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Relative Role of Overwash and Aeolian Processes on Washover Fans, Assateague Island, Virginia-Maryland

R. Craig Kochel and Laura A. Wampfler

Department of Geology
Southern Illinois University at Carbondale
Carbondale, Illinois 62901, USA

ABSTRACT

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There has been considerable controversy in recent years about the relative importance of overwash vs. aeolian processes in the vertical accretion or erosion of barrier islands. Most studies have used sediment budget data sets of two years or less in length. Analysis of coastal climatic data suggests that there are significant secular variations in storm intensity, frequency, and duration over time scales of 10's of years. Annual variations in climatic variables such as the magnitude and frequency of precipitation, high winds, and overwash have a considerable effect on accretion or erosion of washover fan surfaces along mid-Atlantic barrier islands. Conclusions and predictions based on data sets from very stormy years may be dramatically different than those based on data from relatively calm periods.

Sediment budget data for six fans along Assateague Island are presented for a four-year period that includes an exceptionally stormy year, an exceptionally calm year, and two years having average storm history. Accretion due to overwash processes was exceedingly dominant during the stormy year, but still significant in normal years. In contrast, aeolian deflation and deposition dominated during the calm year. Overall, Assateague Island fan surfaces accreted significantly over the course of the study, by an island-wide average of 22 cm. Individual fans accreted by as much as 90 cm. Observed variations in fan surface changes depended primarily upon the frequency of precipitation, frequency of overwash, and topography of the local fan area. The importance of overwash or aeolian processes with regard to fan accretion and erosion appears to depend upon variability and cyclicity of climatic factors. The effects of two exceedingly large storms resulted in extensive accretion on fan surfaces that was greater than the sum of 15 moderate storms during the four years. Longer observations periods may be needed to project future changes on barrier island surfaces.

ADDITIONAL KEY WORDS: *Barrier islands, mid-Atlantic coast, Assateague Island, overwash, washover fan, sediment budget, climate, geomorphology.*

INTRODUCTION

Overwash processes on barrier islands predominantly move sand from the beachface to washover terraces and washover fans in island interiors and along back-barrier environments (HAYES, 1967; MCGOWEN and SCOTT, 1973; SCHWARTZ, 1982). Overwash sedimentation is episodic, occurring during discrete storm events of varying magnitude and frequency. Aeolian processes, which operate on a more continual basis, can deposit or erode sand from washover fan surfaces. There has been considerable controversy in recent years concerning the relative importance of overwash vs. aeolian processes in the vertical accretion of barrier islands. DOLAN (1972), based largely on his work on the Outer Banks of North Carolina, suggested that overwash sedimentation was the primary process responsible for vertical accretion and landward movement of sand on barrier islands. His concerns were that the construction of artificial dunes for the prevention of overwash flooding may actually retard the vertical accretion of barrier islands. Conclusions from a short-term study on Assateague Island in Virginia and Maryland also provided support for the importance of overwash sedimentation in island accretion (KOCHEL and DOLAN, 1986).

LEATHERMAN (1976a,b) concluded that aeolian processes were slightly more dominant than overwash in accounting for changes in sediment budgets along northern Assateague Island during the mid-1970's. His detailed series of surveys between 1973 and 1975 provided new information on overwash hydraulics and sediment budgets for washover fans along

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northern Assateague Island. Leatherman (1976a,b) observed that aeolian deflation between overwash events was significant enough to result in net lowering of fan surfaces by deflation over the period of his study. Similar high deflation rates were observed by FISHER and STAUBLE (1977) on north Assateague following a period of excessive offshore winds during the winter of 1976–1977. Few studies have addressed sediment budgets in regard to climatic factors during the period of study and longer-term secular variations in coastal storm characteristics.

Significant differences in sediment budgets may result between surveys done during periods with dissimilar storm history. The dominance of overwash or aeolian processes with regard to accretion of washover sites should be expected to vary from year to year depending upon relative climatic conditions. In addition, the contrasting effects of storms of varying magnitude and frequency can be expected to complicate studies aimed at assessing the relative importance of aeolian and overwash processes on barrier island sediment dynamics over long periods of time. Most previous studies of washover fan sediment budgets, like earlier studies on Assateague Island (LEATHERMAN 1976a,b), have been based upon data sets of approximately two years or less in duration. Quantitative studies of overwash processes have provided detailed data on surge velocities, quantities of deposited sediment, and documentation of the succession of processes operative during overwash events (FISHER, *et al.*, 1974; LEATHERMAN, *et al.*, 1977; FISHER and STAUBLE, 1977). Interpretations based on such short-term data can lead to erroneous conclusions about long-term geomorphic change (such as erosion or accretion), especially if the study interval coincides with a period of anomalous climatic conditions. Because of the tendency of climatic variations to be cyclic, longer monitoring periods are required to address questions relating to sediment budgets on barrier islands for time scales of 10's to 100's of years. Washover fan sediment budget data should be collected during periods of excessive storminess as well as during periods of relative calm to complete models of island evolution. Similar long-term data sets may be required to properly interpret the significance of infrequent, large magnitude storms upon island geomorphology.

Factors that controlled the relative role of aeolian vs. overwash sedimentation during survey periods included: (1) the frequency of overwash events; (2) single-event and annual thicknesses of overwash sedimentation; (3) amount of precipitation; (4) the frequency of precipitation events; and (5) the nature of the wind climate. We will summarize the results of the first four years of a continuing study of sediment budgets for six washover sites on Assateague Island that began in October, 1982. The sediment budgets will be discussed in relation to the climatic conditions experienced during the survey period. The four years included in this study represent a complete spectrum of climatic conditions experienced at Assateague Island, including some of the stormiest and some of the calmest periods during the past 45 years. Analysis of data collected from these years of highly variable climatic conditions demonstrates the sensitivity of short-term studies to secular variations in climate and may permit us to make reasonable estimates of long-term changes.

ASSATEAGUE ISLAND GEOMORPHOLOGY AND WASHOVER FANS

Six washover fans distributed along Assateague Island (Figure 1) were selected to represent the range of environments and shoreline orientations that occur along the island. Assateague Island has three general geomorphic regions (Figure 2) that are characterized by varying styles of washover morphologies and provide varying degrees of shelter from aeolian deflation. The northern section, extending from Ocean City Inlet to the vicinity of Fan 23 is characterized by low, discontinuous dunes and large, low-relief washover terraces. Fan 18, to a lesser extent, is also a low-relief portion of Assateague Island. Dunes are present near Fan 18, but the topography of its surroundings is lower and more open than fans along the central region. A similar low-relief environment typifies much of the southern tip of the island along the spit adjacent to Chincoteague Inlet (region of Fan 16) and the narrow arm of the island connecting the spit to the main body of Assateague. Overwash in these low-relief areas

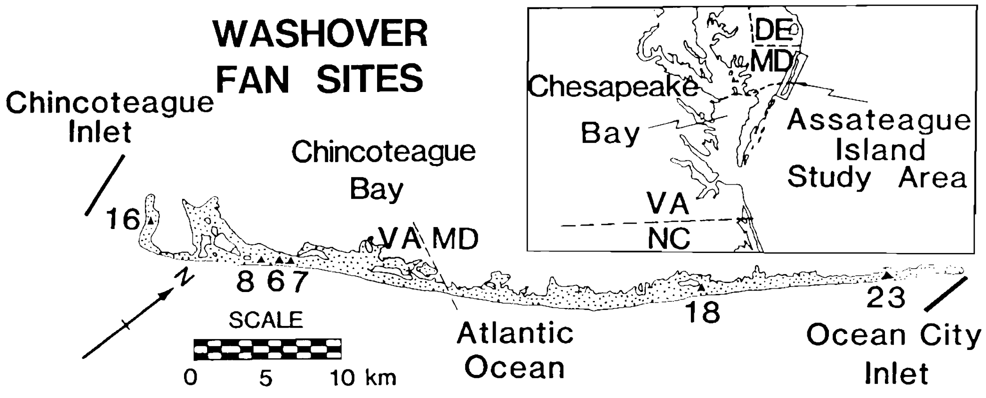


Figure 1. Index map of Assateague Island. Numbered triangles locate the six washover fans used in sediment budget studies.

