coastline. The methodology is site-specific and probably only tested on a small range of storms, but illustrates initial successful efforts to predict overwash occurrence.

Spatial variation in dune elevation can, to an extent, serve to estimate spatial variation in overwash events. SALLENGER (2000) introduced a "storm impact scale" that compares the relative elevations of the dune crest and foot and estimated surge and runup heights. Incorporation of this scale into the airborne Light Detection and Ranging (LIDAR) system is discussed by WETZELL, HOWD, and SALLENGER (2003). They analyzed hindcasts of extreme wave runup and beach elevation data collected by LIDAR to qualitatively predict the longshore variation in overwash occurrence caused by Hurricane Dennis on 17 km of the Outer Banks coastline. Their results were compared with LIDAR surveys collected after the hurricane had passed. Where overwash was predicted, comparisons of pre- and poststorm profiles were consistent with the spatial occurrence of overwash. Predictions based on this system are now shown on the USGS website prior to hurricane landfall.

MORTON and SALLENGER (2003) examined the control by various factors on the overwash penetration distance during extreme storm events on both the Atlantic Ocean coast and the Gulf of Mexico coast. Surge height, dune topography, and nearshore bathymetry (which all combine to produce an excess runup height) were shown to correlate with penetration distance. Existence of vegetation and confinement of flow were also demonstrated to control the penetration distance. Penetration distance decreased with barrier width, but increased with proximity to open water on the landward side. Therefore, lesser overwash distances are observed on mainland beaches where the foredune topography and surge height is similar to that on a barrier experiencing frequent overwash (MORTON and SALLENGER 2003).

Modeling of Washover Volume and Beach Profile Evolution

The modeling of overwash volume and beach profile evolution is a key capability for coastal authorities and engineers, in terms of both development planning and poststorm response planning. Presently, there are only a limited number of models available that can, to some extent, predict overwash profile evolution or washover volume. There remains considerable room for improvement. A suitable goal is a 2-D model that calculates washover quantities and profile evo-

lution based on surge level, offshore wave conditions, and initial condition of the barrier beach morphology and sediment. Many of the studies summarized in this section are steps along the path to achieving this goal. Both physical and empirical approaches are documented, including systematic attempts to model runup, overtopping, and sediment transport, as well as bulk approaches. For example, some studies (*e.g.,* LEATHERMAN, 1976a; SANCHEZ-ARCILLA and JIMENEZ, 1994) have combined formulas for runup or overtopping volume theories with sediment transport theories to obtain an order-of-magnitude estimate of washover volumes and/or profile evolution. Other studies, for example WILLIAMS (1978), have used bulk parameters to relate the offshore hydrodynamics to the washover volume, and these are referred to as "bulk approaches." More sophisticated models to estimate profile evolution (*e.g.,* LARSON, WISE, and KRAUS, 2004, 2005) have also been developed. This section summarizes various attempts to model overwash and evaluates the current capabilities for modeling profile evolution caused by overwash.

WILLIAMS (1978) examined the results of his laboratory experiments to test two different sediment transport models that relate sediment transport rate with ΔR and the inverse of the wave period. The first of these models is based on the assumption that the overwash transport rate is proportional to the excess runup raised to some exponent, α:

$$Q_{\text{sed}} = \frac{K_1}{T}(\Delta R)^{\alpha} \tag{3}$$

where Q_{sed} is the rate of sediment overwashing, K_1 is a proportionality constant, and T is the wave period. The second model is based on the assumption that the overwash transport rate increases rapidly for small values of ΔR and asymptotically approaches zero in an exponential form as ΔR increases:

$$Q_{\text{s}} = \frac{K_2}{T}\Delta R e^{-K_3 \Delta R} \tag{4}$$

where K_2 and K_3 are proportionality constants.

In other words, there is a theoretical maximum sediment transport rate. The two functions were integrated so that volumes of washover sediment measured could be compared to the calculated volumes. Both functions calculated order-of-magnitude volumes (usually within a factor of 3). Neither of the models performed consistently better than the other, nor were the washover volumes consistently under- or overestimated. The values of K_1, K_2, K_3, α, and ΔR were calibrated from the same set of data. Qualitatively, the laboratory model compared well with sediment transport and morphology patterns observed in the field.

TANAKA, SUNTOYO, and NAGASAWA (2002) adopted a similar approach to the first model suggested by WILLIAMS (1978) to calculate the overtopping rate:

$$Q_o = \alpha(R_u + \eta_{\text{tide}} - H_c)^n \tag{5}$$

where Q_o is the overtopping rate per wave per unit width, H_c is the dune crest height, R_u is the wave runup height calculated using OGAWA and SHUTO (1984), η_{tide} is the variation in seawater level caused by tide, α is equal to 0.5 m/s (TOMINAGA and SAKUMA, 1971), and n is equal to 2.0 (TOMINAGA and SAKUMA, 1971).

This formula was then adjusted for irregular waves according to GODA (1985). The sediment overwash rate was calculated assuming that it is linearly related to the overtopping rate (HANCOCK and KOBAYASHI, 1994). The resulting order-of-magnitude estimate was comparable to volumes of sediment deposited in Gamo Lagoon, Japan, following storms causing overwash. Measured volumes were calculated using the average washover depth obtained from pre- and poststorm cross sections (1979 and 1995) multiplied by the area change derived from pre- and poststorm aerial photographs.

Several other, more detailed physical models have been introduced to calculate the volume of washover during a storm. LEATHERMAN (1976a) applied the Einstein sediment transport equation to overtopping velocities measured at mid-depth. He assumed a steady-state velocity profile and ignored percolation losses. The calculated and measured transport rates were within an order of magnitude but showed considerable scatter. For the Trabucador Bar in Spain, SANCHEZ-ARCILLA and JIMENEZ (1994) calculated overwash sediment transport rates by first calculating storm runup by the method of MASE (1989), the current on the back slope using the Chezy formula, and the sediment transport rates according to VAN RIJN (1984). Fluid velocities are slightly less than those measured by LEATHERMAN (1976a), but Leatherman measured velocities in channelized flow. The sediment transport rate calculated by SANCHEZ-ARCILLA and JIMENEZ (1994) is plausible if compared to the quantity of sediment deposited in the bay, but pre- and postoverwash profiles to calculate more accurate volume change were not compared for this study.

HANCOCK and KOBAYASHI (1994) compared the results of their laboratory experiments on overwash by runup (discussed above) to the irregular wave overtopping formulae of DE WAAL and VAN DER MEER (1992). A follow-up study (KOBAYASHI, TEGA, and HANCOCK, 1996) compared the same laboratory measurements with an updated overtopping formula by VAN DER MEER and JANSSEN (1995). The first formula consistently underpredicted the overtopping rate for overwash by runup. The second set of calculations generally fell within the 95% confidence interval of the predictive formula but failed to show the observed variation of overtopping volume for varying runup levels. TUAN (2003) points out that the equivalent slope used for the overtopping equation can represent many different profiles. Given the strong dependence of overwash response on the subaqueous profile, as observed in the constant response of a beach profile to the forcing conditions, and the laboratory experiments discussed above, it can be seen that overtopping formulas developed for hard structures cannot be directly applied to overtopping of sand beach crests. TUAN (2003) aimed to improve the representation of the slope in overtopping formulas. It was recognized that the submerged and subaerial portions of the slope varied quite differently. The subaerial slope was assumed to be constant, whereas the subaqueous slope was assumed to decrease exponentially. Thus, a time-varying expression was developed to represent the equivalent slope in subaerial dune

overtopping calculations; however, the expression is unverified and warrants further investigation.

A numerical model of swash overtopping (M.G. HUGHES and T.E. BALDOCK, unpublished data) based on an analytical (PEREGRINE and WILLIAMS, 2001) and a numerical solution of the shallow-water equations was verified by BALDOCK *et al.* (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data) with the laboratory simulations described above. The model calculates the overtopping volume as a function of E, a nondimensional measure of the truncation point (the theoretical runup limit). The predicted overtopping volume fits the measured well, although there is scatter in the data. BALDOCK *et al.* (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data) suggest that the scatter may be explained because overtopping volume should also be a function of wave period such that the influence of swash interaction is taken into account. A Shields model for bedload was used to calculate washover volumes for individual waves with the velocity field from the numerical model as input. Again, because the overtopping volume is dependent only on E, sediment transport may only be calculated as a function of E, and this is only true if just bedload occurs. The modeled washover volumes fit the measured washover volumes well, indicating that the above assumption was valid for the data set.

