Spatial and temporal controls on overwash occurrence on a Great Lakes barrier spit

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Field measurements from 1985 to 1990 and sequential aerial photography since 1945 show that overwash plays an extremely important role in the dynamics of Long Point, a large barrier spit on the north shore of Lake Erie. Overwash occurs primarily in the transgressive proximal and central zones of the spit, which together account for some 65% of the total shoreline length of 41 km. During periods of high lake level, over 50% of the shoreline in these zones may be overwashed. Washover morphology ranges from continuous washover terraces in areas of low foredunes to isolated washovers with narrow throats and distinct fans where breaching has occurred through high dunes. Individual overwash events commonly produce deposits on the fan surface 0.25–0.75 m or more in thickness. Washover-fan sediments are dominated by nearly horizontal planar bedding, with deposits near the fan margins often having foreset bedding, reflecting deposition in standing water of the bay or of interdune ponds.

The frequency of overwash occurrence is strongly influenced by long-term lake-level fluctuations, which produce a distinct cycle of overwash activity. During the high-water phase more than 40% of the shoreline may consist of active washover fans or inlet breaches. Even storms with a return frequency of 1–2 per year can lead to significant overwash activity, and the washovers are generally reactivated several times in a 2 or 3 year period around the peak water level. During the low-water phase wider beaches offer protection against even extreme storm events, resulting in washover healing and restoration of a continuous foredune.

Les mesures sur le terrain effectuées entre 1985 et 1990, et l'étude des photographies aériennes séquentielles prises depuis 1945, démontrent que le débordement joue un rôle de première importance quant à la dynamique de Long Point, une barre émergée longeant la rive nord du lac Érié. Le débordement se manifeste principalement dans les zones de transgression proximales et centrales de la barre, qui combinées représentent environ 65% de la rive dont la longueur totale est de 41 km. Durant les périodes de haut niveau du lac, le débordement dans ces zones peut se produire sur plus de 50% de la rive. Les dépôts de débordement forment, d'une part, des terrasses continues dans les aires basses des avant-dunes, et d'autre part, aux endroits où l'érosion a percé les hautes dunes, des accumulations isolées caractérisées par des gorges étroites et des éventails distincts. Les débordements individuels déposent fréquemment une épaisseur de 0,25 à 0,75 m, ou plus, de sédiments sur la surface des éventails. Ces sédiments de dépôts de débordement sur les éventails sont formés principalement de couches planaires presque horizontales, et les dépôts localisés près des bordures des éventails exhibent fréquemment un litage frontal oblique, reflétant une sédimentation dans les eaux calmes de la baie ou des étangs entre les dunes.

Les variations à long terme du niveau du lac influencent fortement la fréquence des débordements et créent un cycle distinct d'activité de débordement. Durant la période de haut niveau, plus de 40% de la rive peut être transformée en éventails inondés actifs, ou être envahie par des cours d'eau. Même les tempêtes qui arrivent une ou deux fois par année peuvent contribuer significativement à l'activité de débordement, par conséquent sur une période de deux ou trois années, lorsque le niveau d'eau est près de sa hauteur maximale, les dépôts de débordement sont généralement réactivés plusieurs fois. Durant la période de bas niveau, les plages les plus larges offrent une protection contre les violentes tempêtes, le résultat est un colmatage des dépôts de débordement et une restauration de la zone continue de l'avant-dune.

[Traduit par la rédaction]

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Introduction

Overwash is an important coastal process operating on barrier systems, and results in the transfer of sediments from the open-coast side of the barrier onto the barrier itself or into the bay, lagoon, or marsh backing the feature. Overwash is most prevalent on barriers or portions of barriers that are transgressive, because of rising water levels or a negative sediment budget, but they may occur on stable or even prograding barrier systems during extreme storm events. There is an extensive literature on overwash on barrier systems, particularly from studies carried out on the barriers of the east coast of Canada and the United States, including description of processes during overwash events (Leatherman 1977), morphological and sedimentological characteristics of the washover throat and fan (Schwartz 1975; Morton 1978; Kochel and Dolan 1986), the role of overwash in barrier-island dynamics (Dolan 1973; Godfrey and Godfrey 1973; Niederoda *et al.* 1985), processes of washover healing (Cleary and Hosier 1979), and the relative significance of overwash versus tidal inlets and aeolian processes in effecting landward sediment transfers (Leatherman 1979, 1985; Armon 1979).

Overwash processes also play a significant role on barrier systems in the Great Lakes. However, except for some limited reference in Schwartz (1975) and in some studies of individual barriers (e.g., Coakley 1983), little work has been carried out on these lacustrine features. There are indications that overwash processes on Great Lakes barriers have many similarities with those on marine barriers, but the absence of tides and the influence of seasonal and long-term (decade) changes in mean lake level greatly influence the timing of overwash events, and differences in vegetation associated with the freshwater environment affect the pattern of washover healing.

This paper reports on part of a larger study of overwash on Long Point, a barrier spit on the north shore of Lake Erie (Fisher 1989). Long Point is the largest barrier system in Ontario, indeed in the Great Lakes, and overwash processes

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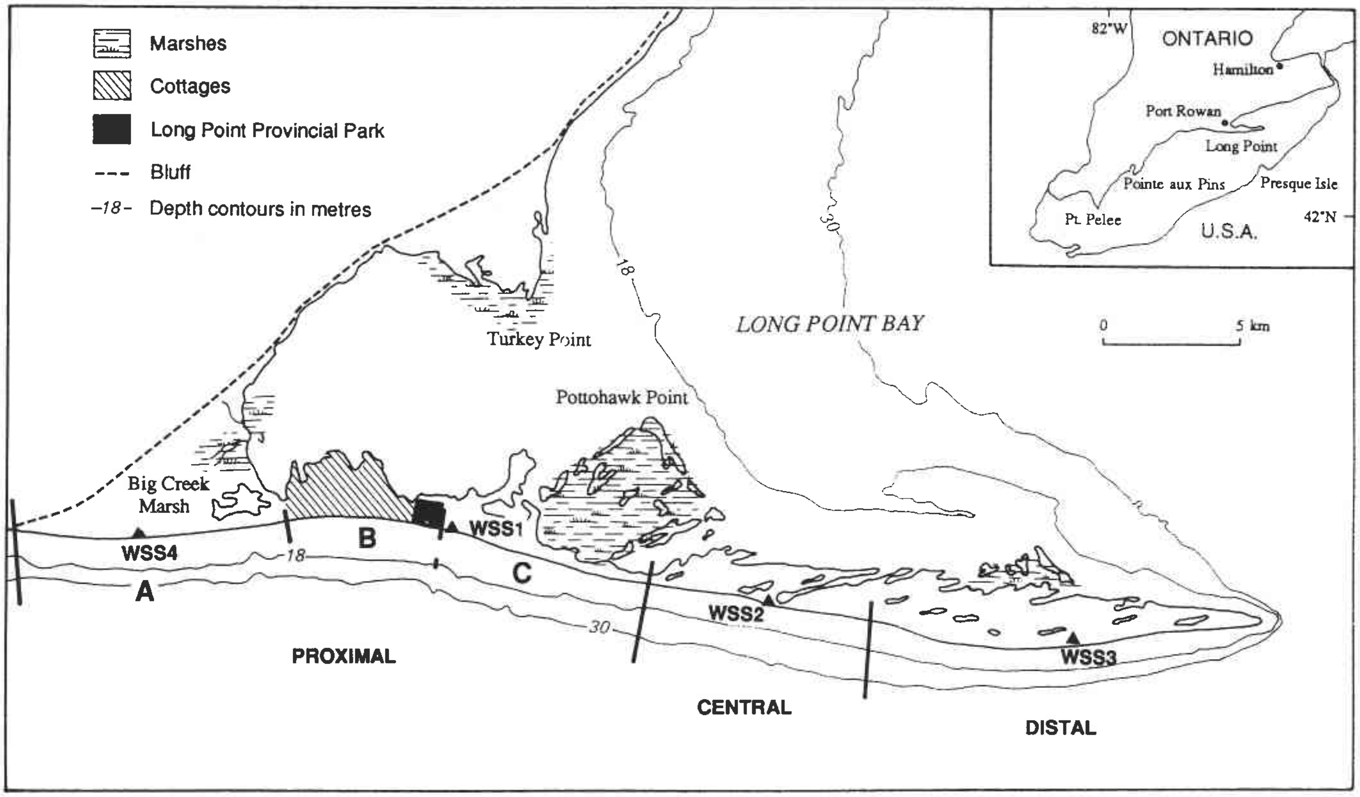


FIG. 1. Map of Long Point, showing physiographic divisions and locations of four washover sites monitored during this study.

have a significant impact on both the natural dune and marsh environments, as well as on the cottage community and provincial park located within the proximal zone. An understanding of the controls on overwash occurrence is thus extremely important in understanding the dynamics of the whole barrier system and for the development of management plans. Attention here is focussed on the controls on spatial and temporal variations in washover occurrence and distribution on the spit and the effects of these variations on washover characteristics.