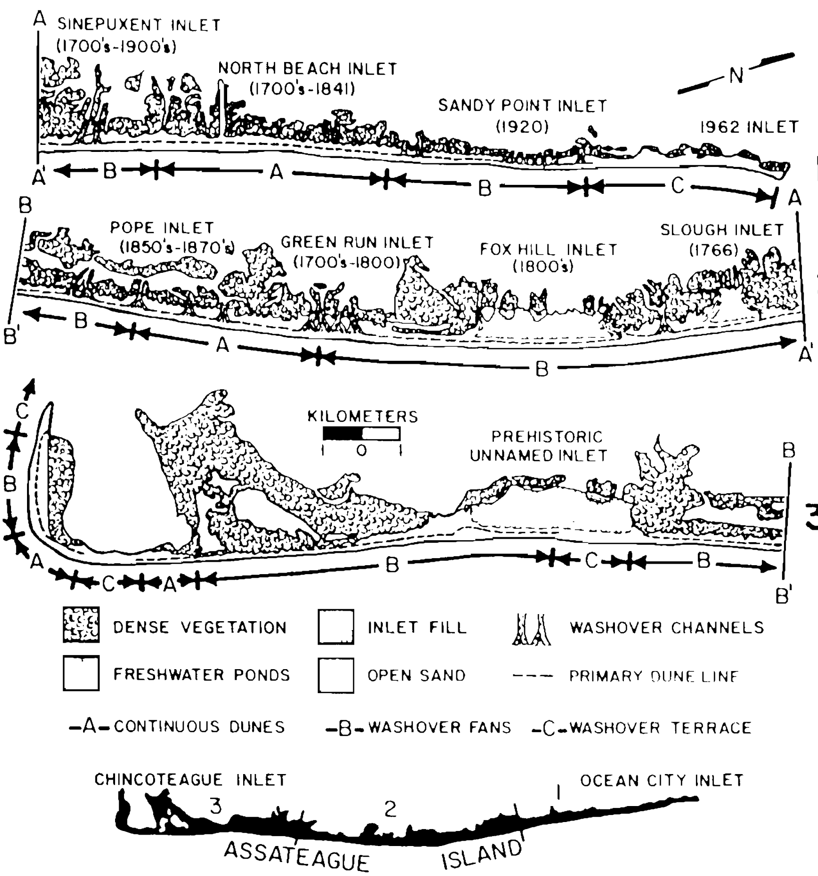


Figure 2. Generalized geomorphic map of Assateague Island.

spreads over extensive washover terraces and interconnected fans (Figure 3a). Little protection from prevailing winds is afforded by dunes in these low-relief sections of the island. Therefore, these areas would be expected to be influenced more by aeolian activity than high-relief areas would be.

The remainder of the Assateague Island (about 80%) exhibits higher relief and contains a rather continuous primary dune line, much of which has been artificially stabilized (Figure 3b). The primary dune line along the high-relief portion of the island is punctuated by numerous small washover fans (*i.e.*, Fans 6,7,8). Because of the sheltering effects afforded these fans by neighboring dunes in the high-relief areas, aeolian activity would be expected to be less important than for fans in low-relief areas.

During the past 45 years, shoreline change varied considerably along Assateague Island (Figure 4). Although most of the island experienced only slight erosion, significant erosion and/or accretion occurred along the northern and southern ends. Erosion rates along the north end of Assateague have been greatly accelerated by the construction of jetties at Ocean City to stabilize the inlet following its formation during a 1933 hurricane. Ocean City Inlet jetties effectively trap the dominantly southward-drifting longshore sand, starving the northern Assateague beaches (DEAN and PERLIN, 1977). High erosion rates estimated at nearly 10 m per year have been documented along the northern few kilometers of Assateague (DOLAN *et al.*, 1977). Northern Assateague erosion rates were lowered slightly following rehabilitation of the south jetty in 1985, but remain excessive compared to the remainder of the island (DEAN, 1986). High erosion rates also occur along the narrow arm connecting the spit at south Assateague where the shoreline makes a right angle bend. Meanwhile, the spit at the south end has been experiencing rapid accretion primarily by progressive welding of bars which become subaerial segments of the island as a series of sub-parallel beach ridges (Figure 5).

Because of their location along north-northeasterly trending shorelines, Fans 6,7,8,18, and 23 are frequently overwashed by large waves approaching from the northeast during extratropical storms (northeasters) each winter. Fan 16 is the only site that does not have a northeasterly-trending shoreline, making it well-protected from the dominant northeasterly winds associated with extratropical storms, but subject to storm surge and, therefore, overwash from tropical storms approaching from the southwest.

SURVEY METHODS AND FAN SEDIMENTS

Net changes on the six washover fan surfaces were monitored between October 1, 1982 and September 18, 1986 during 12 separate surveys (Table 1)using a combination of topographic surveys and inspection of painted sand plugs installed at the sites. Washover fans studied ranged in size from 300 $m^2$to 1400 m^2. The network of red sand plugs were spaced in a rectangular grid on each fan having either 3 or 6 meters between plugs. Plugs ranged in number from 25 to 45, depending on fan size, and generally were spread evenly over the fan surface. These plugs were excavated, measured, and replaced during each survey in preparation for the next visit. Upon excavation, the erosion between surveys was determined by subtracting the length of the remaining red sand from the amount originally installed (25 cm). The amount of sedimentation was equal to the amount of unpainted sand present on top of the red plugs. This technique permits the recognition of the net amount of erosion and accretion at each site (Figure 6).

Washover sediments were distinguished from aeolian sediments in the newly-deposited sand on the basis of grain composition and sedimentary structures. Aeolian strata on the fans are generally composed of structureless quartz sand. Occasional large-scale cross-bedding and wind-ripple drift stratification also occurs in some of the more extensive aeolian deposits as they evolve into dunes. Washover sediment is typically composed of well-laminated, alternating plane-bedded layers of quartz sand and heavy mineral-rich sand (Figure 7a,b) deposited during alternating energy regimes during storms (LEATHERMAN and WILLIAMS, 1983). Observations made during and immediately after several large overwash events in 1982, 1983, 1985, and 1986 showed plane-bedded quartz sand predominating on newly-overwashed fan surfaces. Fresh washover deposits are predominantly plane-bedded due to their

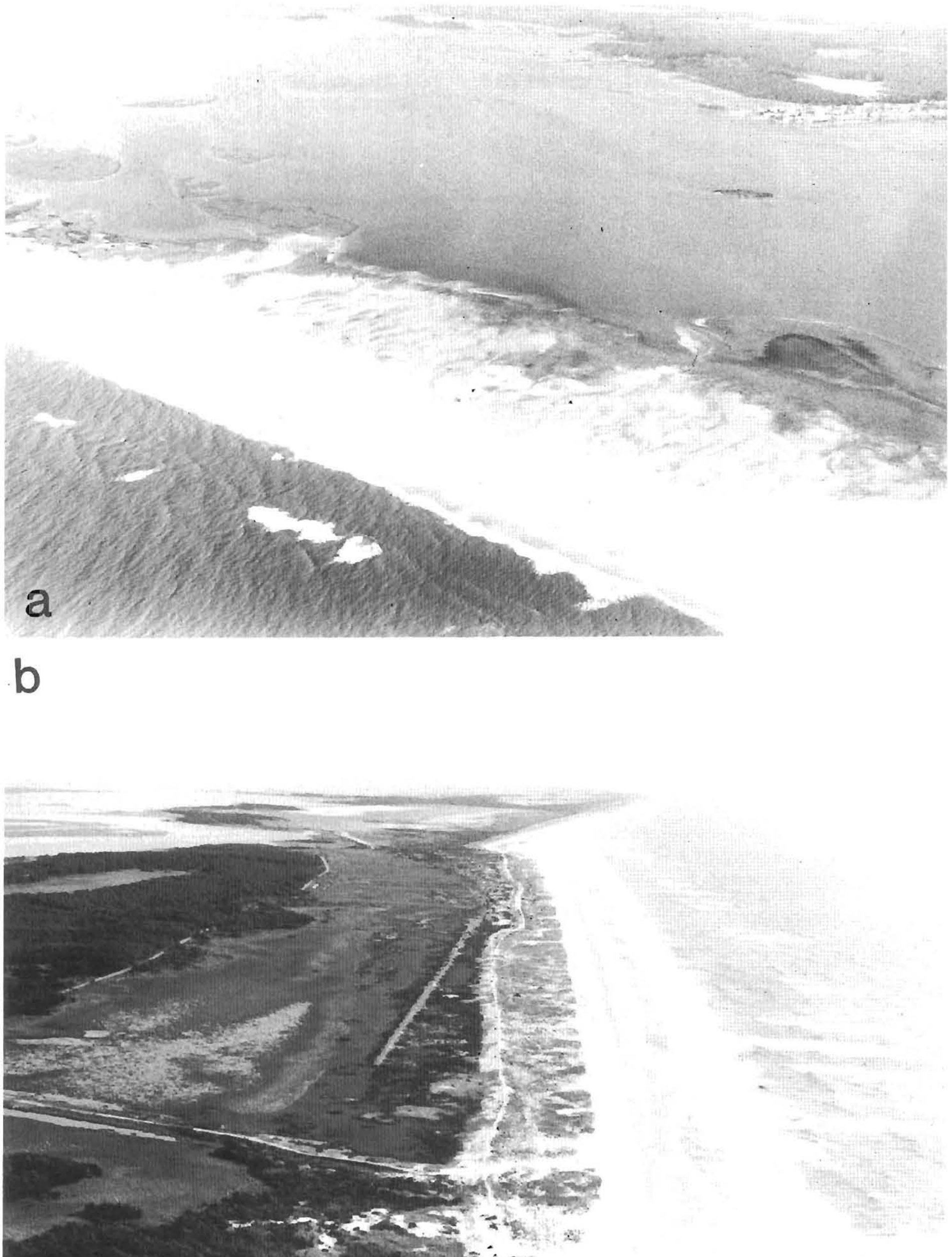


Figure 3. (a) Oblique aerial photograph of the low-relief washover terrace present along northern Assateague in the vicinity of Fan 23. (b) Oblique aerial photograph of part of the central high-relief portion of Assateague containing small, isolated washover fans.