For the case of overwash by inundation, PIRRELLO (1992) employed the wave decay model of DALLY, DEAN, and DALRYMPLE (1985) across a barrier island. Wave transformation before breaking was well estimated, but wave transformation across the island was underestimated. Where a gradient in water surface elevation was simulated across the island, the model correctly estimated the trend of wave height decay, but failed to reproduce the magnitude. This is to be expected, because the model was not modified to take into account the cross-flowing current. A mass flux equation developed by SVENDSEN (1984) for nonoverwash conditions was used to calculate return flow currents in the surf zone and across the island. An imbalance between the mass transport flow and the return flow is characteristic for the occurrence of overwash. As expected, a strong return flow correlates well with the formation of bars. Over the island, flows capable of suspending and transporting suspended sediment were modeled. For the case of simulated water surface gradient, there is no modeled return flow, *i.e.,* all overtopping flow is transported landward. The laboratory measurements were not sufficient to verify this assumption about the currents, and PIRRELLO (1992) suspected that a small return flow might exist near the bottom.

Modeling of Washover Volume and Beach Profile Evolution

More comprehensive algorithms for prediction of dune profile evolution have been based on geometric considerations in combination with physical concepts derived from empirical observations. KRAUS and WISE (1993) (see also WISE and KRAUS, 1993; WISE, SMITH, and LARSON, 1996) developed an algorithm for simulating overwash by runup over sand dunes for inclusion in the SBEACH beach profile change numerical model (LARSON and KRAUS, 1989). The swash zone, dune crest, and landward slope of the dune were treated as separate transport regions with specific formulas developed for each region. The model was applied with success to simulate profile response at Ocean City, Maryland, to the 4 January 1992 storm, a major erosive event. Both the reduction in crest height and the thickness of washover deposits were correctly represented, as well as the quantity and location of offshore transport.

LARSON, WISE, and KRAUS (2005; see also LARSON, WISE, and KRAUS, 2004) enhanced the SBEACH overwash algorithm developed by KRAUS and WISE (1993) to include transport formulas that have improved physical foundation for the three regions. In the swash zone, the sediment transport rate q_{sw} was determined from the formula proposed by LARSON, KUBOTA, and ERIKSON (2001, 2004), which describes the net transport over many cycles,

$$q_{sw} = K_c \frac{u_b^3}{g}(\tan \beta_l - \tan \beta_e)\frac{t_o}{T} \tag{6}$$

where K_c is an empirical transport coefficient, u_b the front speed of the uprushing wave (bore), β_l the local foreshores slope, β_e the equilibrium foreshore slope, t_o the time during which a specific location is submerged, and T the swash period (normally taken to be equal to the incident wave period). Ballistics theory was used to calculate the hydrodynamic quantities u_b and t_o that characterize the swash cycle. At the dune crest, the transport rate, q_D, was assumed proportional to the overwash volume rate in accordance with HANCOCK and KOBAYASHI (1994) and KOBAYASHI, TEGA, and HANCOCK (1996), yielding a transport rate at the crest,

$$q_D = K_B 2\sqrt{\frac{2g}{R}}(R - z_D)^2 \tag{7}$$

where K_B is another nondimensional coefficient, R a fictive runup height neglecting overwash, and z_D the dune crest elevation over the mean water level.

Bore velocity on the back barrier was calculated assuming a linear spreading of the flow and the sediment transport rate was set proportional to the velocity cubed. Thus, the transport rate (q_f) on the landward side of the dune is obtained as

$$q_f = \frac{q_D}{1 - \mu s/B_D} \tag{8}$$

where s is the horizontal distance from the dune crest, B_D the width of the overwash flow in the throat, μ a spreading coefficient, and the subscript D indicates the dune crest location. Percolation effects were neglected in Equation 8. The new algorithm was validated with the previously employed data from Ocean City as well as with topographic change data from Assateague Island, which were obtained during the severe January and February 1998 northeasters (Figure 9).

SRINIVAS and DEAN (1996) developed a research-level 1-D numerical model of cross-shore sediment transport and profile evolution. Emphasis was on resolving the cross-shore flow pattern, both inside and outside the surf zone. Bed load and suspended load were computed separately based on the wave and current calculations. It is not clear from their paper how

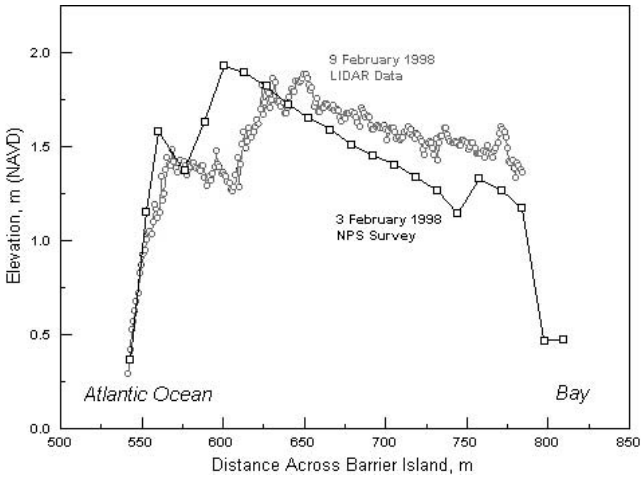

Figure 9. Assateague Island barrier profiles survey prior to and following the January and February 1998 northeasters. The water level for this storm (including surge) was 1.8 m NAVD-88.

the swash zone was treated in terms of hydrodynamics and sediment transport, but the model encompassed the capability to simulate overwash caused by inundation. Model validation was carried out for a limited number of small-scale laboratory studies involving the flow over a flat, broad barrier island that was being submerged at zero mean water level gradient (PARCHURE, DEAN, and SRINIVAS, 1991; see also SRINIVAS, DEAN, and PARCHURE, 1992). The simulation results were judged to be good, with qualitative representation of offshore bar behavior and the effect of overwash on a broad flat barrier island. No applications of the SRINIVAS and DEAN (1996) model in engineering studies were found in this review.

A model to estimate the evolution of a barrier's ocean and bay coasts was presented by JIMENEZ and SANCHEZ-ARCILLA (2004). The evolution of the ocean coast was estimated using a one-line model with a radial coordinate system, with gradients in longshore sediment transport assumed to be the driving mechanism. Overwash processes were assumed to be the driving mechanism for bay coast evolution, and the overwash rate was taken as

$$B_w > B_{\text{crit}}, \qquad Q_{\text{in}} = Q_{\text{out}}\left(\frac{B_{\text{crit}}}{B_w}\right)^{\alpha} \tag{9}$$

$$B_w \leq B_{\text{crit}}, \qquad Q_{\text{in}} = 0 \tag{10}$$

where B_w is the barrier width, B_{crit} the critical barrier width, Q_{out} is the rate of overwash at the ocean coastline, Q_{in} is the overwash contribution to the backbarrier, and α a parameter that determines the amount of material to be contributed to the bay coast.

The critical barrier width B_{crit} is the width for which no overwash will reach the bay under "normal conditions" and is a function of the wind and wave climate and the barrier geomorphology. The bay coast evolution is then calculated from the continuity of sediment equation with the change assumed parallel to the change on the ocean coast. The concept of a critical width under normal sea conditions is based on LEATHERMAN's (1985) conclusion that transgressive barriers that only overwash to the back barrier on a decadal scale generally erode or, in other words, become narrower. The long term modeling of Assateague Island by KOCHEL and WAMPFLER (1989) indicates that LEATHERMAN's (1985) Assateague Island studies were based on unusually calm years, so it is possible that this assumption is not entirely valid. Although the ocean coast evolution model was calibrated and validated, the bay coast model was not.

DISCUSSION

Overwash Processes and Morphologies

Much of the earlier research concerning overwash processes and washover formation was contributed by geologists and geographers. Overwash has traditionally been of lesser interest to most engineers, probably because typical coastal projects in the past did not consider overwash as a hazard. Post-hurricane experience indicates, however, that washover can be a major engineering consideration. Overwash is related to the regional and long-term evolution of the coast, a further factor that influences many coastal engineering projects.

Considerable data and observations concerning overwash and washover are available. As can be seen, overwash produces a variety of morphology changes, in order of increasing severity:

1. Crest accumulation (whether on a dune crest, beach crest or in an overwash throat)
2. Dune rollback (resulting from the erosion of the seaward side of a dune and deposition on the landward side)
3. Dune lowering (with deposition of sediment landward of the dune)
4. Dune destruction (with deposition of sediment landward of the dune)
5. Barrier rollback (sediment eroded from the beach and seaward side of the barrier, transported as sheetwash and deposited over old marsh vegetation or in the bay)
6. Barrier breaching/inlet formation

As discussed above, in the section "Definition of overwash processes and morphology," the hydrodynamic characteristics of the overwash can, to some extent, be related to the washover morphology, although more hydrodynamic observations are required to clearly quantify these links. The relative periods of positive or negative feedback, suggested by ORFORD *et al.* (2003), may explain why beach crests may either increase or decrease in height, maintain their position, or translate landwards following an overwash event, and this is linked to tidal control and the relative storm surge level. For many of the studies referenced in this review, the type of overwash (runup or inundation) has been assumed based on information of the relative levels of surge and beach crest, and the resulting morphology has therefore been related to these inferred quantities. Unambiguous hydrodynamic data are required to strengthen the hypotheses.