Study area and environmental parameters

Long Point spit is located on the north shore of Lake Erie and extends 41 km eastward from the mainland into water depths of 60 m (Fig. 1). The spit has developed over the past 4000 years (Coakley 1983) and is presently extending lakeward at a rate of 4–7 $m \cdot year^{-1}$. It is one of four large barrier complexes in Lake Erie that are nourished by sediment eroded from bluffs formed in glacial sediments, the others being Pointe aux Pins and Point Pelee on the north shore and Presque Isle on the south shore (Fig. 1). Long Point forms the sink for a littoral cell whose updrift boundary is some 95 km to the west. Bluff recession over much of the length of the cell averages 0.6–2.0 $m \cdot year^{-1}$ and contributes approximately 1×10^6 $m^3 \cdot year^{-1}$ of sand to the spit downdrift (Rukavina and Zeman 1987).

The longest fetch is over 270 km to the west-southwest, and both the prevailing and dominant winds are from the west and southwest, thus giving rise to the dominant easterly sediment transport. Storm waves from the southwest quadrant typically have a significant wave height of 1–2 m and a peak period of 4–6 s (Ontario Ministry of Natural Resources 1988), but some waves from this direction can exceed 3 m in height and 8 s in period. There is only limited wave action from the southeast quadrant because of the limited fetch (60 km) and much lower frequency of winds from this direction. Large waves are also generated by winds from the east-northeast blowing over a fetch of over 100 km, but because of the deep water at the end of the spit there is very limited refraction, and waves from this direction affect only the last few kilometres of the distal end (Conliffe-Reid 1991). Wave action and littoral processes are generally restricted for 3–4 months, beginning in late December, by the development of an ice foot along the shoreline and by ice cover on the lake. This effectively protects the dunes from scarping and overwash during the winter season, though some aeolian processes may be enhanced (Law and Davidson-Arnott 1991).

Foredune breaching, overwash occurrence, and subsequent healing of washovers are greatly influenced by water-level fluctuations that occur on three time scales: (*i*) long-term fluctuations in the order of years or tens of years; (*ii*) annual lake-level fluctuations; and (*iii*) fluctuations over a period of hours associated with storm surges and seiching (Blust 1978). Long-term fluctuations are driven by extended periods of above- and below-average precipitation amounts over the whole Great Lakes basin and produce a maximum range in average annual lake level of about 1.4 m (Fig. 2A). Annual fluctuations on the order of 0.3–0.5 m reflect seasonal variations in runoff and evaporation. Typically, spring snowmelt generates highest levels in early summer to midsummer, with a decrease by late summer as runoff is reduced, and levels remain constant or show a secondary peak in the late fall. The most dramatic fluctuations are short-term changes associated with storm surges, which, because of the shallow depth and shape of the basin,

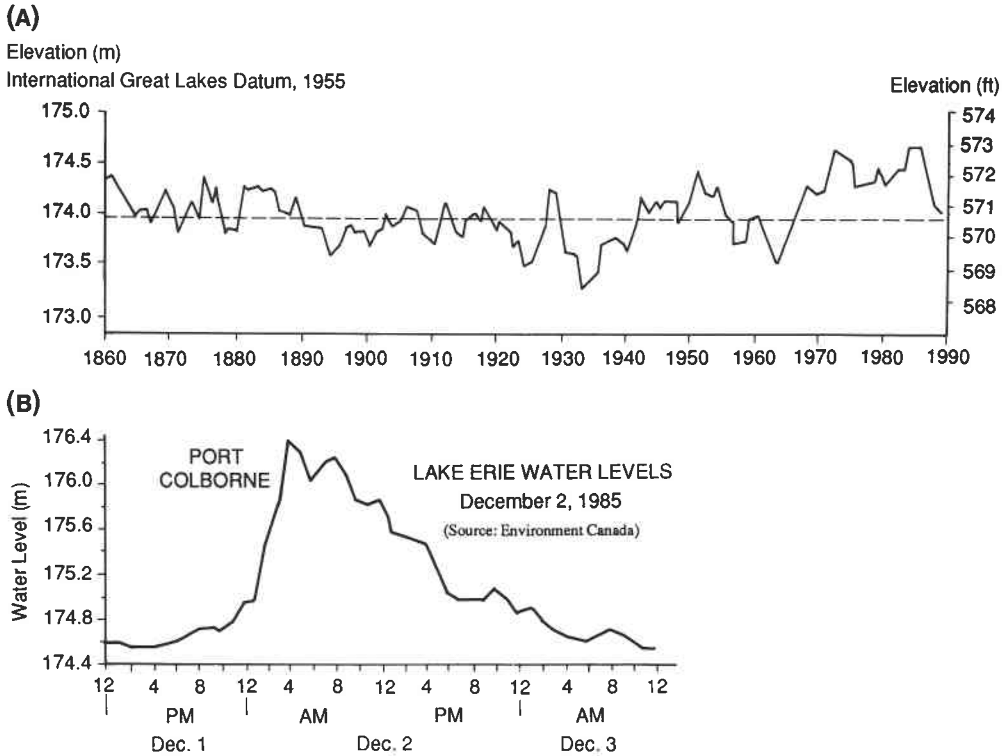


FIG. 2. (A) Mean annual lake level for Lake Erie, 1860–1990. (B) Water levels recorded at Port Colborne during the December 2, 1985, storm event.

can exceed 2 m (Libicki and Bedford 1990).

The water levels of the 1985–1986 period were the highest ever recorded (Fig. 2A), and in addition to seasonal high values in the spring of 1985 and 1986, record rainfall in the Great Lakes basin in November 1985 produced a second peak in late fall. A number of storms in the spring and fall of 1985 resulted in dune scarping, overwash, and inlet development on Long Point. The most extensive disturbance resulted from the severe storm of December 2, 1985, during which the maximum surge recorded at Port Colborne, 60 km to the east, was 1.82 m (Fig. 2B). Lake levels declined rapidly during 1987, but a storm in mid-December 1987 resulted in the reactivation of many of the washovers on the spit.

The cottage community of Long Point and Long Point Provincial Park occupy about 6 km of shoreline at the proximal end of the spit. The distal end of the spit is managed as a wildlife reserve by the Canadian Wildlife Service, as is Big Creek Marsh at the proximal end. Most of the remainder of the spit is owned by duck-hunting clubs and is largely undisturbed. The whole spit complex is recognized as a Biosphere Reserve under UNESCO's Man and the Biosphere Program.

TABLE 1. Dates and scales of aerial photographs used in this study

August 26, 1945	1 : 22 950
August 21, 1951	1 : 36 000
July 10, 1955	1 : 15 800
June 3, 1959	1 : 36 000
August 9, 1964	1 : 16 000
May 26, 1968	1 : 16 000
September 9, 1972	1 : 16 380
June 23, 1973	1 : 20 000
September 24, 1978	1 : 10 000
April 14, 1985	Oblique
July 23, 1985	1 : 8 000
October 3, 1985	Oblique
December 3, 1985	Oblique
April 2, 1986	Oblique
November 6, 1986	Oblique
June 5, 1987	Oblique
July 29, 1987	Oblique
December 18, 1987	Oblique
May 26, 1988	Oblique
October 12, 1988	Oblique

Methodology

The spatial distribution and characteristics of washovers were examined in 10 sets of vertical aerial photographs taken between 1945 and 1985 and in oblique photographs taken from a small plane two or three times a year between 1985 and 1988 (Table 1). Measurements of the extent of overwash along the shoreline were made for six of the years for which photography was available, governed primarily by the scale and quality of the photographs.