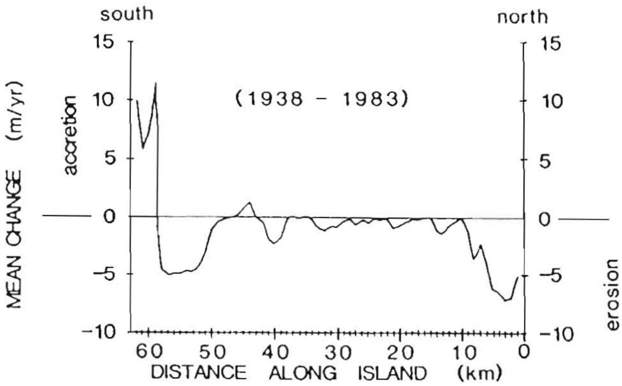


Figure 4. Shoreline change along Assateague Island between 1938 and 1984. Modified from Dolan *et al.* (1977) and unpublished data provided by R. Dolan.

Figure 5. Oblique aerial photograph of a portion of the spit and low-profile reach along southern Assateague Island. Fan 16 is marked by the arrow. Note also the prominent ridge-runnel system along the shoreline where longshore bars are welding to the beach, and the parallel beach ridges landward marking the position of earlier shorelines as the spit progrades toward the southeast.

Table 1. *Field surveys and storm summary for Assateague washover fans.*

Survey Number	Survey Period Dates	Storm Summary
0	10/1/82	initial benchmark survey
1	10/1/82–11/2/82	1 large ET
2	11/1/82–3/12/83	6 moderate ET's
3	3/12/83–8/21/83	2 moderate ET's
4	8/21/83–10/5/83	1 moderate TS
5	10/5/83–6/7/84	4 moderate ET's
6	6/7/84–5/29/85	3 moderate ET's
7	5/29/85–11/28/85	1 hurricane, 1 moderate TS
8	11/28/85–1/17/86	no significant storms
9	1/17/86–3/14/86	no significant storms
10	3/14/86–5/15/86	1 moderate ET
11	5/15/86–7/18/86	no significant storms
12	7/18/86–9/18/86	no significant storms

ET = extratropical storm
TS = tropical storm

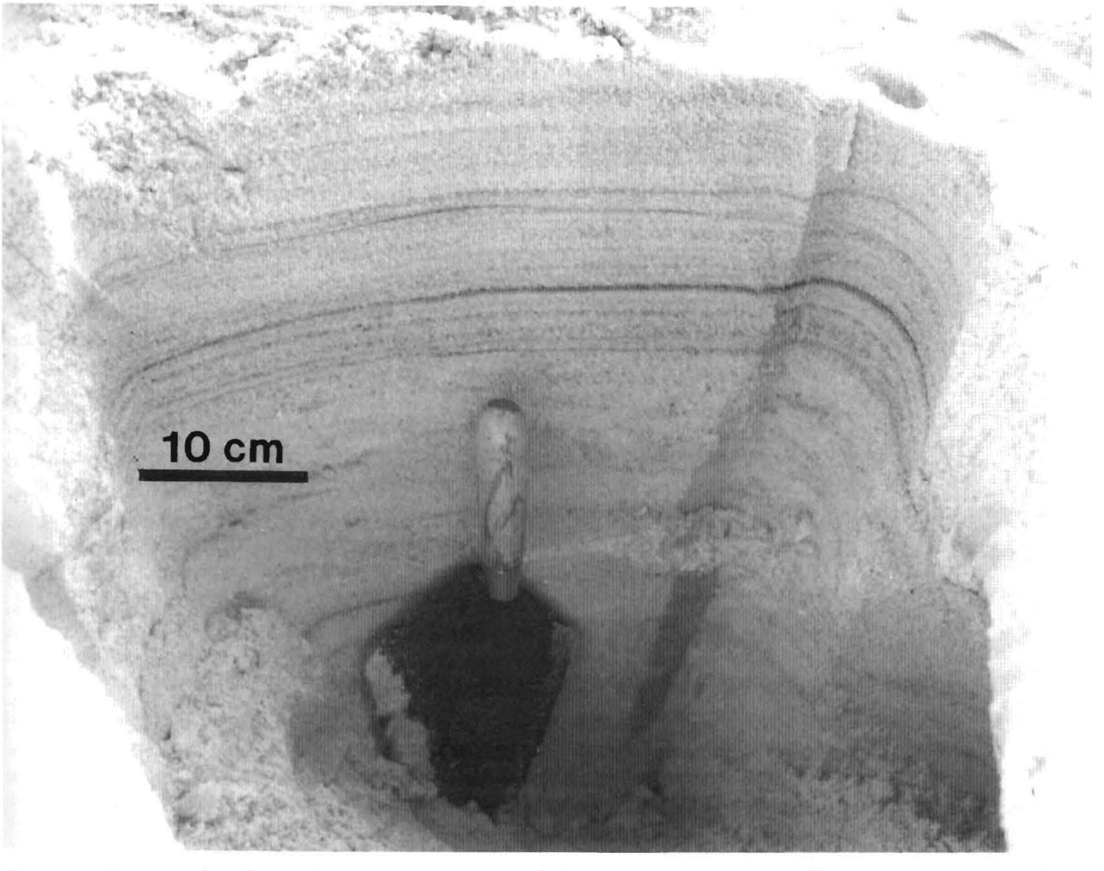
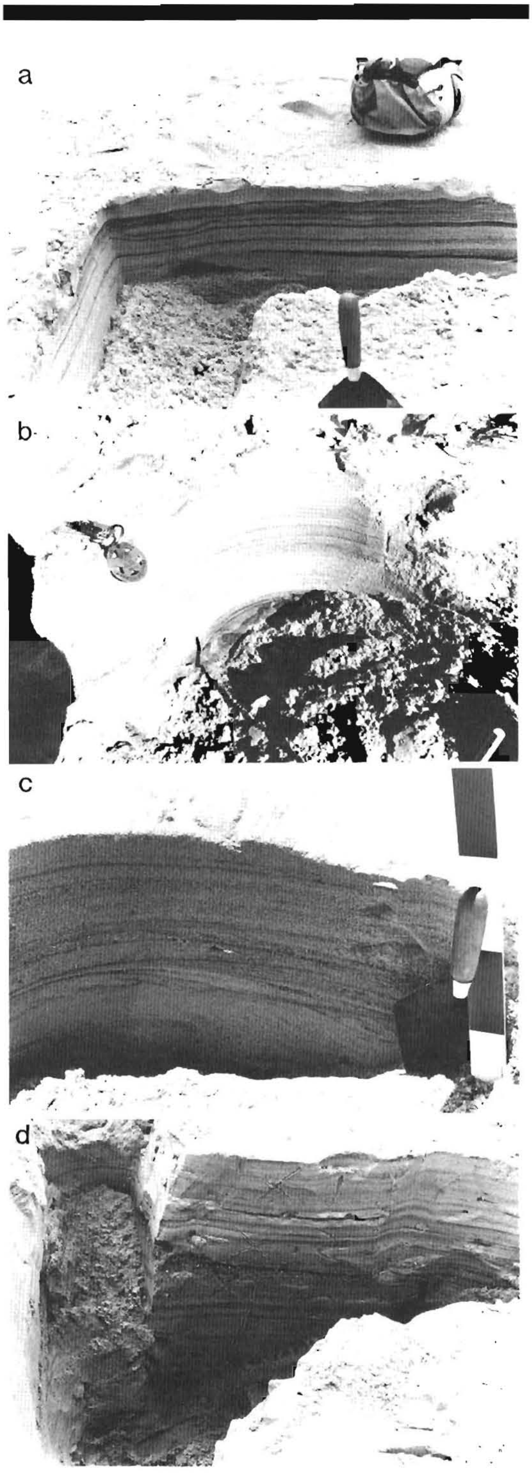


Figure 6. Photograph from Fan 18 showing the method of sand plugs (plug is to right of trowell) used to document net sediment budgets on the washover fans. Erosion of about 4 cm of the plug had occurred prior to the deposition of the parallel-laminated washover sand above the plug between survey periods. Two overwash events occurred since the installation of the red plug.



origin in upper flow regime swash processes (SCHWARTZ, 1982; LEATHERMAN and WILLIAMS, 1983). Rhombohedral marks are also abundant on fan surfaces (Morton, 1978), but few other bedforms are common. Minor small-scale cross-bedding often occurs along distal fan margins where channels drain water off the fans onto barrier flat environments (Figure 7c). Between overwash events, aeolian deflation produces a lag of coarse quartz sand and shells on fan surfaces, small dunes may appear, and the fans often become partly vegetated. Some erosion may accompany overwash in the early phases of a storm (LEATHERMAN, 1976a), therefore, erosional surfaces are common at the base of individual washover sedimention units.

The number of overwash events since installation of the plugs in the preceding survey can usually be determined by careful inspection of the sediments. This number represents the minimum number of events, because there always remains the possibility that erosion between surveys, by aeolian or overwash processes, could have removed all of the sediment deposited by one or more minor overwash events. The degree of uncertainty of overwash event numbers between surveys was minimized by analysis of tidal records for the calculation of storm surge and by hindcasting storm waves using the methods developed by Bretschneider described in the *Shore Protection Manual* (CERC, 1973). Individual storm sedimentation units generally have a coarse quartz sand and shell hash at their tops which represents a deflation lag formed between successive overwash events. Many times there are also buried organic mats preserved at the tops of these deposits from rapid burial of grasses and other vegetal matter growing on the fans between storm events (Figure 7d). Individual units can also be discriminated with textural analyses.