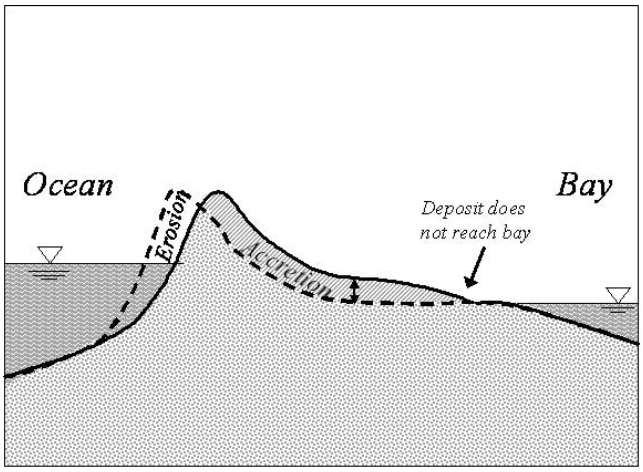

Figure 10. Schematic of barrier island accretion. The erosion of the foredune is roughly equal in volume to the accretion of the back barrier.

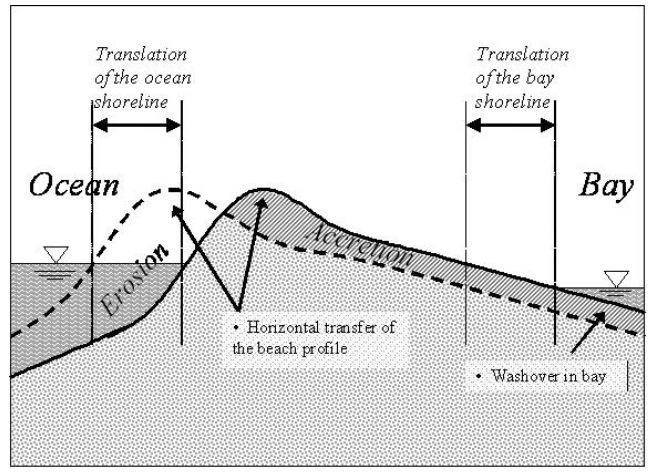

Figure 11. Schematic of barrier island rollover where the barrier shape is preserved (translation).

The Role of Overwash

Much discussion has been devoted to the role played by overwash in barrier island migration. It is beyond the scope of this review to cover the literature of the medium and long-term evolution of barrier islands. It is understood that overwash deposits may in some cases be redistributed by wind, eroded seaward during smaller storms, or in other situations simply be a minor contribution to the sediment budget of a barrier island as compared to processes such as sediment transported inland through inlets by flood tides. Back barrier accretion by overwash has been observed to correspond with ocean shoreline recession, although whether all overwash results in recession is not certain. The general consensus seems to be that where overwash occurs, the bulk of the sediment is transferred inland instead of being deposited offshore; thus, the sediment volume of the barrier island is somewhat preserved in the overwash process. The observed immediate responses of barrier islands to overwash may be summarized as falling into two categories:

1. Barrier accretion—The ocean coast erodes, but there is no deposition in the bay, hence the width of the barrier decreases. The height of the barrier increases (Figure 10).
2. Rollover—For more severe overwash or where barriers are narrow, sediment deposits reach the bay and, although the ocean shoreline erodes, the bay shoreline accretes. It is possible for the foredunes to translate landwards, thus preserving the general shape of the barrier (Figure 11). However, another likely response is the removal of foredunes and deposition of this sand onto the back of the barrier and into the bay (Figure 12).

Overwash Occurrence

Prediction of overwash occurrence locations for an approaching storm or hurricane of certain characteristics is now possible. The storm impact scale (SALLENGER, 2000) and estimated storm surge heights for the storm or hurricane, in association with topographic data collected by LIDAR (WETZELL, HOWD, and SALLENGER, 2003), is currently in use along the U.S. coastline to warn of overwashing locations. The topographic data along a coast are summarized through two parameters, D_{high}, the local beach or dune crest height, and D_{low}, the local dune base. The topographic data are then compared with R_{high} and R_{low}, which are hydrodynamic parameters representing, respectively, the maximum runup height and the maximum runup height minus the expected 2% exceedance swash amplitude. Table 2 summarizes the SALLENGER (2000) storm impact scale, and Figure 13 defines the variables listed in the table. Such information is important for developed coastlines in making decisions on evacuating residents and protecting property. The storm impact scale

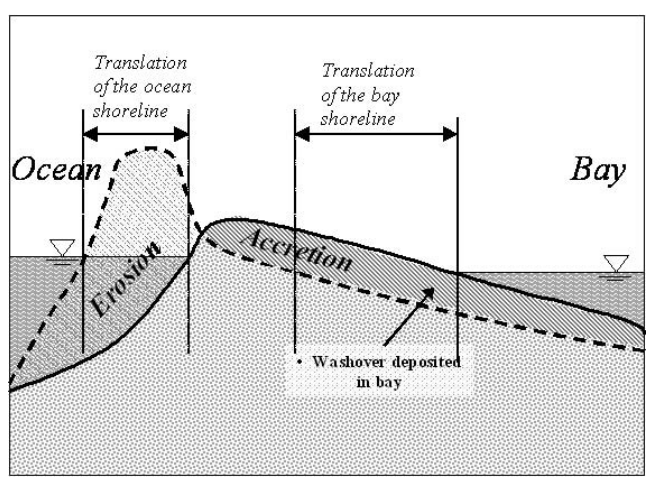

Figure 12. Schematic of barrier island rollover where the barrier shape is not preserved. The erosion of the foredune is roughly equal in volume to the accretion of the back barrier.

Table 2. *Storm Impact Scale for barrier islands (adapted from Sallenger 2000).*

Impact Level	Definition	Regime
1	$0 < R_{high}/D_{high} < D_{low}/D_{high}$	Swash regime—runup is confined to the beach foreshore
2	$D_{low}/D_{high} < R_{high}/D_{high} < 1$	Collision regime—runup reaches the foredune ridge
3	$R_{high}/D_{high} > 1$ and $R_{low}/D_{high} < 1$	Overwash regime—runup exceeds the foredune ridge or beach crest
4	$R_{high}/D_{high} > 1$ and $R_{low}/D_{high} > 1$	Elevation regime—elevation of the base of the swash motion exceeds the foredune ridge or beach crest

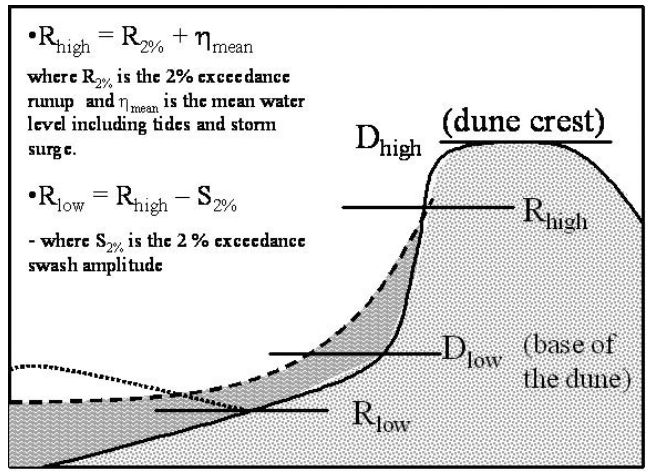

Figure 13. Definition sketch describing variables used in scaling the impact of storms on barrier islands (adapted from Sallenger, 2000).

could also be incorporated in planning development in affected regions and in shore-protection design to reduce overwash.

Many researchers have remarked about observation of some kind of longshore spatial regularity (periodicity) of washover fans or maximum storm surge penetration (*e.g.,* BRADBURY and POWELL, 1992; DOLAN and HAYDEN, 1981; DOLAN, HAYDEN, and FELDER, 1979; MORTON, 1979, ORFORD and CARTER, 1984; and SUTER *et al.,* 1982). It is accepted that where the dune or berm crest is high, overwash exploits existing discontinuities in the crest. In developed areas, this discontinuity might be a beach access path or a boat ramp, but on natural coasts, the discontinuity is usually the site of previous overwash or a closed breach. The spectral analysis of DOLAN and HAYDEN (1981) on longshore overwash penetration positions and shoreline positions indicated periodicities on the order of 10–15 km on sand barriers. The analysis of ORFORD and CARTER (1982) using frequency histograms of the between throat distances indicated periodicities of 30–40 m for a duneless gravel barrier. It has been suggested, though, that the periodicity must originally be linked to a coastal process. Suggested causes include edge waves, standing waves trapped between two capes, or simply alongshore variations in the runup height. The work of DOLAN, HAYDEN, and FELDER (1979) and DOLAN and HAYDEN (1981) explores some of these possibilities, but firm conclusions have not been drawn. For example, one must be cautious in interpreting a random signal as a periodicity.