Three washover sites (WSS1, WSS2, and WSS3) were selected for detailed study, one in each of the three zones (Fig. 1). At each of these sites the morphology of the washover and the adjacent nearshore, beach, and dune was surveyed using standard levelling techniques along profiles established both perpendicular to the beach and, on the washover throat and fan, parallel to the beach. The initial surveys were made in May 1987, and subsequent surveys in

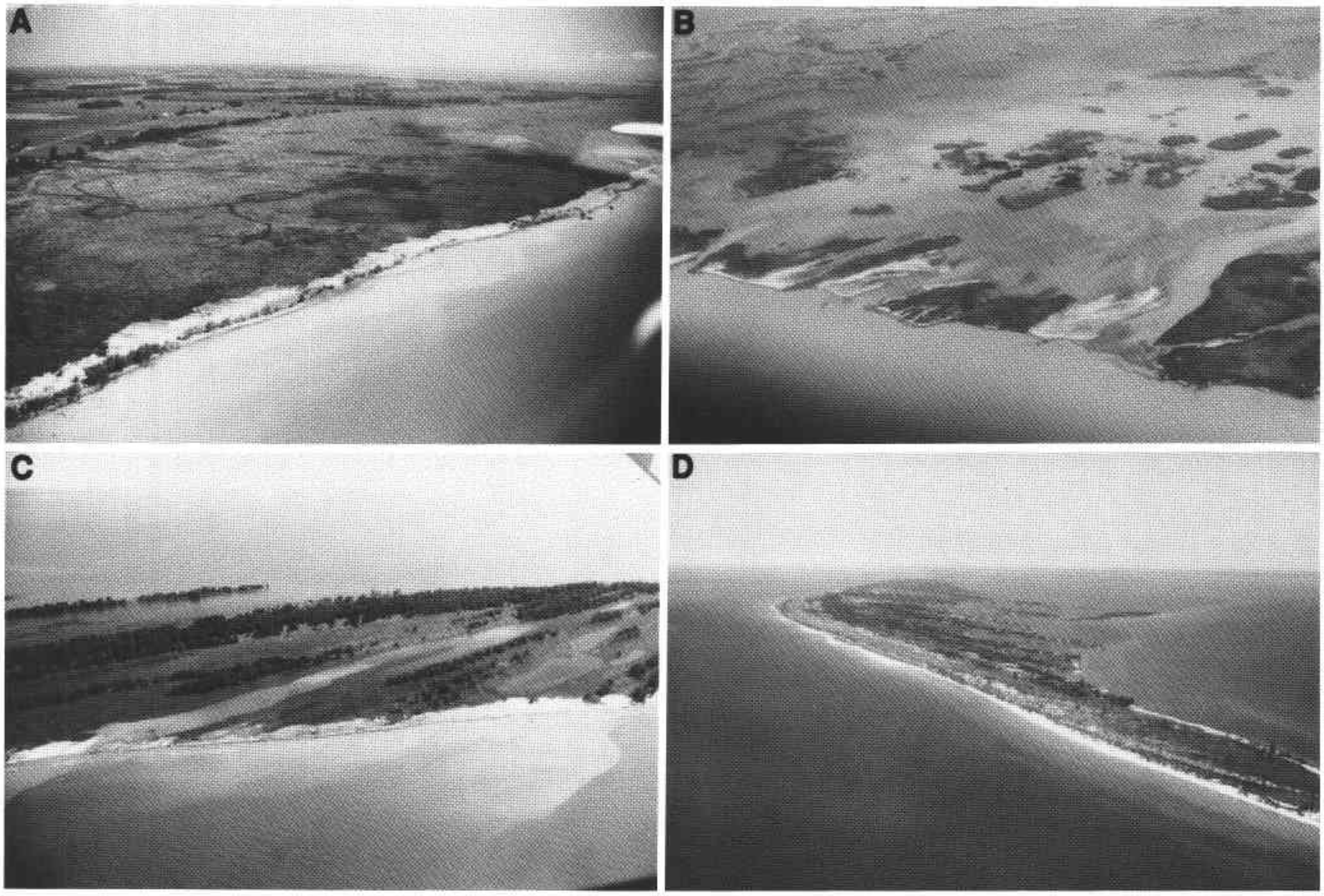


FIG. 3. Oblique aerial photographs, showing washover and inlet development in the three physiographic zones. (A) Proximal zone, view looking northeast, showing nearly continuous washovers into Big Creek Marsh, July 29, 1987. The inner bay is visible at the top right, and the former shoreline is marked by a line of trees and the edge of fields. Most of the channels and water bodies in the marsh have been dredged to promote waterfowl habitat. (B) East end of proximal zone, view looking northwest, October 5, 1985, showing inlets resulting from storms during April 1985. Some of the inlets have been partially infilled, but they were reopened during the December 2 storm. (C) Central zone, view looking north, June 5, 1987. The older dune recurves here have been truncated and are marked by lines of trees trending at an angle of 30° to the modern shoreline and foredune. Overwash is taking place into the ponds and slacks between the older dune ridges. WSS2 study site is located at the extreme right of the photograph. (D) Distal zone, view looking west. The shoreline curvature marking the fulcrum point between the transgressive central section and the progradational distal section is clearly visible.

November 1987 and July 1988. Site 1 was also surveyed on December 17, 1987, following an overwash event on the 15th. A fourth site (WSS4, Fig. 1), located in the portion of the proximal zone backed by continuous marsh, was monitored less frequently. Sites WSS2, WSS3, and WSS4 are only accessible by boat.

Stratigraphy and sedimentary structures were examined in pits dug along a line through the washover throat to the fan margin and also along a line perpendicular to this across the fan surface. Short (0.5 m) cores were taken of sediments below the water table near the fan margins. Changes in the surface of the washover throat and fan at site 2 were also monitored using erosion pins set up on lines across the throat entrance and along the long axis of the fan.

Results

Physiography and overwash occurrence

Long Point can be divided into proximal, central, and distal zones on the basis of sediment budget and morphology (Fig. 1), accounting for 21.0, 6.3, and 14.2 km, respectively, of the total shoreline length of 41.5 km. The proximal and central zones have a negative sediment budget and are transgressing northward through overwash, inlet formation, and aeolian processes, whereas the distal section has a positive sediment budget and is prograding southward and eastward. A similar pattern is shown in computer modelling of potential littoral sediment transport (Conliffe-Reid 1991).

In the proximal zone the transgression has completely removed the old dune recurves, and there is a single foredune ridge backed by marsh and the open waters of the inner bay (Fig. 1). The proximal zone itself can be subdivided into three sections (A, B, and C in Fig. 1). In section A the beach and foredune are narrow and backed by a continuous marsh complex. This section was overwashed several times during 1985–1986, with washover fans coalescing into a broad washover terrace (Fig. 3A). In some areas the foredune was eroded, but is still marked by a row of standing trees (*Populus deltoides*). Section B includes most of the cottage community of Long Point and Long Point Provincial Park. The barrier width is quite variable here, with extensive marshes fringing the inner bay. Severe damage to cottages at the western end occurred during storms in 1985 and 1986, but the presence of the structures and cottages prevented washover fan development. The barrier is quite narrow in section C and in places is open to the inner bay. This section was also extensively overwashed during 1985–1986, and at the eastern end a number of inlets were created (Fig. 3B).

The central area is also transgressive, but here old dune recurves and intervening ponds and dune slacks are still preserved, trending at an angle of 30° to the shoreline (Fig. 3C). The modern foredune ridge consists of short segments connecting the truncated ends of the older dune recurves. Overwash fan development here is constrained by the recurves, which act as headlands and control the shape of the ponds or slacks into which the overwash occurs.

The distal zone has a positive sediment budget, a progradational dune system up to 5 km wide, wide beaches, and extensive embryo dune development (Fig. 3D). The latter act to protect the foredune, so although there was extensive scarping of the dune during the 1985–1986 high-water period, actual overwash was limited to one location.

Temporal and spatial variations in overwash occurrence

The distribution of washovers along the south shore of Long Point for six of the years for which photography is available is shown in Fig. 4. The proportion of the shoreline in washovers in photographs taken in 1955, 1973, and 1988 reflects the effects of storm activity during and immediately following the high-water periods of 1952–1953, 1972–1973, and 1985–1986. During these periods more than 25% of the spit was subject to overwash and inlet breaching. The proportion of the spit occupied by washovers in photographs taken in 1978 is approximately the same as in 1973 because washover healing was not yet complete. However, few of the washovers were active at this time. Photographs taken in 1945 and 1972 show less than 5% of the spit occupied by washovers, and these low values reflect long periods of washover healing during the periods between the lake-level peaks. At the end of the washover healing period the proportion of the spit in washovers usually jumps abruptly as a result of one or two severe storms. This is particularly noticeable in the large increase shown between photographs taken in September 1972, just as lake levels were reaching record highs, and those taken in June 1973 after severe storms in late fall 1972 and spring 1973.