Figure 7 (Adjacent column). Sedimentology of washover sediments and units. (a) Plane-bedded alternating layers of heavy mineral (dark) and quartz sand (light) in Fan 23 (b) Plane bedded sand from two overwash events in 1983 on Fan 8. Boundary between the units is erosional and is marked by the color change less than half-way up the cut face. (c) Sediment from two overwash events in the distal reaches of Fan 18. Note the small-scale cross-beds at the top of the lower unit. (d) Trench in Fan 7 showing plane bedded sediment from three overwash events in 1982 and 1983. The contacts of the units are marked by a coarse gravel and shell-hash lag at the top of each unit formed by deflation. Buried plant fragments also occur along the contacts between the two lower units.

Samples collected immediately after several overwash events on Fans 6 and 18 in 1982 and 1983 showed significant fining trends distally from the fan throat to the backfan region. This fining trend reflects the loss of competence coincident with rapidly expanding flow across mid-fan and backfan areas. Three sets of fan throat sediments ranged between 0.6 ϕ - 0.8 ϕ, mid-fan sediments ranged between 1.0 ϕ - 1.2 ϕ, and distal fan sediments ranged between 1.3 ϕ - 1.5 ϕ, compared to beachface samples that ranged between 1.0 ϕ - 1.2 ϕ.

CLIMATE SUMMARY

Sediment dynamics on washover fans appear to depend heavily upon the character of the local climate. The frequency of significant fan wetting, the direction and strength of prevailing winds, and the frequency and magnitude of overwash events appear to be the major factors that regulate changes in sediment budgets on most washover fan surfaces. When fans are wet, they resist deflation by all except the most powerful winds during major storms. Fan wetting can be accomplished either by overwash or a significant rainfall, typically rainfall exceeding 1 cm over a 24 hour period. Long periods between fan wetting events promote conditions favorable for significant aeolian reworking of washover fan sediments. Deflation tends to be particularly rapid during periods of strong offshore winter winds (FISHER and STAUBLE, 1977). LEATHERMAN (1976a) stated that northeasterly winds blow the majority of the washover sand back to the oceanic beaches along north Assateague.

The combination of storm surge and large waves associated with coastal storms produced overwash at the Assateague Island washover sites. LEATHERMAN (1976a) showed that storm surge is the most significant parameter controlling efficiency of overwash on Assateague. Most of our sites received overwash when storm surge approached 70 cm. However, a few overwash events from storms having less surge were observed when they coincided with exceptionally high waves or high astronomical tides. Typically, storms with deep water wave heights of between 2.5 - 3 m and storm surge between 0.5 - 1 m produced overwash at all of our sites.

Coastal storms affecting the mid-Atlantic region are of two main types. Extratropical storms (northeasters) are the most common and occur predominantly between October and April. Analysis of storm tracks between 1888 and 1980 by HAYDEN and SMITH (1982) indicated that an average of four extratropical storms of the size capable of producing significant overwash can be expected annually at Assateague Island. The number of annual extratropical storms decreases southward along the Atlantic coast. Tropical storms (such as hurricanes) occur less frequently at Assateague Island, usually between June and November, and many years typically pass without significant tropical storm activity. Tropical storms affect Atlantic coastal areas south of Cape Hatteras with much greater frequency.

Extratropical storms are generally less intense than hurricanes, hence, they usually have lower sustained wind velocities. Typical extratropical storms have sustained wind velocities around 55–60 km/hr, while hurricane winds can far exceed 120 km/hr. Exceptional extratropical storms, like the April 12–13, 1988 storm along the Outer Banks of North Carolina, can have winds exceeding 120 km/hr. Storm surge from hurricanes can exceed 5 meters, while extratropical storm surge is rarely more than 1–2 meters. Hurricanes usually affect only a small portion of the coast except for very large storms or those that trend nearly parallel to the shoreline. Extratropical storms often produce overwash along hundreds of kilometers of the mid-Atlantic coast for several days as they move slowly into the Atlantic Ocean. The combination of the greater frequency of extratropical storms (typically 4 large ones per year) and their great aerial extent implies that mid-Atlantic washover fans may be dominantly adjusted to extratropical storms.

During the course of our surveys, we were especially fortunate to have experienced a wide range of climatic conditions at Assateague Island. Between October, 1982 and September, 1986, Assateague experienced some of the stormiest and some of the calmest years in its historical record, based on observations recorded at the nearby Wallops Island, Virginia climatologic station. Table 2 summarizes the gross storm history variability during this period. Survey years, selected to coincide with the normal onset of the winter storm season, extended from October through September in our study. Year 1 (1982–1983) was exceedingly stormy,

Table 2. *Mean climatic data 1982-1986.*

Variable	Mean Value
precipitation frequency	11.4%
mean daily precipitation	0.25 cm
avg. time between precip.	10.6 days
frequency of high winds	29.0%
frequency of storm surge	3.2%
frequency of overwash	1.7%

with a very large extratropical storm in October, 1982, followed by eight smaller extratropical storms that produced moderate overwash later that year. One tropical storm affected the area in September 1983 (tropical storm Dean). In contrast, year 4 (1985–1986) was exceptionally calm and devoid of overwash-producing storms, having only one event that resulted in modest overwash. During years 2 and 3 (1983–1984 and 1984–1985), the island experienced 3 or 4 moderate extratropical storms, typical of average conditions predicted by HAYDEN and SMITH (1982). Assateague was also affected by the offshore passage of a hurricane in September, 1985 (Hurricane Gloria), which provided the opportunity to view the effects of a major tropical storm.

Figure 8 shows that annual variation in Assateague climate is normal and may be somewhat cyclic. Dolan *et al.* (1988) showed that there has been significant periodicity in the frequency of mid-Atlantic coastal storms that are strong enough to generate overwash between 1942 and 1984. Figure 8 indicates that the 1960's and late 1970's–early 1980's have been stormy compared to the intervening mid-1970's. Storms between 1973 and 1977 were characterized by exceptionally short durations, hence, the resulting overwash would have been short-lived compared to the stormier periods of the 1960's and 1980's. DOLAN *et. al.* (1988) noted that data collected during the mid-1970's should be treated with caution because of this anomaly in storm frequency and duration. Assessments of long-term geomorphic change on Assateague Island must take these kinds of variations into consideration. Projections of long-term change may be heavily biased from sediment budget data collected during exceptionally stormy or calm periods. We can make reasonable assessments about long-term changes at Assateague washover sites because our study period (1982–1986) transcended a wide range of climatic conditions expected to be experienced on the island.

RESULTS AND DISCUSSION

Fan Sediment Budget Variation Between Surveys

Between October, 1982 and September, 1986, washover fan surfaces on Assateague Island accreted between 40 cm and 145 cm, chiefly by overwash sedimentation (Figure 9). These values do not account for sediment deposited and eroded prior to the subsequent survey, but represent net change for the period. The least amount of net accretion occurred on Fan 16, at the south end of the island, because this fan receives overwash sedimentation generally only during tropical storms. Most of the observed accretion on Fan 16 was produced by Tropical Storm Dean and Hurricane Gloria. Greater accretion occurred on the remaining fans because their throat orientations are exposed to the northeast winds accompanying the more frequent extratropical storms. Figure 9 also shows net erosion data for each site during the four year period. Combining the erosion and accretion data indicates that the three central fans experienced between 60 cm and 80 cm of total net accretion while the northern and southern fans experienced between 10 cm and 20 cm accretion between 1982 and 1986. No sites experienced total net erosion during our survey period, unlike the erosion reported by LEATHERMAN (1976a,b) from a study in the mid-1970's.

Sediment budgets for the washover fans showed remarkable differences between survey periods, depending upon the climatic conditions experienced (Figure 10). Comparing changes during stormy periods (Surveys 1,2,3, and 7) and calm periods (Surveys 8–12) illustrates the magnitude of these differences. Survey 1 shows exceptionally great accretion due to the single large extratropical storm of October 25–26, 1982. The recurrence interval of that storm is estimated at between 10–12 years, based on hindcasts of deepwater wave heights between 1942 and 1986. The net accretion of fan surfaces during the storm (with the exception of Fan 16) was greater than the sum of four subsequent overwash events during Survey Period 2 (Figure 10). Surveys 5 and 6 show that significant

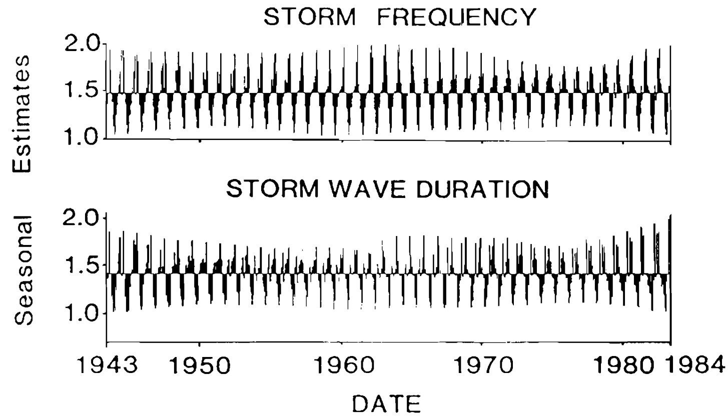


Figure 8. Secular variation in storm history along the mid-Atlantic (from Dolan *et al.*, 1988). Seasonal estimates of storm wave duration and storm wave frequency are shown as a time series. Storm frequency and storm wave duration increase with the amplitude of the bars. Note the high frequency annual fluctuations as well as a pronounced longer period oscillation showing anomalously low storm wave duration and frequency during the mid-1970's. These seasonal trend data are decomposed components from the raw data (see Dolan *et al.*, 1988).