Present Modeling Capabilities

Presently available overwash modeling capabilities can be separated into the categories of (1) sediment volume estimation and (2) profile response modeling.

1. Sediment Volume Estimation

Most models calculate the volume of sediment in runup overwash. Table 3 represents an effort to summarize the characteristics of such models, although variations in model type make it difficult to present a consistent comparison. The recent model by BALDOCK *et al.* (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data) appears to be the most accurate and robust of the approaches included, but it is also the most complicated and to date has been verified only with laboratory data. It is difficult to distinguish between the performances of the other five models. The model of SANCHEZ-ARCILLA and JIMENEZ (1994) applies the Chezy equation for open channel flow to calculate the velocity on the back slope. Such an approach assumes gravity-driven flow across the back barrier and omits the contribution of swash momentum to the overtopping flow velocities. This is probably a reasonable assumption for inundation overwash if inundation levels are large compared to wave heights, but it is questionable for runup overwash.

As shown in Table 3, most of the volume calculation models require the extent of runup as input, but it may be conjectured that because of the lack of return transport for overwashing flow, the amount of swash interaction will change; hence, runup extent may increase. Development of the bottom boundary layer may also be altered. Runup velocity would therefore be greater for overwashing waves, and the bedload greater, because of the longer duration of positive flow at the bed. State of knowledge for swash zone hydrodynamics and sediment transport can be found in ELFRINK and BALDOCK (2002).

2. Profile Response Prediction

The only model that has successfully predicted 1-D cross-shore profile change caused by overwash for field conditions is SBEACH (LARSON, WISE, and KRAUS, 2005). The recently enhanced overwash model in SBEACH is based on mesoscale formulas for sediment transport within the swash zone, across the dune crest, and landward of the crest, where the hydrodynamic input is estimated based on ballistics and shallow-water wave theory. A linear lateral spreading of the overwashing wave at the landward side of the dune is assumed when simulating the development of overwash fans. Development of overwash fans occurs under certain conditions and the fan shape is primarily determined by the local topogra-

Table 3. *Summary of modeling capabilities for calculating volumes of overwash.*

Author	Input	Calculation of R, the Theoretical Runup Limit	Theoretical Basis	Model Calibration	Model Validation and Performance	Limitations and Comments
Leatherman (1976a)	u_c	na[1]	Calculated volume of sediment crossing the crest by applying the Einstein sediment equation to velocities measured at the crest.	na	Sediment volumes are within one order of magnitude of the measured field volumes, but display considerable scatter.	Uses velocity measured at the crest. Alternatively suggested that $u_c = (gh)^{1/2}$, but Holland (1991) has since shown that this is probably closer to $u_c = 2.6 \times (gh)^{1/2}$
Williams (1978), model 1	ΔR, $1/T$	Saville (1958) and Savage (1958) empirical curves	Assumed that overwash transport rate is proportional to $1/T \times \Delta R$ raised to some exponent, α.	The model was calibrated against Williams' own laboratory data set.	Sediment volumes are within one order of magnitude of measured laboratory volumes (usually within a factor of 2, but with the largest error being 700%). The model neither consistently under- nor overestimates the sediment volumes.	To date, this approach has been calibrated and validated with the same set of laboratory data. It has not been tested against field data.
Williams (1978), model 2	ΔR, $1/T$	Saville (1958) and Savage (1958) empirical curves	Assumes that the overwash transport rate increases rapidly for small values of $1/T \times \Delta R$ and asymptotically approaches 0 in an exponential form as ΔR increases.	The model was calibrated against Williams' own laboratory data set.	Sediment volumes are within one order of magnitude of measured laboratory volumes (usually within a factor of 3, but with a largest error of 500%). The model neither consistently under- nor overestimates the sediment volumes	As yet, this approach was calibrated and validated with the same set of laboratory data. It has not been tested against field data.
Sanchez-Arcilla and Jimenez (1994)	R	Mase (1989)	The Chezy equation was used to calculate the velocity on the backslope of the barrier and the Van Rijn (1984) method for bedload, and in the area of breaches, for suspended load, was used to calculate the sediment transport rate.	na	Order of magnitude only. The calculated sediment transport rates were reasonable when compared to the measured total volume of sediment deposited on the barrier.	Assumes that runup is constantly overtopping the barrier.
Tanaka *et al.* (2002)	ΔR	Ogawa and Shuto (1984)	Assumed that the overtopping rate is proportional to ΔR raised to some exponent, n (overtopping of a coastal dike, Tominaga and Sakuma, 1971). The overtopping rate is modified for irregular waves (Goda 1985).	The coefficients, n and a, are give fixed values proposed by Tominaga and Sakuma (1971) for overtopping of the dikes.	Amount of sediment deposited in lagoon by overwash is estimated by comparing aerial photographs; depth of deposit is assumed constant. The concentration of sediment in the overtopping flow is then calculated. The calculated values lie on the empirical line of Kobayashi *et al.* (1996).	In this case, the overtopping rate is assumed independent of the wave period. Note that the calculated overtopping rate could be used with Kobayshi *et al.* (1996) empirical formula for sediment concentration in overwash to calculate the overwash rate.
Baldock *et al.* (2004)	E^*	Shallow-water equations (numerical solution)	Overtopping flow at a theoretical cutoff at the point of maximum runup is calculated using a numerical solution of the shallow water equations. Sediment transport is calculated using the Shields model with standard coefficients. Suspended load is assumed negligible.	na	For overtopping rates, the numerical model fits the measured data well, but with some scatter, which may indicate a dependence on the wave period. Agreement of calculated overwash rates and measured laboratory overwash rates is excellent (generally within a factor of 2).	Q is assumed not to be a function of the wave period and swash interaction is not taken into account. The author suggests that such considerations may improve the model.

[1] na = not applicable.

phy, as seen in Figures 4 and 5. However, it may be that the assumption of a linear spreading performs well within a 1-D framework, because it can broadly take into account losses by lateral spreading (which for most washover fans is less than 45°), friction, and percolation.

The cross-shore numerical model of SRINIVAS and DEAN (1996) does not represent overwash spreading on the back beach, percolation, or friction. The model was employed to simulate profile response in connection with inundation of a flat, broad laboratory barrier island, but no field verification was carried out. The published results, compared to modeled overwash caused by 0.16-m waves and 0.1 m of inundation, indicate the model's capability to predict a washover that thins toward its landward boundary, as well as rollback of the beach crest, but it is unknown how this model performs for prototype conditions, in particular for dunes or a landward-sloping back beach. The modeled volume of laboratory washover is within 30% of the measured. PIRRELLO (1992) showed that the wave transformation model of DALLY, DEAN, and DALRYMPLE (1985) was not able to accurately predict the wave height decay across a barrier island modeled in the laboratory, suggesting this was probably because the net mass flux through the system increased, thus reducing wave height decay. Therefore, in considering inundation overwash, a refined wave transformation model may improve the results. As yet, no 2-D model for overwash prediction of sediment transport and topographic change exists.

Future Model Development

Although only a small amount of overwash hydrodynamic data have been collected, valuable observations have been made. For runup overwash, bed load is typically the dominant mode of transport, whereas information is lacking about what prevails during inundation overwash. If suspended load contributes significantly, it would more likely be where overwash velocities are greatest—for example, in channeled inundation overwash where large gradients in elevation may exist. For large-scale inundation overwash or the inundation of a prominent dune feature, the hydrodynamics on the back slope are similar to those described by VISSER (1998) for sand dike breaching; flow on the back slope is supercritical, and sediment transport is dominated by suspended load.

Several processes have not been taken into account in 1-D models. It is acknowledged that bar location and magnitude may affect the level of runup and hence the amount of runup and the type of overwash (SMITH and KRAUS, 1991). It is suspected that this lack of return flow for larger overwash events (HANCOCK, 1994) may reduce the size of a storm bar or hinder its formation, but more research is needed to determine the magnitude. Other processes that have yet to be taken into account in overwash profile models are percolation, friction (*e.g.,* flow impedance by vegetation), local topography including channeling of overwash through gaps in the beach crest, and wind-induced currents.