The proportion of each zone overwashed is shown in Fig. 4B. It can be seen that washovers are absent during low-water periods in the distal zone and that even during the high-water periods less than 3% is overwashed. In contrast, roughly half of the shoreline of the proximal zone is overwashed during high-water phases and a small proportion remains active even at the end of a low-water phase. In fact, the proportion of shoreline overwashed in the proximal zone during the high-water phase of 1985–1986 is probably close to 65%, since the presence of cottages and shore-protection structures prevented overwash development along several kilometres of the shoreline. The proportion of the central zone overwashed has increased from <10% in 1955 to >50% in 1988. This may reflect an increase in peak water levels, but the fact that the proportion of the shoreline overwashed in the other two zones remained roughly constant suggests that some other factor, such as a change in sediment budget in this zone, may be operating here.

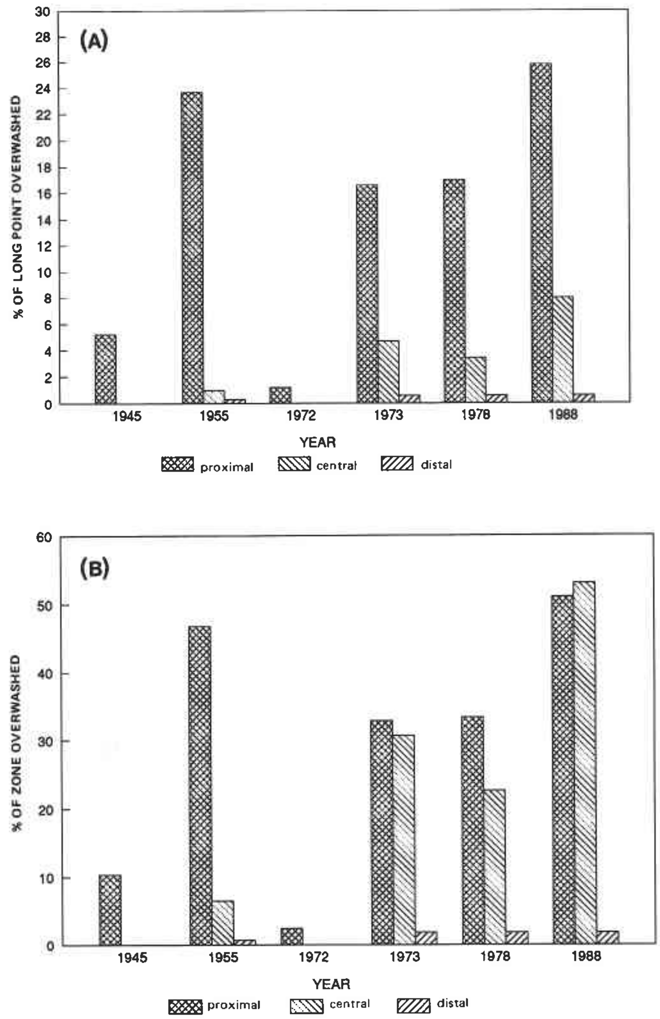


FIG. 4. Percentage of shoreline characterized by washover development at several dates between 1945 and 1988. (A) Percentage of total Long Point shoreline occupied by washovers. (B) Percentage of each zone occupied by washovers. Data were measured on the aerial photographs listed in Table 1.

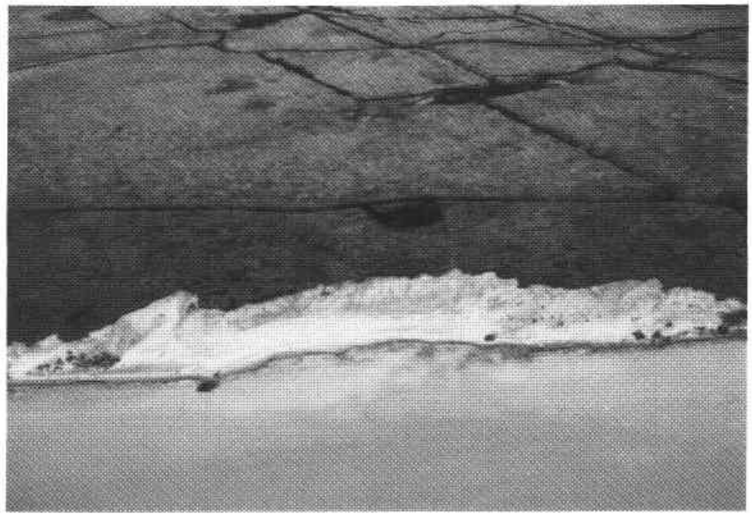
Washover morphology and sedimentology

As noted above, spatial variations in sediment budget, foredune morphology and orientation, and the nature of the barrier behind the foredune ridge lead to systematic variations in the characteristics of the washover form from one zone to the next. In this section individual washovers in each of the three sections are described and the effects of reactivation by an overwash event are also noted.

WSS4, proximal zone

This site is located in reach A of the proximal zone and is backed by the Big Creek Marsh (Fig. 5A). A section of the washover terrace extending 330 m alongshore was surveyed on May 26, 1987. Observations and photographs were made on other dates but no other surveys were conducted. The average depth of washover penetration into the marsh was 65 m, and it varied from 54 to 74 m. The foredune in this area was completely eroded, and this is reflected in the very low crestal elevation in Fig. 5B, formed by the beach berm. This low ele-

(A)



(B)

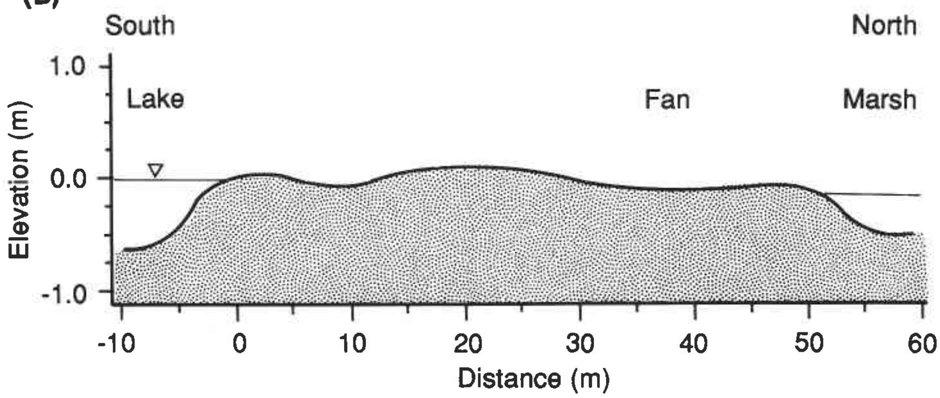


FIG. 5. (A) Oblique aerial photograph taken on July 29, 1987, of WSS4. The width of view is approximately 600 m. (B) Cross profile measured on May 26, 1987.

vation resulted in a high susceptibility to overwash, and overwash did occur during storms on June 7–8, 1987, and December 15, 1987. Overwash sediments were quite coarse, with large quantities of cobble-sized material being deposited on the fan surface after the storm of June 7–8. The uniformity of the overwash reflects both the low crestal elevation and the absence of significant topographic controls from old dune ridges or channels within the marsh.

WSS1, proximal zone

This site is located just east of the boundary of the provincial park within reach B of the proximal zone and is the only site accessible on foot (Fig. 1). There is no evidence in the aerial photographs that this area had been overwashed between 1945 and 1985. However, an oblique aerial photograph taken on April 14, 1985 (Fig. 6A) shows that storms during the early part of the high-water phase had resulted in dune scarping and the creation of a number of blowouts and low points in the foredune ridge, which must have increased the susceptibility of this area to overwash. The December 2, 1985, storm breached the foredune in two places, around a central remnant of the foredune, with the overwash coalescing on the dune flat and marsh area behind the ridge to form a compound fan (Fig. 6B). The cottage visible in Fig. 6A was lifted off its foundations and deposited about 50 m landward, and sediment from the fan reached the semicircular channel behind the cottage (Fig. 6B). There were several minor overwash events in 1986, but none had any significant impact on the washover throat or fan. During 1987 there was some sediment redistribution by aeolian processes and fairly rapid growth of vegetation on the fan surface and on the backshore across the washover throats (Fig. 6C). However, a major storm on December 15, 1987, resulted in reactivation of the whole fan surface and further extension into the marsh (Fig. 6D).