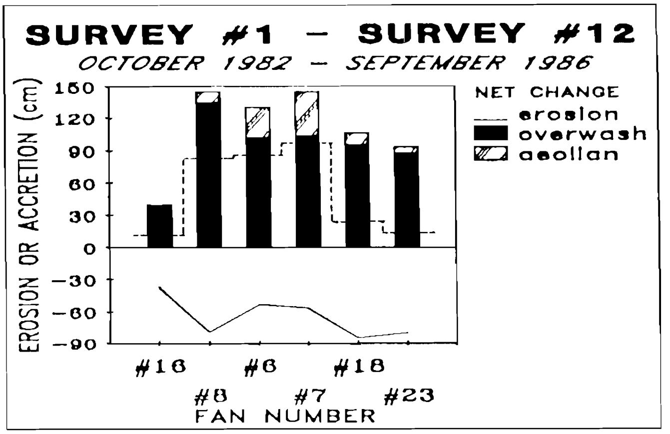


Figure 9. Summary of changes in surface elevation for each fan for during 4-year survey period. The dashed line represents overall net change (accretion minus erosion). The solid line represents erosion during the period, while the bar graph shows the accretion.

accretion occurred during years of normal storm frequency (1983–1984 and 1984–1985) when Assateague Island experienced three or four significant overwash events. Although no storms occurred that were as large as the October 1982 storm, fans accreted because of overwash from moderate-sized storms. Aeolian activity was minor during the first three years of the study compared to overwash activity. Survey 7 showed extensive accretion due to a single large storm, Hurricane Gloria.

During years of frequent overwash, accretion predominated over erosion. Observations of the sedimentology of the accreted deposits indicated that most of this accretion can be attributed to overwash. These first three years also experienced frequent wetting of the fans by rainfall. Periods of lower deflation rates and

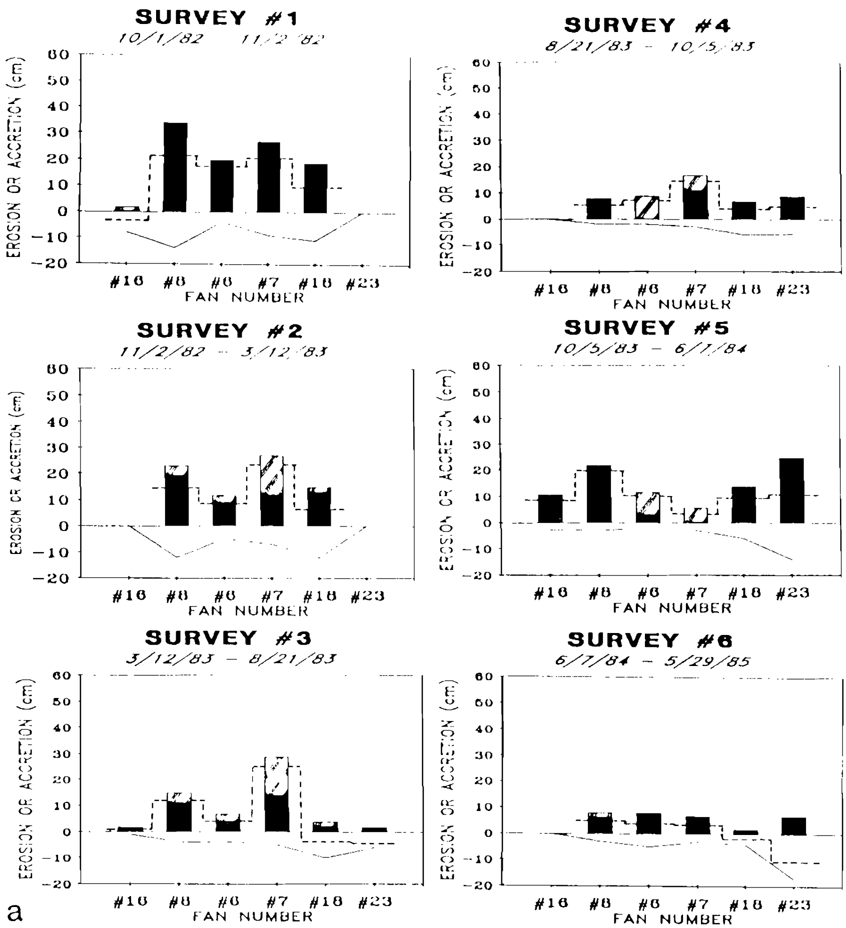


Figure 10. Changes in fan surface elevation during each of the 12 survey periods. Dashed line shows overall net change. See Figure 9 for explanation of the symbols.

higher accretion by overwash generally coincided with periods of more frequent significant rainfall, while the opposite tended to occur during periods of less frequent rainfall (Figures 10, 11).

Precipitation data in Figure 11 illustrate the asymmetry of annual rainfall common at Assateague. Most of the precipitation was associated with the winter extratropical storm season. Exceptions were the occasional large rains associated with tropical storms such as during the early fall of 1985. The combined effects of the three processes shown in Figure 11 influence the efficiency of aeolian deflation on fan surfaces. Deflation was significant in months 38–48 compared to months 1–37. Although the frequency of high winds during months 38–48 was slightly lower than the four-year mean and precipitation was only slightly below that mean, the average time between precipitation events was high. Therefore, winds were effective in deflating the fans during this period because dry fans offered little resistance to aeolian erosion.

Survey periods 8–12 (Figure 10) show changes that occurred on Assateague Island washover fans during periods of relative calm, *i.e.*, when there were no large extratropical winter storms. These surveys show minor amounts of accretion due to aeolian processes, but erosion dominated at the sites. This pattern of erosion by aeolian processes was dominant

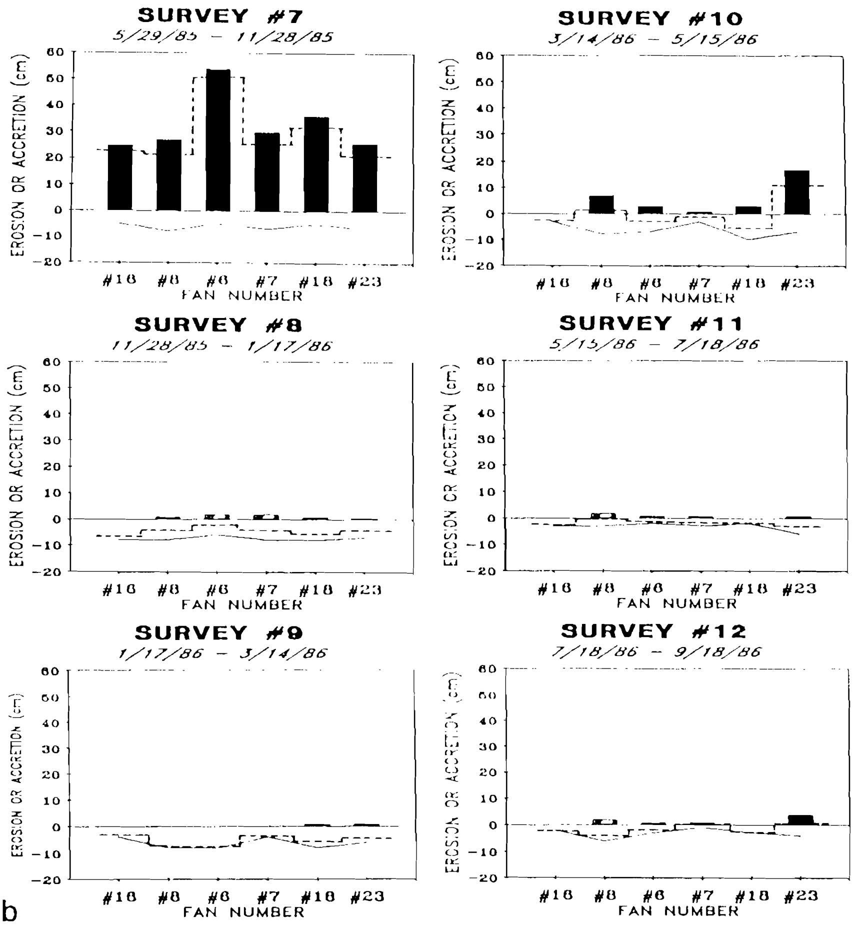


Figure 10. Continued. Changes in fan surface elevation during each of the 12 survey periods. Dashed line shows overall net change. See Figure 9 for explanation of the symbols.

throughout the 1985–1986 year because of the lack of overwash and relatively low frequency of fan wetting by rainfall. During that year, washover fans remained relatively dry and were therefore susceptible to greater deflation than in the previous three years.

The most important variables affecting fan sediment budgets appeared to be those relating to the magnitude and frequency of precipitation and overwash (Table 3). Maximum accretion (Survey periods 1, 2, 3, 5, 7) coincided with periods of frequent overwash events, periods of frequent rainfall, or a combination of both. Overwash was responsible for accretion while frequent precipitation greatly retarded deflationary processes during these periods. Maximum erosion occurred on fans during surveys when either overwash was infrequent, or, when rainfall was infrequent and overwash was relatively minor (surveys 4, 8, 9, 10, 11, 12). Although mean wind velocity and frequency of windy days between surveys was important for deflation, the variability in wind seemed to be less important than the magnitude and frequency of fan wetting events.