For the initial overwashes of a storm, percolation into dry sand results in rapid deceleration of the overwash and rapid deposition. As the fan becomes wetter, these losses decrease and overwash may penetrate further inland. Heavy rain during a storm event may decrease this effect. Vegetation, too, plays a large role in slowing overwash. Salt-resistant grasses begin to populate washover fans within a year, and less-frequently-overwashed areas may support small bushes and shrubs. In developed regions, roads, buildings, fences, *etc.* contribute greatly to the funneling and slowing of overwash. Wind stress currents during an overwash can significantly alter the expected shape of an overwash fan, usually biasing the shape in the direction of wind propagation (MORTON, 1979). Also, subaerial wind stress reworking of deposits directly after a storm (FISHER and STAUBLE, 1978; LEATHERMAN, 1976c) can modify the expected poststorm profile.

For most purposes, such as poststorm planning by local authorities, a 1-D cross-shore model of profile change, such as that by LARSON, WISE, and KRAUS (2005), is convenient for forecasting overwash penetration and depth in the washover channel. Although the 1-D model of LARSON, WISE, and KRAUS (2005) performs well for estimation of beach profile change along the centerline of a washover fan or during sheet wash, it cannot predict the 2-D geometry of a washover. In more sensitive regions—for example, on developed coastlines—the lateral spread of a single washover fan may be of concern to planning authorities, and a 2-D model would be more appropriate. Additionally, such a model could forecast overwash development, such as overwash channel widening, which may precede breaching. Also, procedures exist to predict overwash occurrence alongshore (SALLENGER *et al.,* 2004; WETZELL, HOWD, and SALLENGER, 2003). These procedures can be used to formulate evacuation plans as a storm approaches.

In calibration or verification of an overwash model, processes that may have occurred during the period spanned by the pre- and poststorm profile surveys must be considered. If the wind has been strong and the weather dry, the potential for eolian redistribution of the washover sediments is high, and the poststorm profile may contain substantial contributions from both the storm processes and eolian redistribution. Additionally, beach recovery processes will also alter the poststorm profile. Current profile change models have only been calibrated and tested for sandy beaches. Overwash is also an important process on gravel and shingle barriers (*e.g.,* BRADBURY and POWELL, 1992; CARTER and ORFORD, 1981), and although understanding of overwash processes has been advanced as a result of studies on such barriers, there remains scope to develop profile change models for coarse sediment beaches.

In summary, it appears that overwash profile evolution on a channel centerline or for overwash by runup can be reasonably modeled by a series of 1-D initial beach profiles, with input data of variable water levels, wave heights, and wave periods. Such models run fast and have given reliable results. To improve predictive capability, the next most important factors are the 2-D beach topography, vegetative impedance, and percolation. Wind stress can also be a significant factor that could eventually be incorporated in overwash modeling. Wind setup and setdown are already included in 1-D models, but not eolian sediment transport or cross-shore wind forces that may act on subaqueous overwash deposits as a hurricane crosses a coast (MORTON, 1979). Based on this, the following sections describe the present status of data availability and

make recommendations for future data collection and modeling.

Data Availability

Although many poststorm profile surveys were made immediately after overwash occurred, the availability of corresponding prestorm profiles immediately before an event is much more limited. For most sites, prestorm profiles originate from any time between 1 month and up to 10 years prior to the storm. Nevertheless, there are several sets of pre- and poststorm profile survey data sets in the literature suitable for studying overwash. The development of LIDAR techniques for obtaining high-density spatial data has increased the availability of such information and also allows 2-D profile change study.

On the other hand, forcing data sets associated with overwash occurrence are rarer. Offshore wave and water levels depend on the presence of instruments located near the site, supplemented by hindcasts as necessary. The collection of such data for severe storms is difficult, both to prepare and to maintain the integrity of instrument platforms. Instrumentation of the barrier portion of a potential site requires confidence that overwash will occur. Pressure transducers and capacitance wave and water level gauges can fail when water depths are too small and are subject to movement or burial. Remote sensing, such as by X-band radar and video, is hampered by requirements of sturdy high platforms and rain and, in the case of video, lack of daylight.

Available data sets that include detailed hydrodynamic and sediment transport measurements have typically been collected during small storms or during nonstorm overwash. Offshore wave data and water levels were collected by CARTER and ORFORD (1981), whereas HOLLAND, HOLMAN, and SALLENGER (1991), BRADBURY and POWELL (1992), and MATIAS *et al.* (2003) collected nearshore wave data and water levels. These authors also presented pre- and poststorm profiles. Other data sets related to overwash modeling have been collected during storm conditions and include overwash depths and velocities (HOLLAND, HOLMAN, and SALLENGER, 1991; LEATHERMAN, 1976a; MATIAS *et al.,* 2003), and suspended sediment (LEATHERMAN, 1976a), although data from the older studies are generally unavailable in detail.

Two excellent data sets are those from the combined 11 November 1991 and 4 January 1992 storms at Ocean City, Maryland, assembled by KRAUS and WISE (1993) and LARSON, WISE, and KRAUS (2004), and those from the combined January and February 1998 storms at northern Assateague Island, Maryland, assembled by LARSON, WISE, and KRAUS (2005). Nearshore wave characteristics and water levels at 10-m depth were recorded for both storms, and high-quality surveys extending sufficiently seaward and landward were made. The earlier data set shows runup overwash of relatively narrow to high dunes, whereas the later data set shows inundation overwash of a wide-low barrier island. The only limitation of these two data sets is the time interval between surveys. Although the surveys closely bracket the two storms, beach face recovery and eolian transport may have occurred during the period between the storms. LARSON, WISE, and KRAUS (2005) modeled all erosive wave conditions within the entire 2-month interval between the pre- and poststorm profile surveys of 1992 (and the same for the 1998 storm surveys) to model the cumulative response of the barrier island. The data of the 1998 storms and how the information was collected are summarized in RAMSEY *et al.,* (1998).

Future Study

Recent renewed interest in overwash indicates that the modeling of overwash quantities and profile evolution is improving; however, the biggest hurdle at the moment is lack of field data or large-scale laboratory data. The performance of field measurement equipment under extreme storm conditions is doubtful, so low-lying sites that overwash on extreme tidal cycles or in minor storms should be sought. Alternatively, the large-scale model tests of shingle beaches by BRADBURY and POWELL (1992) appear to have been successful, and similar physical model tests might be conducted with experiment design based on reference to measurements made on a barrier island such as Assateague Island.

Processes identified in this review that have yet to be quantitatively studied or validated with accurate measurements are:

1. Sediment transport rates across a barrier island. Measurements are lacking and might best be obtained in a large-scale physical model. Laboratory measurements should include both monochromatic and random wave forcing for examination of the detailed processes.
2. Hydrodynamics across a barrier island.
3. Lateral spreading on the back beach.
4. Threshold between runup and inundation overwash.
5. Threshold between crest accumulation and crest lowering.
6. Percolation and friction losses.
7. Swash interaction during overwash.
8. Channelization in the throat (particularly for localized overwash by inundation).
9. Widening of the throat.
10. Initiation of breaching.

Additionally, for overwash by inundation, the efforts of PIRRELLO (1992) to predict wave decay across the beach crest and shoreward onto the back barrier should be continued. Such modeling is vital in considering the contribution of waves to sediment transport during large overwash events.

Future data-collection efforts should include:

1. Water level; nearshore wave height, period and direction; and wind speed and direction. Ideally, these should be measured together with offshore wave information to validate predictive models that are typically driven by offshore information.
2. Water depth at the crest and, if possible, at other points on the landward side of the crest.
3. Water velocity on the beach face, at the beach crest, and at other points on the landward side of the crest.
4. Wave height and period across the profile.

5. Real-time monitoring of profile change such as the vertical and horizontal movement of the crest.
6. Lateral spreading of the washover and its thickness.

Many of the previously published beach profile surveys did not extend to the point of closure on either the sea side or the bay side. The collection of more complete beach profile data would greatly contribute to the verification of overwash models. As remarked by BRADBURY and POWELL (1992), the chronology of waves becomes significant in studying the threshold between crest accumulation and crest lowering because smaller overwashes may accumulate sediment on the crest preventing further overwash until a large enough wave occurs to erode the accumulated sediment. The effects of wave chronology can be documented in a laboratory study of threshold overwashing conditions.

With the development of modern instrumentation, the monitoring of overwash has and will become easier. For laboratory studies, digital video imaging can be used to continuously monitor time-development of the beach profile, overwash bore velocity, and overwash depth. As demonstrated by HOLLAND, HOLMAN, and SALLENGER (1991), this technique can, to some extent, be applied in the field. The use of video during a hurricane is limited by the design of a stable platform and visibility during driving rain, and is likely not available in darkness. Media footage shown after Hurricane Ivan varies from good visibility, where the borders between sand and water are clear and wind waves on an overwash are visible, to images totally obscured by rain. Careful camera setup in relation to the expected wind direction during overwash and with external lighting could reduce these limitations. Data from such imaging will probably only include overwash borefront velocities, and estimations of overwash depth.