The compound nature of the washover is shown in Fig. 7. The eastern margin has a long, oblique channel and throat between the main foredune ridge and a remnant knoll. Overwash through this channel built a lobe into the marsh, which coalesced with one formed by water flowing through a broader throat to the west of the remnant knoll. Some of the water flowing through the western washover throat was deflected towards low ground on the left (west), building a fan into the dredged channel and leaving a section of back barrier between the lobes, which was unaffected by the overwash event. The total area covered by the overwash was approximately 11 200 m^2, and the overwash penetrated up to 110 m inland from the former dune line.

The thickness of overwash sedimentation on the fan surface,

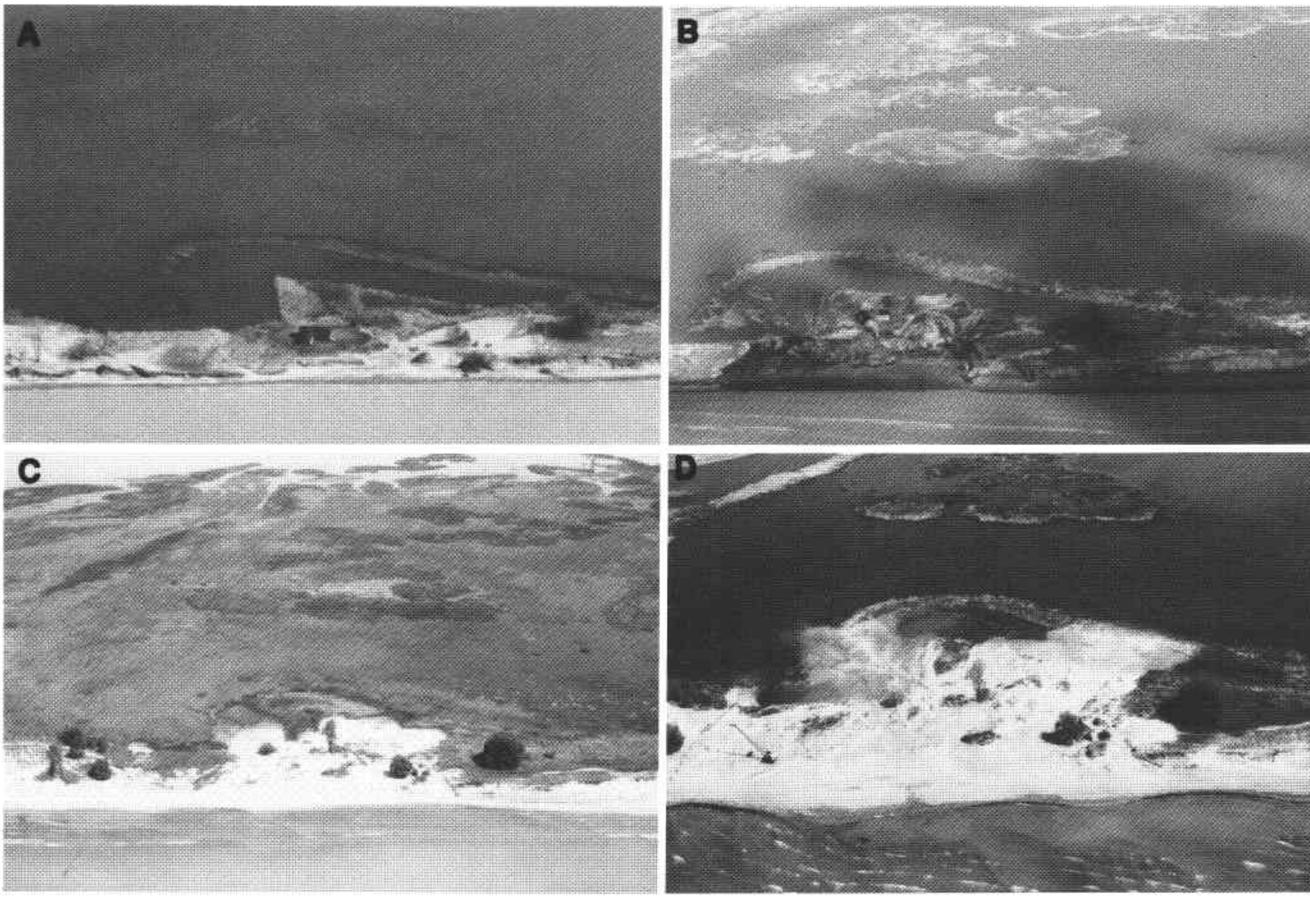


FIG. 6. Oblique aerial photographs showing the development of the washover at WSS1 from 1985 to 1988. (A) April 14, 1985, prior to overwash. Note the intact cottage and lawn near the centre and the distinctive channel and berm in the marsh behind. There has already been considerable scarping of the foredune and blowout development. (B) Photograph taken on December 3, 1985, the day after the severe storm. The cottage has been moved back about 50 m, and the fan has built out into the channel in two places. (C) Photograph taken on July 29, 1987. There have only been small changes in the fan surface since the initial overwash event, and recolonization by vegetation is evident on the backshore and on the fan surface. (D) Photograph taken on May 26, 1988. Note the extension of the fan across the channel and berm following the December 15, 1987 storm. The width of the washover throat is approximately 100 m.

measured in a number of pits, ranged from 0.25 to 0.50 m. In many cases the original surface is marked by a line of buried vegetation (Fig. 8), and in the vicinity of the former cottage, the grass sod visible in Fig. 6A was easily located. Sedimentary structures observed in the trenches were similar to those described from washover fans elsewhere in the literature (e.g., Schwartz 1975), consisting of parallel lamination or small-scale ripple cross-lamination forming units 0.5–3.0 cm in thickness with bedding surfaces nearly horizontal or dipping gently towards the marsh. Near the fan margins cross-bedded units up to 30 cm thick were present, indicating that deposition took place in standing water as the fan extended into the channel in the marsh. In the centre of the fan the underlying sediments appear to be primarily back-barrier aeolian sands, whereas at the fan margins the underlying sediments have a high organic and fine sediment content typical of the marsh environment.

Surveys carried out on December 17 and 21, 1987, mapped changes in the washover surface following an overwash event on December 15 (Fig. 9A). The overwash led to a slight widening of the eastern channel and the removal of sand from incipient dunes close to the beach and on the central fan surface (Fig. 9B). The major impact, however, was a 44% increase in the fan area due to lateral expansion and extension of the two main fan lobes (Figs. 9A, 9B). Both lobes extended completely across the channel onto the higher ground beyond, and there was also considerable deposition on the west side of the western lobe (Figs. 6D, 9A). The eastern lobe was extended by an average of 15 m and the western lobe by nearly 30 m. The average thickness of deposits in the extended fan lobes was 0.7 m and the volume of sand deposited was approximately 2500 m^3.

WSS2, central zone

Ths site was a small, discrete washover with well-defined fan situated between two oblique dune recurves in the central zone. It is located just west of Cedar Creek, a large interdune pond that extends across the whole width of the barrier (Fig. 1). This site was not overwashed during the high-water phases of 1952–1953 and 1972–1973, and a photograph taken in October 1985 reveals a continuous foredune and well-vegetated backdune surface (Fig. 10A). The site was overwashed on December 2, 1985, as was much of the central zone.

The foredune was breached over a distance of approximately 45 m, with the washover fan extending obliquely to the shoreline into the marshy interdune swale between the dune

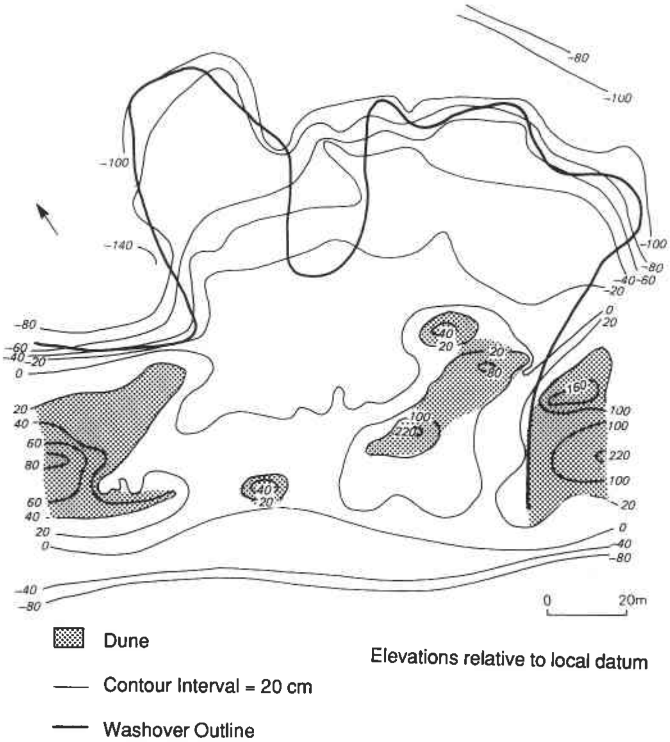


Fig. 7. Contour map of WSS1 surveyed on May 8, 1987. Note the dune remnant on the east side and the relatively confined east channel compared with that of the west channel.