Multivariate Analysis Table 4 and Figure 12 present a summary of the data from our 12 surveys that were shown to be significant at the 0.15 level in stepwise multiple regression analyses using net change of the fan surfaces as the dependent variable. The outlier with excessive

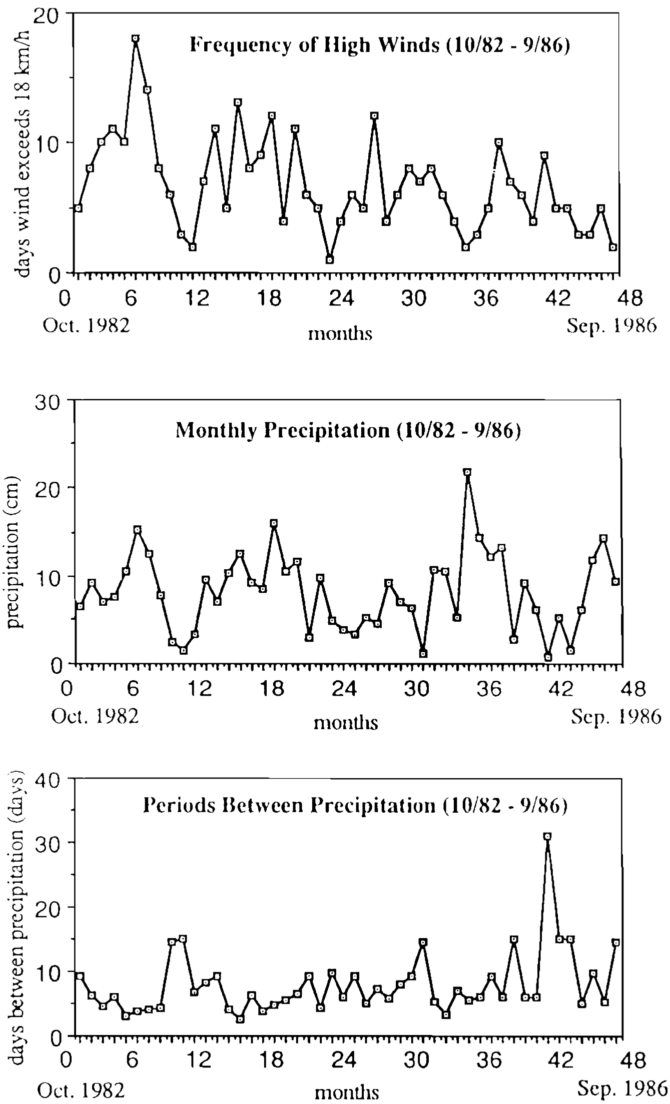


Figure 11. Summary of precipitation and wind data during the survey period. Winds were considered erosional if they exceeded 18 km/hr because studies by Bagnold (1941) indicate that would be the threshold velocity for motion of the size sand found on the fans.

accretion in each plot in Figure 12 is from Survey 7 which contains Hurricane Gloria. Accumulation was dominant from 10/82 through 11/85 (Surveys 1–7), while erosion dominated fan surfaces from 11/85 to 9/86. Periods of high accumulation occurred when fans remained wet, correlating with periods of frequent overwash and precipitation. These conditions resulted in fans remaining wet and more resistant to aeolian deflation during these periods. The lowest accumulation during Surveys 1–7 was Survey 6 which had the lowest overwash and precipitation frequency. Erosion dominated in later surveys where precipitation and overwash frequency was lower. The lowest erosion during Surveys 8–12 occurred in Survey 12, which had the lowest average time between precipitation events. These observations suggest

Table 3. *Variables used in statistical analyses.*

Variable	Units and Special Notes
net erosion or accretion	fan averaged (in cm)
shoreline orientation	azimuth along shoreline (in degrees)
distance from Ocean City Inlet	(in km)
fan elevation	in October 1982 (in cm above mean sea level)
topographic index	surrounding terrain (1 = lowest, 10 = highest)
precipitation frequency	percent of days with ppt. exceeding 0.25 cm
overwash frequency	percent of days with overwash from hindcast
mean daily precipitation	(in cm)
average time between precip. events	(in days)
frequency of storm surge	percent of days with surge exceeding 0.5 m
frequency of fan wetting	percent of days fans wet by ppt or overwash
average time between overwash	(in days)
mean wind direction	sin and cos of azimuth of daily wind
survey number	1–12 as defined in Table 1

Table 4. *Net change on fans compared to overwash and precipitation.*

Survey Number	Net Change (cm)	Overwash Frequency (%)	Time Between Precip. Events (days)	Precipitation Frequency (%)	Time Between Overwash Events (days)
1	+4.7	3.0	10.7	9.1	16.5
2	+3.8	3.9	5.1	17.1	23.5
3	+2.7	3.0	7.3	19.8	53.7
4	+2.0	2.2	10.6	11.1	39.0
5	+4.1	1.2	6.7	13.7	48.2
6	+0.8	0.8	9.4	9.0	121.7
7	+9.6	1.1	6.9	12.6	61.0
8	−2.0	0	13.8	8.0	48.0
9	−2.2	0	9.4	12.5	55.0
10	−0.7	3.3	24.6	4.9	31.0
11	−1.7	0	13.7	9.5	63.0
12	−0.3	1.6	8.8	9.8	58.0

that the aeolian erosion of fan surfaces is greatly affected by how wet the fan remains, due to the combination of overwash flooding and precipitation, because wet fans are more resistant to deflation.

Principal Components Analyses (PCA) was used to investigate relationships between the variables in Table 3 and net changes of fan surfaces. (PCA has been used successfully in partitioning variance in multivariate geomorphic systems (KUTZBACH, 1967; HAYDEN *et al.*, 1975; KOCHEL and PEAKE, 1984). The independent variables created by PCA are transformed into a new coordinate system where the axes are linear combinations of the original variables and are mutually orthogonal. The first eigenvector (PC1) explains the largest amount of variance in the system, while subsequent eigenvectors explain successively smaller amounts of the total remaining variance. Loadings on the eigenvectors are used to determine the relative importance of each original variable in explaining variance for the particular eigenvector. Only those eigenvectors determined to be significant at the 0.05 level (OVERLAND and PREISENDORFER, 1982) were used in our analysis.

Table 5 summarizes the principal components statistics using island-averaged data from all fans for the net change variable. These data were averaged by using a weighted percentage of the geomorphic area of Assateague Island that the fan type represents. Principal component 1 (PC1) indicates that during the early surveys (Surveys 1–7) there was a greater frequency of precipitation events, fan wetting was more frequent, and high winds were more frequent than in later surveys. Principal component 4 supports the suggestions from PC1 and also indicates that later surveys (Surveys 8–

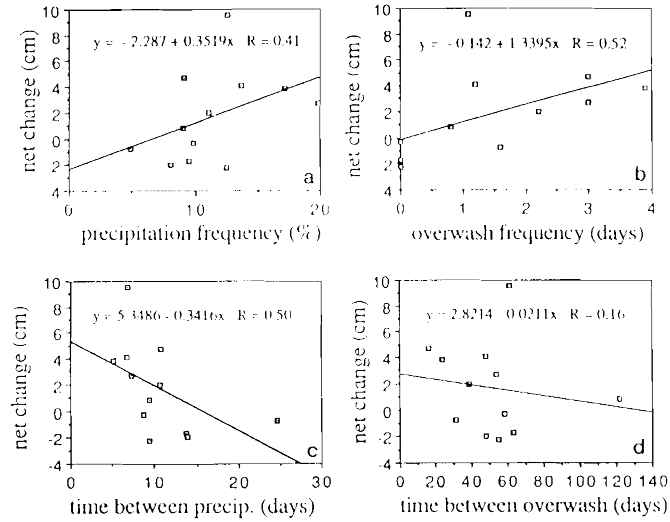


Figure 12. Correlations between significant variables used in stepwise multiple regression analysis to predict net change between survey periods. See Table 4. Net change (erosion or accretion) as a function of: (a) precipitation frequency; (b) overwash frequency; (c) time between precipitation events; and (d) time between overwash events. Best-fit regression lines are shown along with their equations.

Table 5. *Statistical summary of island averages for 12 surveys using principal components analysis.*

Eigenvector (PC)	Proportion of Variance Explained	Cumulative Variance Explained	High Loadings and Sign for Eigenvectors
1	0.35	0.35	(−) survey number (+) precipitation frequency (+) frequency of high winds (+) frequency of fan wetting
2	0.21	0.56	(+) mean daily precipitation (−) days between precipitation (−) frequency of storm surge (+) days between overwash
3	0.18	0.74	(+) overwash frequency (−) frequency of high winds (+) easterly winds (+) net accumulation
4	0.09	0.83	(+) survey number (+) days between precipitation (+) easterly winds

12) were characterized by longer periods between successive precipitation events. Principal component 3 indicates that the greatest net accumulation occurred during periods of frequent overwash, lower frequency of high winds, and dominance of easterly winds.