Modern commercially available acoustic and optical instrumentation could be applied to great advantage in measurement of overwash dynamics. Small and robust acoustic current meters are now available (KRAUS, LOHRMANN, and CABRERA, 1994) that can measure velocities through a wide range of flow speeds while requiring only 5–10 cm of water depth. Optical backscatter sensors (DOWNING, STERNBERG, and LISTER, 1981) have been miniaturized to allow high-resolution measurements of sediment concentration. Airborne LIDAR significantly improves the capability to collect wide-area coastal topography and shallow-water bathymetry data. Coastal volume change can be quantified by comparing pre- and poststorm surveys. Vertical accuracy is expected to have a root mean square value of about ± 15 cm (SALLENGER *et al.,* 2004). Such data sets are suitable for verifying beach profile change models, as has been done by LARSON, WISE, and KRAUS (2004). Collection of bathymetric data is limited to nonturbid water and the landward limit of the survey does not always include the landward limit of overwash penetration (SALLENGER *et al.,* 2004).

FREEMAN, BERNSTEIN, and MITASOVA (2004) described modern 3D survey design using real-time kinematic GPS, and ultra shallow-water single-beam and multibeam sonar technologies. Instruments were either handheld or mounted on all-terrain vehicles for land surveys, and mounted on a wave-runner personal watercraft and boat for bathymetric surveying. These techniques together with appropriate survey strategy allow seamless integration between the bathymetric and topographic surveys. Such techniques would provide high-quality pre- and poststorm beach profiles.

CONCLUSIONS

A comprehensive review of the literature on coastal overwash and washover was presented. The review covers general observations of overwash processes, studies from a geological perspective, physical modeling, field observations including measurements of washovers and related hydraulics, and numerical modeling capability to predict overwash. A methodology was introduced to classify overwash processes by relative elevations of water level (surge, runup) and the elevation of the dune or beach crest. Emphasis in the review was on information that can contribute to development of predictive analytical procedures and numerical models, either by the presentation of relative data or by insights into physical processes.

Most of the existing attempts to model overwash are limited to estimation of the net volume of sediment transported landward of the beach crest. The accuracy of such models varies from a factor of two, as verified by laboratory experiments (T.E. BALDOCK; K. DAY; M.G. HUGHES, and F. WEIR, unpublished data) to order of magnitude, as verified by field measurements (LEATHERMAN, 1976a). To date, most of these models have been verified with only one set of laboratory data, one set of storm conditions, or at one field site. The exception is the SBEACH profile change model (LARSON and KRAUS, 1989), which has been validated against multiple beach profile measurements made at Ocean City, Maryland (KRAUS and WISE, 1993; WISE and KRAUS, 1993; WISE, SMITH, and LARSON, 1996), possessing high dunes, and at northern Assateague Island, Maryland, a broad flat barrier island (LARSON, WISE, and KRAUS, 2004, 2005). At the present time, the SBEACH model can simulate only overwash by runup, and extension of SBEACH to model overwash by inundation is recommended.

One-dimensional models such as SBEACH are valid as design and decision-support planning tools, but an ultimate goal should be development of 2-D models that can describe overwash over variable topography and the 2-D situation of multiple overwash breakthroughs colliding. Other factors that should also be incorporated in improved models of overwash include wind stress, dune topography, percolation, friction, and coarse sediments. Presently, there exist procedures to predict the longshore occurrence of overwash (WETZELL, HOWD, and SALLENGER, 2003), which can be used to in emergency management operations for warnings as a storm approaches.

Calculation methods for overwash volume could be improved by modifying runup and overtopping equations in describing reduced swash interaction and return flow, and in combining these equations with sediment transport equations and verifying against field measurements. Overwash can occur either by runup or inundation, but both these conditions may occur during one event, as a result of varying surge levels and tidal control. The location of the threshold

between these two conditions becomes pivotal, and a comprehensive profile change model should deterministically describe both conditions. Consideration of overwash by inundation and runup and the relative periods over which they occur leads to distinguishing variations in type of washover morphology. Prediction of washover morphology type within profile models by location and storm will require both two-dimensionality and successful modeling of threshold conditions. Lack of data is the greatest hurdle in model development, and field and large-scale laboratory models of overwash processes are needed. In particular, beach profile surveys documenting overwash by inundation are difficult to find, and the collection of such data is essential to the development of profile change models, such as SBEACH, for modeling overwash by inundation. Based on review of the processes and state of numerical model prediction, recommendations were given for design of field and laboratory data collection that will aid in developing the next generation of overwash models.

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LITERATURE CITED

BRADBURY, A.P. and POWELL, K.A., 1992. The short term profile response of shingle spits to storm wave action. *Proceedings of the 23rd Coastal Engineering Conference* (Venice, Italy, ASCE), 2694–2707.

BUREAU OF BEACHES AND COASTAL SYSTEMS, 2004. Hurricane Charley, Post-Storm Beach Conditions and Coastal Impact Report with Recommendations for Recovery and Modifications of Beach Management Strategies. Division of Water Resource Management, Department of Environmental Protection, State of Florida.

BYRNES, M.R. and GINGERICH, K.J., 1987. Cross-island profile response to Hurricane Gloria. *In: Proceedings Coastal Sediments '87* (New Orleans, Louisiana, ASCE), pp. 1486–1502.

CARTER, R.W.G. and ORFORD, J.D., 1981. Overwash processes along a gravel beach in South-East Ireland. *Earth Surface Processes and Landforms,* 6(5), 413–426.

CLEARY, W.J. and HOSIER, P.E., 1979. Geomorphology, washover history, and inlet zonation: Cape Lookout, N.C. to Bird Island, N.C. *In*: LEATHERMAN, S.P. (ed.), *Barrier Islands, from the Gulf of St. Lawrence to the Gulf of Mexico.* New York: Academic Press, pp. 237–271.

DAHL B.E.; COTTER, P.C.; WESTER, D.B., and DRBAL D.D., 1983. Posthurricane Survey of Experimental Dunes on Padre Island, Texas. Ft. Belvoir, Virginia: U.S. Army Corps of Engineers, Coastal Engineering Research Center.

DALLY, W.R.; DEAN, R.G., and DALRYMPLE, R.A., 1985. Wave height variation across beaches of arbitrary profile. *Journal of Geophysical Research,* 90(C6), 1277–1302.

DAVIDSON-ARNOTT, R.G.D. and FISHER, J.D., 1992. Spatial and temporal controls on overwash occurrence on a Great Lakes barrier spit. *Canadian Journal of Earth Sciences,* 29(1), 102–117.

DE WAAL, J.P. and VAN DER MEER, J.W., 1992. Wave runup and overtopping on coastal structures. *Proceedings 23rd Coastal Engineering Conference* (Venice, Italy, ASCE), 1758–1771.

DOLAN, R. and GODFREY, P., 1973. Effects of Hurricane Ginger on the barrier islands of North Carolina. *Geological Society of America Bulletin,* 84, 1329–1334.

DOLAN, R.; HAYDEN, B., and FELDER, W., 1979. Shoreline periodicities and linear offshore shoals. *Journal of Geology,* 87, 393–402.

DOLAN, R. and HAYDEN, B., 1981. Storms and shoreline configuration. *Journal of Sedimentary Petrology,* 51(3), 737–744.

DONNELLY, C.; KRAUS, N.C., and LARSON, M., 2004. Coastal Overwash. Part 1: Overview of Processes. Regional Sediment Management Demonstration Program Technical Note, ERDC/RSM-TN-14. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center,

DOWNING, J.P.; STERNBERG, R.W., and LISTER, C.R.B., 1981. New instrumentation for the investigation of sediment suspension processes in the shallow marine environment. *Marine Geology,* 42, 19–34.

EISER, W.C. and BIRKEMEIER, M., 1991. Beach profile response to Hurricane Hugo. *Proceedings Coastal Sediments '91* (Seattle, Washington, ASCE), pp. 1681–1696.

ELFRINK, B. and BALDOCK, T., 2002. Hydrodynamics and sediment transport in the swash zone: a review and perspectives. *Coastal Engineering,* 45(3–4), 149–167.

FISHER, J.S.; LEATHERMAN, S.P., and PERRY, F.C., 1974. Overwash processes on Assateague Island. *Proceedings 14th Coastal Engineering Conference* (Copenhagen, Denmark, ASCE), 1194–1211.

FISHER, J.S. and STAUBLE, D.K., 1977. Impact of Hurricane Belle on Assateague Island washover. *Geology,* 5, 765–768.

FISHER, J.S. and STAUBLE, D.K., 1978. Washover and dune interaction on a barrier island. *Proceedings Coastal Zone '78* (San Francisco, California, ASCE), pp. 1611–1618.