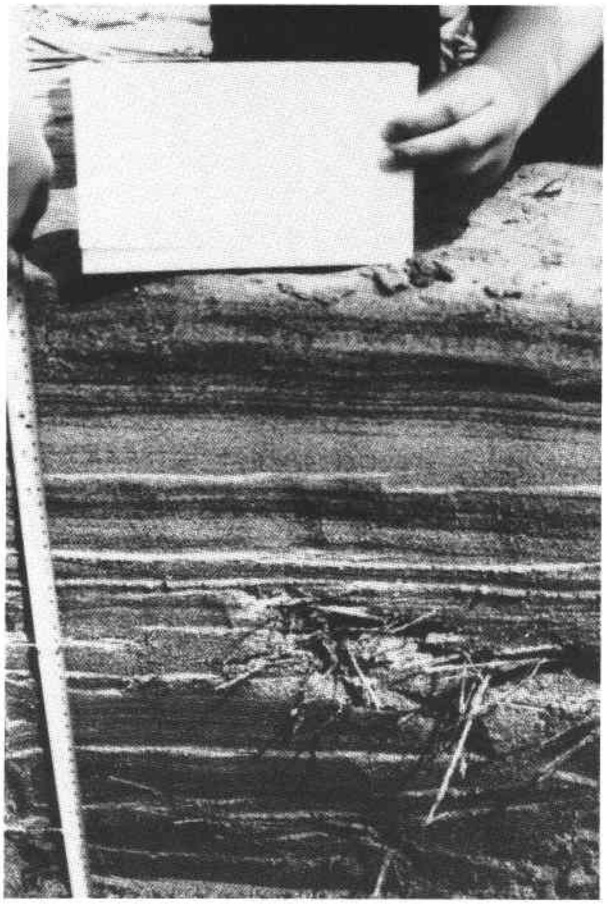


FIG. 8. Photograph of overwash sediments in a pit on the mid-fan surface of WSS1. The former surface is shown by the buried plant remains, which have been bent over as a result of flow towards the marsh. The overwash sediments are about 20 cm thick here and consist primarily of thin beds of planar lamination dipping gently towards the north (left).

ridges (Fig. 10B). The maximum depth of penetration from the shoreline was 60 m and maximum fan width 95 m, with a washover-fan area of 4100 m^2. In the mid-fan area burial of marram (*Ammophila breviligulata*) and other dune grasses indicates deposition of 0.3–0.4 m of sediment, with slightly greater depths over vegetation in the marsh (Fig. 11). Sedimentary structures in the overwash sediments were similar to those at WSS1, consisting primarily of thinly bedded, subhorizontal parallel lamination (Fig. 11).

The site was overwashed again on December 15, 1987 (Fig. 10C), leading to considerable landward extension of the fan surface. Because the site is inaccessible during the winter, it was not resurveyed until July 5, 1988. It is expected that there will have been some redistribution of sediment on the fan surface during the spring, but most of the changes between survey dates (Fig. 12A) can be attributed to the overwash. There was little lateral expansion of the fan due to the confining influence of the dune ridges, particularly the western ridge, but the fan was extended some 35 m into the swale (Fig. 12B) and the surface area increased by about 20%. As was the case at WSS1, there was some erosion in the washover throat area, with surface lowering of 0.1–0.2 m. There was also some flattening of the original fan surface, but the surface elevation remained essentially the same near the centre, with 0.2–0.3 m of deposition occurring near the former fan edge and in the extended portion.

WSS3, distal zone

This site is situated in a portion of the distal zone where most of the overwash since 1945 has occurred (Fig. 1). The site consisted of two isolated washovers separated by about 200 m of intact dune (Fig. 13A). Vertical aerial photographs indicate that overwash occurred during the 1953 high-water phase at a site roughly halfway between the two washovers. This washover had healed by 1972, but two new washovers developed on either side during the 1972–1973 high-water phase, and these same two sites were overwashed during storms on April 6 and December 2, 1985.

Both washovers were surveyed in May 1987, and the eastern one was monitored through 1987 and 1988. The throat of the eastern washover was relatively narrow (Fig. 14B) and one lobe of the fan was built into the swale area just west of the throat. A small dune ridge located about 60 m from the foredune line and almost opposite the breach apparently deflected much of the overwash flow towards the east and led to the building of an extensive lobe into the interdune pond, which lies parallel to the beach. The surface area of the fan covered some 4500 m^2, making it approximately the same size as WSS2. The sediments associated with the most recent overwash on the fan surface were similar to those found on WSS1 and WSS2 (Fig. 14A), though there is more evidence of small-scale ripple development. However, one and sometimes two layers of pebbles are commonly found in sediments underlying the most recent overwash deposits and probably represent lag deposits formed through deflation of the 1972–1973

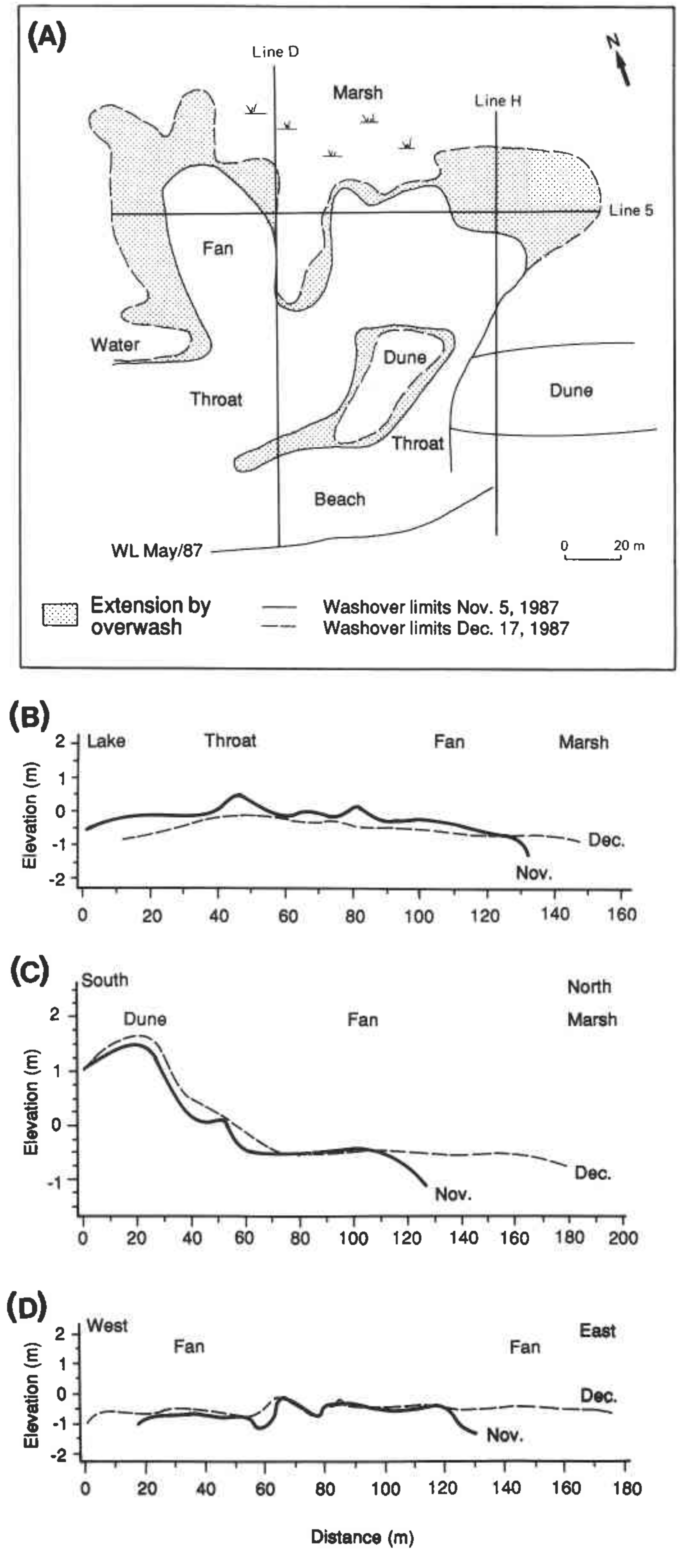


FIG. 9. Changes in the fan surface at WSS1 following an overwash event on December 15, 1987. (A) Plan view showing extension of the two primary fans. The locations of selected topographic profiles in (B–D) are also shown. (B) Profile of line D, along the centre of the west channel, showing removal of incipient dunes from the fan surface. (C) Line H across the eastern lobe, showing extension of the fan into the marsh. (D) Line 5, parallel to the shoreline, across the rear margin of the fan, showing lateral extension and some infilling of low spots on the fan surface.

washover-fan surfaces. Sediments deflated from the surface of these earlier washover fans probably form the source for the small dune ridge that developed at the back of the site.