Single, large magnitude overwash events like the October 1982 storm and Hurricane Gloria, (September 1985) resulted in a major sediment accretion. Accretion by these individual events typically exceeded 50 cm on most fans and provided a significant buffer against deflation of the underlying fan sediment. Deposition of a thick, wet sand layer appears to retard the deflationary action of the wind longer than that which occurs following deposition of only a few cm from a moderate overwash event. Based on the deflation rates observed during our study, several years of continuous deflation, uninterrupted by overwash sedimentation, would be required to remove the deposition from either of these big storms.

Spatial Variations in Fan Sediment Budgets Along the Island

Sediment budgets for the various washover fans along Assateague Island followed similar trends. However, there were significant differences in dominance of overwash and aeolian sedimentation or erosion between washover sites during any given survey period (Figure 13). Fans 6, 7, 8, and 18 along the central, high-relief portion of Assateague Island generally received the greatest net accretion by overwash sedimentation and suffered the least loss due to deflation. These fans are well-sheltered from erosional winds compared to the northern and southern fans because they are surrounded by well-established dunes. Fans 6 and 7 also showed significant aeolian accretion during the later surveys (Figure 13). If unaffected by overwash for long periods (several months), fans can accrete and erode by aeolian processes. Fans 6 and 7 also became increasingly more densely vegetated during these later surveys (year 4), which may have contributed to their ability to trap aeolian sediments. FISHER and STAUBLE (1977) noted significant deflation in fan throats due to a venturi effect created by constriction of the wind between adjacent dunes. Most of our points, however, were landward from the fan throats and did not show significant erosion on fans surrounded by dunes.

Fan 23, along the northern end of the island, also received significant overwash sedimentation but suffered the greatest amount of reworking by aeolian processes between overwash events. Fan 23 is located on the low-relief part of Assateague Island, where winds blow across the washover terrace unimpeded by substantial dunes. The region along Fan 23 experienced considerable beach erosion during the four-year period. Landward retreat of the shoreline caused Fan 23 to become closer to the beach and increasingly subject to wave attack during overwash in later surveys. Some of the erosion recorded at Fan 23 was attributed to erosion during overwash. The record of net gains by overwash vs. losses by aeolian activity was intermediate for Fan 18. Fan 18 occurs along the northern part of the island in a transition between high-relief and low-relief characteristics, hence, it is not as well sheltered as Fans 6, 7, and 8, but much better protected from deflation than Fan 23.

Fan 16 (at the south end) occurs in an unsheltered low-relief section of Assateague Island, but it recorded only nominal losses due to deflation during the four year period, in spite of experiencing overwash fewer times than any of the other fans. The reason for the anomalous behavior and resistance of Fan 16 to deflation probably is due to the proximity of the local water table to the fan surface. For the other fans, the mean water table during survey visits was always in excess of 1 m below the surface. However, the water table at Fan 16 remained within 15 cm to 30 cm of the surface. The shallow water table apparently keeps the sand wet nearly year round and, may be responsible for the observed lack of aeolian reworking. Finally, vegetation was enhanced (perhaps by the shallow water table) on this fan which may have helped retard aeolian deflation and promote accretion during overwash.

Although differences in surface changes between fans discussed above appear common during most survey periods, they are especially pronounced during periods of frequent storm overwash. The amount of deflation between overwash events appears to be significantly affected by the degree of local sheltering afforded by dunes proximal to the washover fans. Fans in low-relief areas, such as northern Assateague Island, tend to deflate much more readily than those in protected, high-relief regions. During exceedingly calm periods, such as 1985–1986, deflation was the rule for all washover fans, but was significantly greater in low-relief areas.

Principal components analysis of net change on fan surfaces along the island indicated that there were significant differences in the behavior of individual fan sites, based primarily upon their elevation and topographic index (Table 6). Principal component 1, which accounts for 69% of the variation, indicates that accumulation was greatest for fans with higher topographic indices (Fans 6, 7, and 8) and for fans with higher elevations (also Fans 6, 7, and 8). There was consistently more accretion on the fans

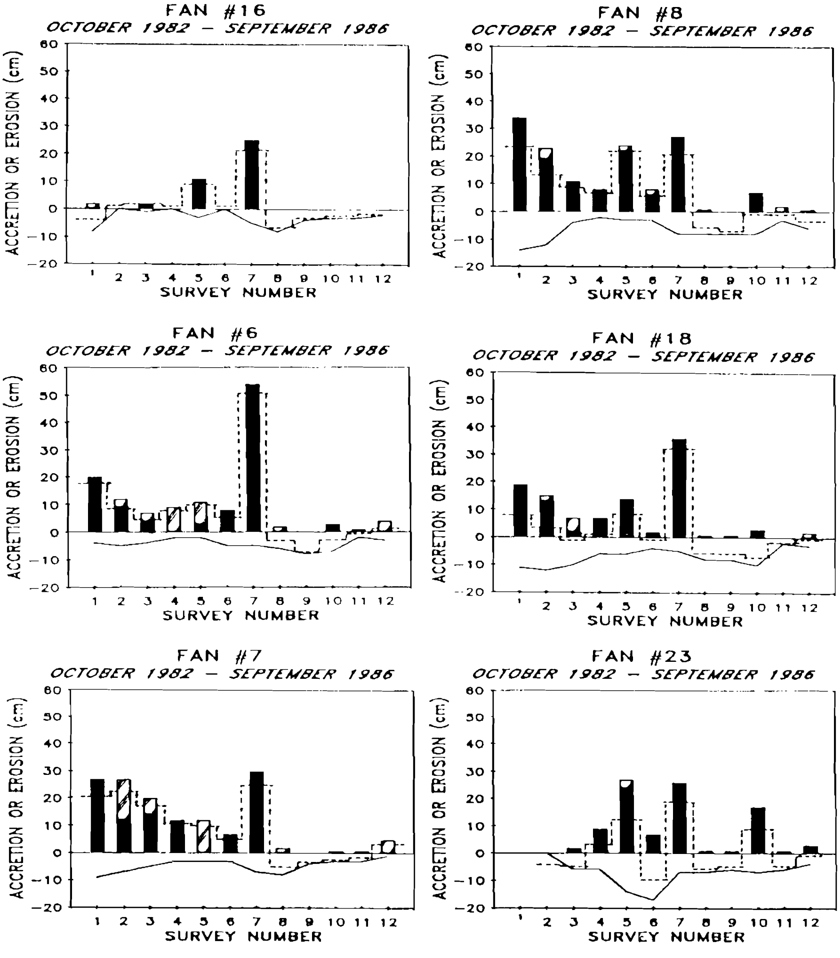


Figure 13. Changes in surface elevation for each fan during individual survey periods. Dashed line shows overall net change. See Figure 9 for explanation.

Table 6. *Statistical summary of net change over entire period for 6 fans using principal components analysis.*

Eigenvector (PC)	Proportion of Variance Explained	Cumulative Variance Explained	High Loadings and Sign for Eigenvectors
1	0.69	0.69	(+) central fans, fans 6,7,8 (+) net accumulation (+) fan elevation (+) topographic index
2	0.28	0.97	(+) shoreline orientation (+) distance from Ocean City

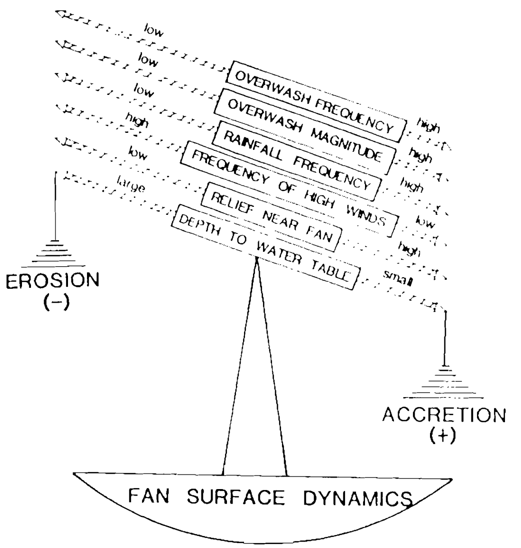


Figure 14. Schematic of factors affecting sediment budgets on washover fans. The scale tips toward accretion or erosion depending on symmetry of factors toward their end values. Accretion is shown here to represent the 1982–1986 data.

along the central high-relief part of the island than along the northern regions of Assateague, which were less sheltered from winds by surrounding topography. Projections of long-term changes should take into account data from both geomorphic zones.

There are a large number of process variables likely to exert influence on sediment budgets of washover fans. Figure 14 summarizes the trends, resulting from multivariate analysis of variables, likely to affect sediment budgets and the data acquired from our twelve surveys. The lower values for relationships in Figure 12 indicate that net change on fan surfaces is a complex function of many process variables. A more complicated formula for predicting net change could be developed with more data that would include adjustments for antecedent conditions between overwash and rainfall events as well as including a factor relating to the magnitude of these events. We felt that our analysis represents a level of sophistication consistent with the modest duration (4-years) of the study and the frequency of our surveys. More sophisticated models will require more frequent surveys and a dataset, probably in excess of ten years.

Long-Term Projections

Table 7 summarizes some rough projections of long-term changes expected on Assateague Island washover areas based on our 4-year dataset. Because we experienced two large magnitude events (October, 1982 and Hurricane Gloria in 1985) having recurrence intervals of approximately 10–12 years, we feel it would be inappropriate to simply make projections based on taking multiples of these 4-year averages to reach the desired number of years being projected. Therefore, Table 7 presents projections for 10-year and 25-year periods by assuming the occurrence of only one 4-year sequence like our survey period every 12 years. The remaining years, 6 years for the 10-year projection and 17 years for the 25-year projection, represent the cumulation of changes expected during average years at Assateague. We selected the 1984–1985 year (Survey 6) as the average year because it experienced four moderate overwash events, which was shown to be the average number of washover-producing storms from the mid-Atlantic region (HAYDEN and SMITH, 1982). Annual precipitation during that year was close to the long-term average at the Wallops Island station.