FREEMAN, C.W.; BERNSTEIN, D.J., and MITASOVA, H., 2004. Rapid response 3D survey techniques for seamless topo/bathy modeling: 2003 Hatteras Breach, North Carolina. *Shore and Beach,* 72(2), 25–29.

GODA, Y., 1985. *Random Seas and Design of Maritime Structure.* Tokyo, Japan: University of Tokyo Press, pp. 145–154.

GODFREY, P.J. and GODFREY, M.M., 1974. The role of overwash and inlet dynamics in the formation of salt marshes on North Carolina barrier islands. *In*: REINOLD, R.A. (ed.), *Ecology of Halophytes.* New York: Academic Press, pp. 407–427.

HANCOCK, M.W., 1994. Experiments on Irregular Wave Overtopping and Overwash of Dunes. Newark, Delaware: Department of Civil Engineering, University of Delaware, Master's thesis, 88 pp.

HANCOCK, M. and KOBAYASHI, N., 1994. Wave overtopping and sediment transport over dunes. *In: Proceedings 24th Coastal Engineering Conference* (Kobe, Japan, ASCE), pp. 2028–2042.

HAYES, M.O., 1967. Hurricanes as geological agents, south Texas coast. *American Association Petroleum Geologists Bulletin,* 51, 937–942.

HOLLAND, T.K.; HOLMAN, R.A., and SALLENGER, A.H., JR., 1991. Estimation of overwash bore velocities using video techniques. *Proceedings Coastal Sediments '91* (Seattle, Washington, ASCE), pp. 489–497.

JIMENEZ, J.A. and SANCHEZ-ARCILLA, A., 2004. A long-term (decadal scale) evolution model for microtidal barrier systems. *Coastal Engineering,* 51, 749–764.

JOHNSON, D.W., 1919. *Shore processes and shoreline development.* New York: John Wiley and Sons, 548 pp.

KOBAYASHI, N.; TEGA, Y., and HANCOCK, M.W., 1996. Wave reflec-

tion and overwash of dunes. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 122(3), 150–153.

KOCHEL, R.C. and DOLAN, R., 1986. The role of overwash on a mid-Atlantic coast barrier island. *Journal of Geology,* 94, 902–906.

KOCHEL, R.C. and WAMPFLER, L.A., 1989. Relative role of overwash and aeolian processes on washover fans, Assateague Island, Virginia-Maryland. *Journal of Coastal Research,* 5(3), 453–475.

KRAUS, N.C.; LOHRMANN, A., and CABRERA, R. 1994. New acoustic meter for measuring 3D laboratory flows, *Journal of Hydraulic Engineering,* 120(3), 406–412.

KRAUS, N.C.; MILITELLO, A., and TODOROFF, G., 2002. Barrier breaching processes and barrier spit breach, Stone Lagoon, California. *Shore and Beach,* 70(4), 21–28.

KRAUS, N.C.; SMITH, J.M., and SOLLITT, C.K., 1992. SUPERTANK Laboratory Data Collection Project. *Proceedings 23rd Coastal Engineering Conference* (Venice, Italy, ASCE), 2191–2204.

KRAUS, N.C. and WAMSLEY, T.V., 2003. Coastal Barrier Breaching, Part 1: Overview of Breaching Processes. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-56, Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center. http://chl.wes.army.mil/library/publications/chetn/pdf/chetn-iv-56.pdf (accessed January 12, 2005).

KRAUS, N.C. and WISE, R.A., 1993. Simulation of January 4, 1992 storm erosion at Ocean City, Maryland. *Shore and Beach,* 61(1), 34–41.

LARSON, M. and KRAUS, N.C., 1989. *SBEACH. Numerical Model for Simulating Storm-induced Beach Change; Report 1. Empirical Foundation and Model Development.* Technical Report CERC-89-9, Vicksburg, Mississippi: U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, 267p.

LARSON, M.; KUBOTA, S., and ERIKSON, L., 2001. Modeling sediment transport and profile evolution in the swash zone. *Proceedings Coastal Dynamics '01* (Lund, Sweden, ASCE), pp. 908–917.

LARSON, M.; KUBOTA, S., and ERIKSON, L., 2004. Swash-zone sediment transport and foreshore evolution: field experiments and mathematical modeling. *Marine Geology* 212(1–4), 61–79.

LARSON, M.; WISE, R.A., and KRAUS, N.C., 2004. Coastal Overwash. Part 2: Upgrade to SBEACH. Regional Sediment Management Demonstration Technical Note, ERDC/RSM-TN-15. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center.

LARSON, M.; WISE, R.A., and KRAUS, N.C., 2005. Modeling dune response due to overwash transport. *In: Proceedings 29th Coastal Engineering Conference.* Lisbon, Portugal: World Scientific Press, pp. 2133–2145.

LEADON, M.E.; NGUYEN, N.T., and CLARK, R.R., 1998. Hurricane Opal. Beach And Dune Erosion and Structural Damage Along the Panhandle Coast of Florida. Report No. BCS-98–01. Tallahassee, Florida: Bureau of Beaches and Coastal Systems, Florida Department of Environmental Protection, 60p.

LEADON, M.E., 1999. Beach, dune and offshore profile response to a severe storm event. *In: Proceedings Coastal Sediments '99* (Long Island, New York, ASCE), pp. 2534–2549.

LEATHERMAN, S.P., 1976a. Quantification of Overwash Processes., Charlottesville, Virginia: Department of Environmental Sciences, University of Virginia, Ph.D. dissertation, 245 pp.

LEATHERMAN, S.P., 1976b. (Reprint 1979.). Assateague Island: A case study of barrier island dynamics. *In: Proceedings Conference on Science Research in the National Parks* (New Orleans, Louisiana), Volume 1, 16p.

LEATHERMAN, S.P., 1976c. Barrier island dynamics: overwash processes and eolian transport. *Proceedings 15th Coastal Engineering Conference* (Honolulu, Hawaii, ASCE), pp. 1959–1974.

LEATHERMAN, S.P., 1977. Overwash hydraulics and sediment transport. *Proceedings Coastal Sediments 1977* (Charleston, South Carolina, ASCE), pp. 135–148.

LEATHERMAN, S.P., 1979a. Migration of Assateague Island, Maryland, by inlet and overwash processes. *Geology,* 7, 104–107.

LEATHERMAN, S.P., 1979b. Barrier dune systems: a reassessment. *Sedimentary Geology,* 24, 1–16.

LEATHERMAN, S.P., 1979c. Beach and dune interactions during storm conditions. *Quarterly Journal of Engineering Geology,* 12, 281–290.

LEATHERMAN, S.P., 1981. *Overwash Processes.* Benchmark Papers in Geology, Volume 58. Stroudsburg, Pennsylvania: Hutchinson Ross Publishing Co., 376p.

LEATHERMAN, S.P., 1985. Geomorphic and stratigraphic analysis of Fire Island, NY. *Marine Geology,* 126, 143–159.

LEATHERMAN, S.P.; WILLIAMS, A.T., and FISHER, J.S., 1977. Overwash sedimentation associated with a large-scale northeaster. *Marine Geology,* 24(2), 109–121.

LE MEHAUTE, B., 1976. *An Introduction to Hydrodynamics and Water Waves.* New York: Springer-Verlag, 315p.

LOBECK, A.K., 1939. *Geomorphology.* New York: McGraw-Hill Book Company, 349p.

MASE, H., 1989. Random wave run-up height on gentle slopes. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 115(5), 649–661.

MATIAS, A.; VILA-CONCEJO, A.; FERREIRA, Ó., DIAS, J.A., 2003. Field measurements of morphologic variations during an overwash event. *Thalassas* (special issue for the 4th Symposium on the Iberian Continental Margin), 19(2b), 164–165.

MORRIS, B.D.; BELL, P.S.; MATIAS, A.; FERREIRA, Ó., and WILLIAMS, J.J., 2004. Estimates of swash processes using a high resolution radar. *In: Proceedings of the Workshop: Methods for Determining and Representing Coastal Hazards,* pp. 21–22.

MORTON, R.A., 1979. Subaerial storm deposits formed on barrier flats by wind-driven currents. *Sedimentary Geology,* 24, 105–122.

MORTON, R.A.; GONZALEZ, J.L.; LOPEZ, G.I., and CORREA, I.D., 2000. Frequent non-storm washover of barrier islands, Pacific coast of Columbia. *Journal of Coastal Research,* 16(1), 82–87.

MORTON, R.A.; GUY, K.K.; HILL, H.W., and PASCOE, T., 2003. Regional Morphological Responses to the March 1962 Ash Wednesday Storm. *In: Proceedings Coastal Sediments '03.* Corpus Christi, Texas: World Scientific Press and East Meets West Productions, CD-ROM, 11p.