The wide beaches and progradational dune field of the distal zone considerably reduce the potential for overwash occurrence, and this is reflected in the very small proportion of the shoreline that is overwashed even during high-water phases (Fig. 2B). The area where WSS3 is located is characterized by a relatively narrow, low foredune ridge backed by a wide interdune pond, and this makes it the area most susceptible to overwash within the distal zone. However, the occurrence of overwash here also appears to have been influenced by migration of longshore sandwaves in this zone (Stewart and Davidson-Arnott 1988). Oblique aerial photographs showed that the overwash site in 1985 was located in the erosional zone downdrift of a large sandwave characterized by a narrow beach and scarping of the foredune. This would have rendered the location more vulnerable to breaching and overwash development than areas on either side that were protected by the wider (50–100 m) beaches opposite longshore sandwaves. Between 1985 and 1986 the updrift sandwave migrated only a few tens of metres eastward. A photograph taken in October 1986 (Fig. 13B) shows the downdrift end of this sandwave located about 200 m updrift of the west washover. Emergence of a nearshore bar attached to the downdrift end of the sandwaves indicates that downdrift migration through the ''jumping'' mechanism described by Stewart and Davidson-Arnott (1988) is about to occur. The effect of this jump is shown in Fig. 13A, with the downdrift end of the sandwave located about 100 m east of the east washover site and the 60 m wide beach of the downdrift end of the sandwave providing protection against further overwash. The effectiveness of this protection is indicated by the fact that neither of these two washovers was affected by the December 12, 1987, storm, which resulted in reactivation of most of the other washovers on Long Point.

Model of overwash occurrence

The most important control on overwash occurrence at Long Point, and on Great Lakes barriers generally, is the long-term water-level cycle. Observations and measurements made during the period 1985–1990, together with the record in vertical aerial photographs covering the previous two lake-level cycles, have led to the recognition of distinct sets of features and processes related to overwash activity during different phases of the lake-level cycle, and these are illustrated schematically in Fig. 15. The features associated with each of the stages are summarized below.

Stage 1 (*pre-overwash phase*) is associated with rising water levels, which lead to a reduction in overall beach width and thus increase the potential for dune scarping even during minor storms. Along most of the shoreline there is a sufficient volume of sediment stored in the embryo dune zone and in the foredune to prevent complete breaching, but overwash will occur in a few vulnerable locations in the proximal zone, particularly if there is a very severe storm.

During stage 2 (*primary overwash phase*), lake levels reach their peak. Beaches are very narrow, in part because of the water-level rise, but also because of a lag between the water-level rise and the onshore movement of sediment as the nearshore profile adjusts to a new equilibrium (Hands 1983). Much of the shoreline in the proximal and central zones is now

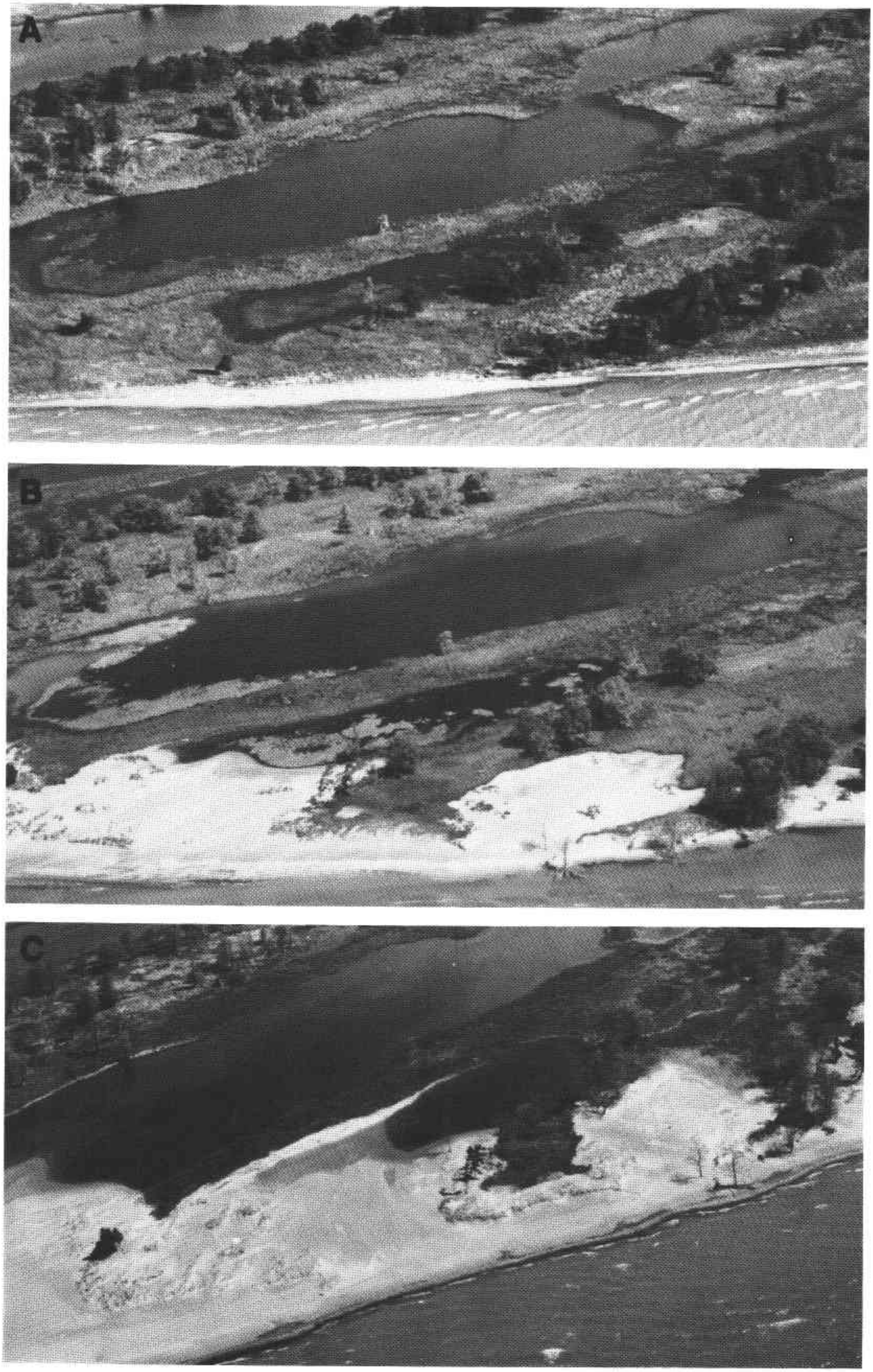


FIG. 10. Oblique aerial photographs of WSS2. (A) Photograph taken on October 3, 1985, prior to the overwash event. Note the continuous foredune and stable backdune area. (B) Photograph taken on July 29, 1987. Overwash has occurred into the ponds on either side as well as at WSS2 itself. (C) Photograph taken on October 12, 1988, showing extension of the washover-fan surface following the December 15, 1987, storm. The fan built into the pond immediately to the west has also been extended by this storm. The washover throat is about 50 m wide.