Instead of taking a grand mean for Assateague Island by combining data from the six washover sites, we feel it is more appropriate to divide the island up into three geomorphic segments (Figure 2) because of their disparate influence on sediment dynamics on the fan surfaces. In this manner, the northern 9% of the island is best represented by data from Fans 23 and 18; the central 80% is represented by Fans 6, 7, and 8; and the southern 11% by activity on Fan 16. Table 7 reports projected changes for washover sites in each of these regions as well as an island average calculated by taking a weighted mean using the areas represented by the three geomorphic segments.

Figure 15 summarizes our predictions of change in elevation to the mean washover area of Assateague Island. Island-averaged changes for washover sites are expected to be accretionary, with approximately 30 cm accretion expected during the next 10 years and about 60 cm of accretion over the next 25 years. Our data indicate that the central, high-relief areas will experience more rapid accretion of about 2m over the next 25 years. However, as Figure 15

Table 7. *Long-term estimates for Assateague washover surfaces.*

Geomorphic Zone (Fans)	Mean Change For Region (cm)	Island-Averaged Change (cm)
4-Year Data Set (1982-1986) Including Large Storms		
South (#16)	+3	
Central (#6,7,8)	+78	+22
North (#18,23)	+18	(+5.5cm/yr)
1-Year, Normal Storm Conditions (Survey 6, 1984-85)		
South (#16)	+1	
Central (#6,7,8)	+5	+1.5
North (#18,23)	−5	
10-Year Period		
South (#16)	+9	
Central (#6,7,8)	+108	+29
North (#18,23)	−12	
25-Year Period (assumes two 4-year totals + seventeen 1-year totals)		
South (#16)	+23	
Central (#6,7,8)	+241	+63
North (#18,23)	−49	

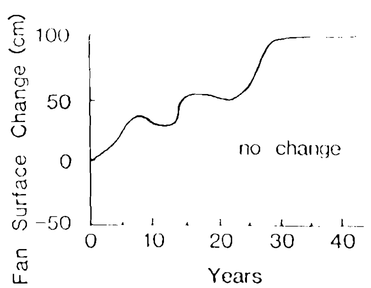


Figure 15. Approximate projections of fan surface change for island-averaged washover fan surfaces. See text for discussion.

indicates, the accretion rate will probably decrease rapidly as washover surfaces accrete to elevations accessible to only the rare, large magnitude overwash events. Because of the low frequency of large storms, deflation processes will probably keep the accretion rate in check, and may even result in net erosion of the sites. This plateau in accretion is analogous to floodplain accretion in fluvial systems described by WOLMAN and LEOPOLD (1957). Other washover fans on Assateague and the Outer Banks of North Carolina not included in our sediment monitoring studies were observed to become inactive once they accreted above the level of overwash storm surge during moderate events. Fan throats typically filled from the combination of longshore drift, aeolian deposition, and overwash sedimentation that only penetrated to the edge of the active beach. In some cases, fan throats sealed up during a single large storm. On the other hand, one large overwash event can easily reactivate a fan by removing the sediment that accumulated in the throat since the last exceptionally large storm.

The fluctuations about a smooth curve like Figure 15 represent expected shifts between periods dominated by deflation and periods dominated by overwash accretion due to secular variations in storminess of the type described by DOLAN *et al.* (1988). Figure 15 should be viewed only as an approximation because the length of the historical record of climate is still very short. The magnitude of accretion is suggested by our island-averaged projections, while the temporal scale of variations are in the range of 20 years, based on the apparent cyclicity storm history over the past 45 years. These projections do not account for significant changes in rates of shoreline erosion or sea level rise which could affect the island slightly over the period.

Very slow accumulation is projected for washover areas along the southern sector of Assateague Island. However, overall island accretion rates along the south end may exceed those observed on washover fans due to the steady accretion of bar material as beach ridges to this region. Net erosion similar to the results of studies by LEATHERMAN (1976a,b) is projected along the northern reach of the island. Unchecked deflation, combined with beach erosion induced by the sand starvation at northern sites from Ocean City jetties, is likely to result in net erosion there.

CONCLUSIONS

Changes in washover fan sediment budgets on Assateague Island between 1982 and 1986 closely corresponded to the combined influence of overwash frequency and precipitation frequency. Maximum accretion occurred during periods characterized by either frequent overwash or nominal overwash during periods of frequent and significant precipitation. Wet fans were relatively resistant to deflation, hence, erosion was minor during these periods. Maximum erosion, mostly by deflation, occurred when overwash was infrequent and when rainfall between overwash events was sparse.

The importance of overwash vs. aeolian processes appears to be highly dependent upon the variability and cyclicity of climatic factors. Compared to the mean of the last 45 years, the mid-1970's were unusually calm. In contrast, the early 1980's were particularly stormy. Fluctuations about the mean seem to occur on approximately 20 year cycles. Over periods of 10's to 100's of years there may exist a balance between the geomorphic work resulting from aeolian and washover processes, but either one may predominate when viewed over shorter time intervals of less than 10 years. LEATHERMAN (1976b), based on a 2-year study in the mid-1970's, concluded that aeolian processes were slightly dominant because he observed net erosion at washover sites located along northern Assateague. Our 4-year study in the mid-1980's showed a significant dominance of overwash sedimentation over aeolian deflation. No sites in our study experienced net deflation. KOCHEL and DOLAN (1986), summarizing two years of data from a stormy period on Assateague Island, showed overwhelming dominance of overwash processes above aeolian deflation. The disparity between these studies indicates that we need to acquire data sets for longer time periods, probably more than 10 years before reliable estimates for long-term models of barrier island sediment budgets can be made. Our data between 1982–1986 may be adequate for long-term projections because we were fortunate that they spanned a range of climatic variations of the type expected during a range of 10-years or more. This data may be more appropriate for use in predictions of long-term island evolution than the data collected during the anomalously calm period of the mid-1970's.

Our data indicate similar trends from all six sites located along Assateague Island. Local variations can be explained by differences in the geomorphological characteristics of Assateague Island and shoreline orientation. The central high-relief region (Fans 6, 7, 8, 18) experienced between 60 cm and 100 cm of accretion during the four years. Most of this accretion was caused by overwash. Fan 23, on the low-relief north end, experienced more erosion and more aeolian activity relative to the other sites, but still remained in a net accretion regime over the duration of the study. The increased importance of aeolian processes at Fan 23 can be explained by the low relief of the site and its exposure to the wind compared to central sites that are sheltered from the wind by adjacent dunes.

The aeolian dominance of washover sediment budgets on Assateague suggested by LEATHERMAN (1976b) was based on data taken in the vicinity of Fan 23. This data should be viewed with caution for several reasons. First, Leatherman's study period during the mid-1970's (1973–1975) coincided with the most anomalously non-stormy period within the past 42 years (DOLAN *et al.*, 1988). Hence, the greater aeolian influence observed by Leatherman would be expected due to the lower frequency of extensive overwash compared to stormier periods. Second, Leatherman's sites were restricted to the northern end of the island, which always has more aeolian activity than the remainder of Assateague because of its low topography that can not shield fans from deflation. The northern end of the island also experiences extremely high erosion rates (Figure 4) due to the entrapment of southerly littoral drift by the Ocean city jetties (DEAN and PERLIN, 1977). Interception of the longshore sand starves the northern Assateague beaches and has greatly accelerated landward migration of that part of the island. Therefore, sediment budgets on northern Assateague do not appear to be representative of the majority (some 80%) of the island. Leatherman's data may only apply to low-profile islands; high-relief islands, typical of the majority of the mid-Atlantic barrier system (even though most result from anthropogenic activity) may be better represented by our data from the central region of Assateague. Our data indicate that overwash processes dominate over aeolian activity in contributing to the net accretion of sediment on washover fan surfaces on Assateague Island.

Large storms like the October 1982 northeaster or the September 1985 hurricane (even though it passed by during the low astronomical tide) produced accretion on washover fans that was greater than the cumulative sum of some 15 smaller overwash storms during the four years. Several years of continuous deflation of the kind experienced in our study would be required to remove large storm deposits of this type. It is likely that deflation will outpace overwash sedimentation only during abnormally calm years such as those in the mid-1970's and the fourth year of our study (1985–1986). Over the long-term, based on an average of about four overwash producing storms per year suggested by HAYDEN and SMITH (1982), the Assateague washover fans are likely to accrete at a rate of between 10 cm to 15 cm per year due predominantly to overwash sedimentation.

Over long time periods (10's to 100's of years), it is likely that the amount of sedimentation from more frequent but moderate overwash events versus will be equal to the amount of sand deposited during infrequent, large magnitude storms. Sediment budget studies need to extend for periods of 10 years or more to be able to assess the relative role of infrequent, large magnitude events versus the cumulation of frequent events of smaller magnitude in the perspective of geomorphic work discussed by WOLMAN and MILLER (1960). It is exceedingly important to view the dynamics of sediment budgets at washover sites in relation to climatic variability.

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