MORTON, R.A. and SALLENGER A.H., Jr., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research,* 19(3), 560–573.

OGAWA, Y. and SHUTO, N., 1984. Run-up of periodic waves on beaches of non-uniform slope. *Proceedings 19th Coastal Engineering Conference* (Houston, Texas, ASCE), 328–344.

ORFORD, J.D. and CARTER, R.W.G., 1982. Crestal overtop and washover sedimentation on a fringing sandy gravel barrier coast, Carnsore Point, Southeast Ireland. *Journal of Sedimentary Petrology,* 52(1), 265–278.

ORFORD, J.D. and CARTER, R.W.G., 1984. Mechanisms to account for the longshore spacing of overwash throats on a coarse clastic barrier in southeast Ireland. *Marine Geology,* 56(1–4), 207–226.

ORFORD, J.; JENNINGS, S., and PETHICK, J., 2003. Extreme storm effect on gravel dominated barriers. *In: Proceedings Coastal Sediments '03.* Corpus Christi, Texas: World Scientific Press and East Meets West Productions, CD-ROM, 14p.

PARCHURE, T.; DEAN, R.G., and SRINIVAS, R., 1991. Laboratory Study of Overwash on Barrier Islands. Progress Report, Coastal and Oceanographic Department, University of Florida, 59p.

PENLAND, S. and SUTER, J.R., 1984. Low-profile barrier island overwash and breaching in the Gulf of Mexico. *In: Proceedings 19th Coastal Engineering Conference* (Houston, Texas, ASCE), pp. 2339–2345.

PENLAND, S.; SUTER, J.R.; SALLENGER, A.H. JR.; WILLIAMS, S.J.; MCBRIDE, R.A.; WESPHAL, K.E.; REIMER, P.D., and JAFFE, B.E., 1989. Morphodynamic signature of the 1985 hurricane impacts on the Northern Gulf of Mexico. *In: Coastal Zone: Proceedings of the 6th Symposium on Coastal and Ocean Management* (Charleston, South Carolina), pp. 4220–4234.

PEREGRINE, D.H., and WILLIAMS, S.M., 2001. Swash overtopping a truncated plane beach. *Journal of Fluid Mechanics,* 440, 391–399.

PIERCE, J.W., 1969. Sediment budget along a barrier island chain. *Sedimentary Geology,* 3, 5–16.

PIERCE, J.W., 1970. Tidal inlets and washover fans. *Journal of Geology,* 78, 230–234.

PIRRELLO, M.A., 1992. The Role of Wave and Current Forcing in the

Process of Barrier Island Overwash. Gainesville, Florida: Coastal and Oceanographic Engineering Department, University of Florida, M.S. thesis, 117p.

PRICE, W.A., 1947. Equilibrium of form and forces in tidal basins of coast of Texas and Louisiana. *Bulletin of the American Association of Petroleum Geologists,* 31(9), 1619–1663.

RAMSEY, K.W.; LEATHERS, D.J.; WELLS, D.V., and TALLEY, J.H., 1998. Summary Report, the Coastal Storms of January 27–29 and February 4–6, 1998, Delaware and Maryland. Open file report no. 40. Newark, Delaware: University of Delaware, 43 pp.

SALLENGER, A.H., JR., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research,* 16(3), 890–895.

SALLENGER, A.H.; WRIGHT, C.W.; GUY, K., and MORGAN, K., 2004. Assessing storm-induced damage and dune erosion using airborne Lidar: Examples from Hurricane Isabel. *Shore and Beach,* 72(2), 3–7.

SANCHEZ-ARCILLA, A. and JIMENEZ, J.A., 1994. Breaching in a wave-dominated barrier spit: the Trabucador bar (north-eastern Spanish coast). *Earth Surface Processes and Landforms,* 19, 483–498.

SCHWARTZ, R.K., 1975. Nature and Genesis of Some Storm Washover Deposits. Technical Memorandum 61. Ft. Belvoir, Virginia: U.S. Army Corps of Engineers, Coastal Engineering Research Center, 99p.

SEELIG, W.N. and AHRENS, J.P., 1995. Estimation of wave reflection and energy dissipation coefficients for beaches, revetments, and breakwaters. Technical Paper No. 81-1. Ft. Belvoir, Virginia: U.S. Army Corps of Engineers, Coastal Engineering Research Center, 40p.

SMITH, E.R. and KRAUS, N.C., 1991. Laboratory study on wave-breaking over bars and artificial reefs. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 117(4), 307–325.

SRINIVAS, R.; DEAN R.G. and PARCHURE, T.M., 1992. Barrier Island Erosion and Overwash Study, Volume 1. Gainesville, Florida: Coastal and Oceanographic Engineering Department, University of Florida, 92p.

SRINIVAS, R. and DEAN, R.G., 1996. Cross-shore hydrodynamics and profile response modelling. *Journal of Coastal Engineering,* 27, 193–221.

STAUBLE, D.K., 1979. The Interaction of Swash and Sediment on the Backshore in the Presence and Absence of Barriers. Charlottesville, Virginia: Department of Environmental Sciences, University of Virginia, Ph.D. dissertation, 127p.

STAUBLE, D.K., 1991. Coastal impacts of Hurricane Hugo. *Proceedings Coastal Sediments '91* (Seattle, Washington, ASCE), pp. 1666–1680.

STAUBLE, D.K., 2001. Morphodynamic evaluation of a highly dynamic inlet to improve channel navigation: Chatham Harbor, Massachusetts, USA. *Proceedings Coastal Dynamics '01* (Lund, Sweden, ASCE), pp. 232–241.

SUTER, J.R.; NUMMEDAL, D.; MAYNARD, A.K., and KEMP, P., 1982. A process-response model for hurricane washovers. *Proceedings 18th Coastal Engineering Conference,* (Capetown, South Africa, ASCE), pp. 1459–1789.

SVENDSEN, I.A., 1984. Mass flux and undertow in the surf zone. *Coastal Engineering,* 8, 347–365.

TANAKA, H.; SUNTOYO, and NAGASAWA, T., 2002. Sediment intrusion into Gamo Lagoon by wave overtopping. *In: Proceedings 28th Coastal Engineering Conference* (Cardiff, Wales, ASCE), pp. 823–835.

TOMINAGA, M. and SAKUMA, N., 1971. Wave overtopping on coastal dikes. *Proceedings of the Japanese Conference on Coastal Engineering,* 17, 133–140 (in Japanese).

TUAN, T.Q., 2003. Time-Varying Beach Slope for Overwash Models in Simulation of Lagoon Initial Breaching. Paper 089. *In: Proceedings 6th International Conference on Coastal and Port Engineering in Developing Countries,* (Colombo, Sri Lanka). CD-ROM, 7p.

U.S. GEOLOGICAL SURVEY (USGS). http://coastal.er.usgs.gov/hurricanes (accessed September 12, 2004).

VAN DER MEER, J.W. and JANSSEN, J.P.F.M., 1995. Wave run-up and wave overtopping at dikes. *In*: MEYER, R.E. (ed.), *Wave Forces on Inclined and Vertical Structures.* New York: Academic Press, 95–121.

VAN RIJN, L.C., 1984. Sediment transport, part I: bed load transport. *Journal of Hydraulic Engineering,* 110(10), 1431–1456.

VISSER, P.J., 1998. Breach growth in sand dikes. Delft, The Netherlands: Delft University of Technology, PhD thesis, 172 p.

WEIR, G.M., 1977. Inlet formation and washover processes at North Pond, eastern Lake Ontario. Buffalo, New York: University of New York at Buffalo, Masters Thesis, 75p.

WETZELL, L.M.; HOWD, P.A., and SALLENGER, A.H., 2003. Simple models for predicting dune erosion hazards along the Outer Banks of North Carolina.. *In: Proceedings Coastal Sediments '03.* Corpus Christi, Texas: World Scientific Press and East Meets West Productions, CD-ROM, 10p.

WILLIAMS, P.J., 1978. Laboratory Development of a Predictive Relationship for Washover Volume on Barrier Island Coastlines. Newark, Delaware: Department of Civil Engineering, University of Delaware, Master's thesis, 141p.

WISE, R.A. and KRAUS, N.C., 1993. Simulation of beach fill response to multiple storms, Ocean City, Maryland. *In*: STAUBLE, D.K. and KRAUS, N.C. (volume eds.), *Beach Nourishment Engineering and Management Considerations, Proceedings Coastal Zone '93* (New Orleans, Louisiana, ASCE), 133–147.

WISE, R.A.; SMITH, S.J., and LARSON, M., 1996. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. Report 4, Cross-Shore Transport under Random Waves and Model Validation with Supertank and Field Data. Technical Report CERC-89-9. Vicksburg, Mississippi: U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center.