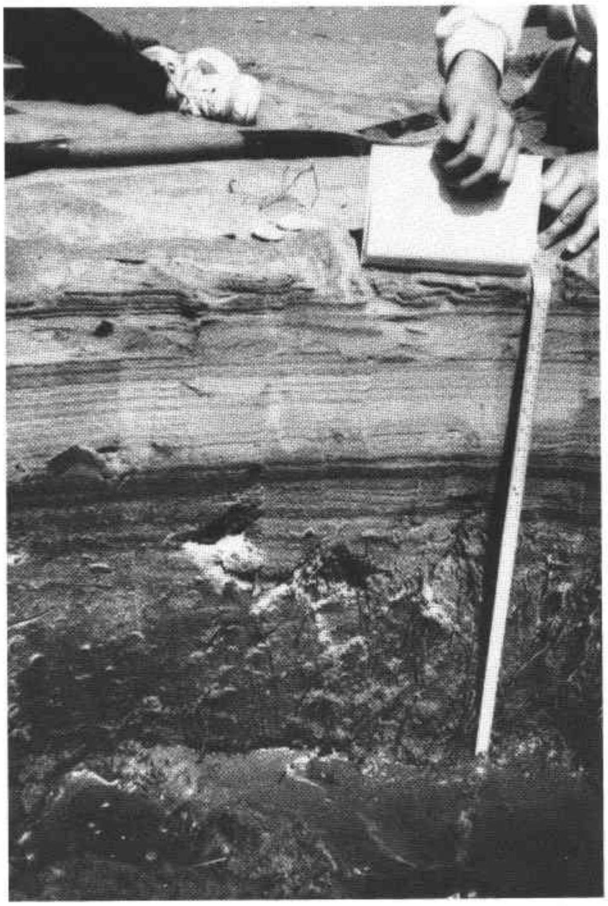


FIG. 11. Overwash sediments in a pit near the margins of the fan at WSS2. The deposits here are about 0.3 m thick and consist of subhorizontal parallel lamination. The overwash sediments have buried some vegetation in place. The high organic content reflects the location at the edge of the marshy interdune swale.

vulnerable to overwash during even a moderate storm because of erosion of the foredune during the previous stage of rising lake levels. Depending on the magnitude of storm events, some 30−50% of the proximal and central zones will be overwashed and inlet breaching may also occur. Some localized overwash may also occur in the distal zone.

During stage 3 (*secondary overwash phase*), lake levels have peaked and begin to recede. Beaches remain narrow, but volumes of sediment in the beach increase as profile adjustments catch up with the water-level change. There is little formation of new washover sites, but the majority of washovers will be reactivated several times, since surges associated with even moderate storms will be sufficient to overtop the berm crest and to remove incipient dunes forming across washover throats.

Stage 4 (*primary passive phase*) is associated with falling lake levels, which result in a marked increase in beach width, thus reducing the potential for further overwash. In general, moderate storms are no longer sufficient to generate overwash, and passive-phase processes such as deflation of washover-fan surfaces and the growth of dunes across washover throats are initiated.

During stage 5 (*intermediate passive phase*), lake levels reach their low point. Most of the shoreline is characterized

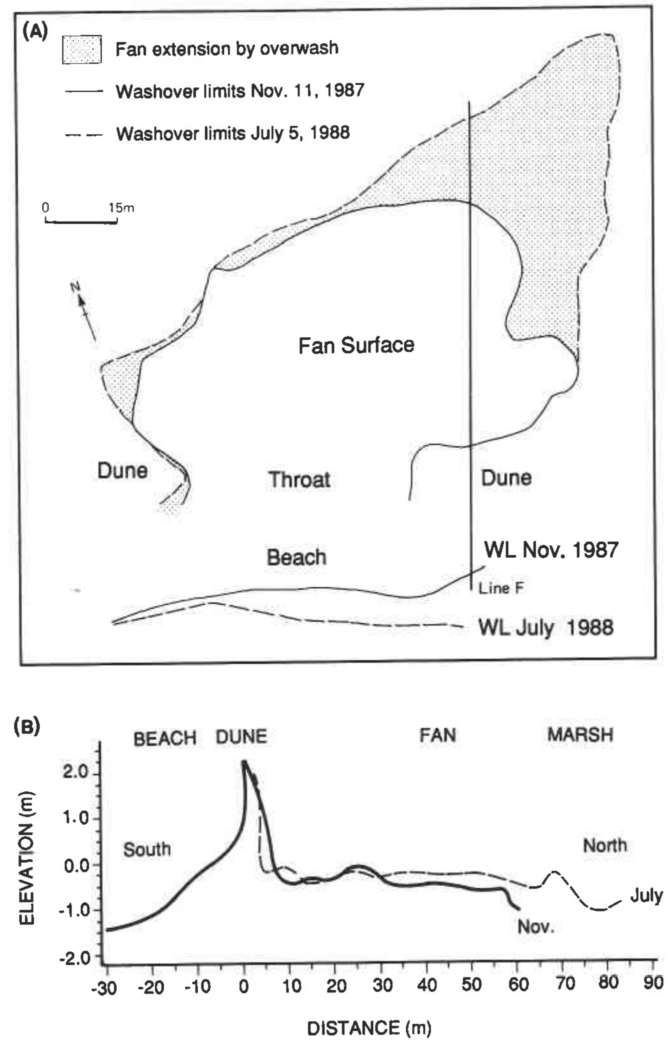


FIG. 12. Extension of the washover-fan surface at WSS2 following the storm of December 15, 1987. (A) Plan view based on location of the fan edge on surveys carried out on November 11, 1987, and July 5, 1988. (B) Profile along line F on the same two dates. The profile location is shown in (A).

by wide beaches, which offer protection from even intense storms and which supply abundant sediment for growth of embryo dunes and foredune regeneration. Only one or two sites in the proximal zone show recent overwash activity, and in most areas washover healing is well established.

Stage 6 (*advanced passive phase*) is characterized by rising lake levels, but beaches still remain relatively wide. Dune rebuilding and healing of washover fans continues, so the proportion of the shoreline occupied by washovers decreases steadily to a minimum and then begins to increase as water levels near their peak.

Discussion

The long-term lake-level cycle that provides a framework for the scheme outlined above and in Fig. 15 produces a major difference in the controls on overwash occurrence in the Great Lakes compared with the marine environment. In the marine environment, at any one location overwash occurrence is a largely random event determined by the frequency of storms

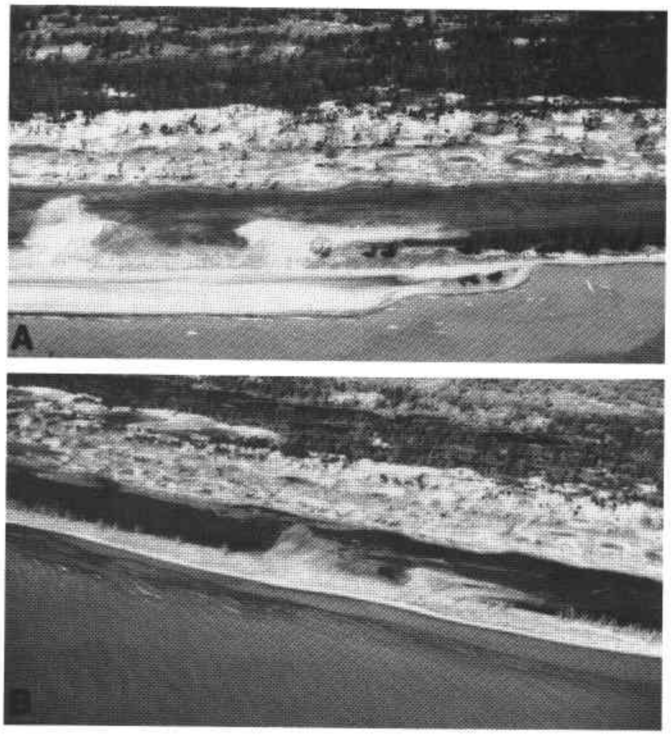


FIG. 13. (A) Oblique aerial photograph of WSS3 taken on June 5, 1987. The two washovers were first formed during the 1972–1973 high-water phase and were reactivated in 1985. The washovers are now protected from reactivation by the 60 m wide beach at the downdrift end of a longshore sandwave. (B) Photograph taken on October 26, 1986. The downdrift end of the sandwave shown in (A) is located just west (left) of the photograph. The inner nearshore bar has attached to the downdrift end of the sandwave, and the crest has built up above the water line, enclosing a runnel. In the period between the two photographs, infilling of the runnel resulted in an eastward migration of the downdrift end of the sandwave of 550 m.

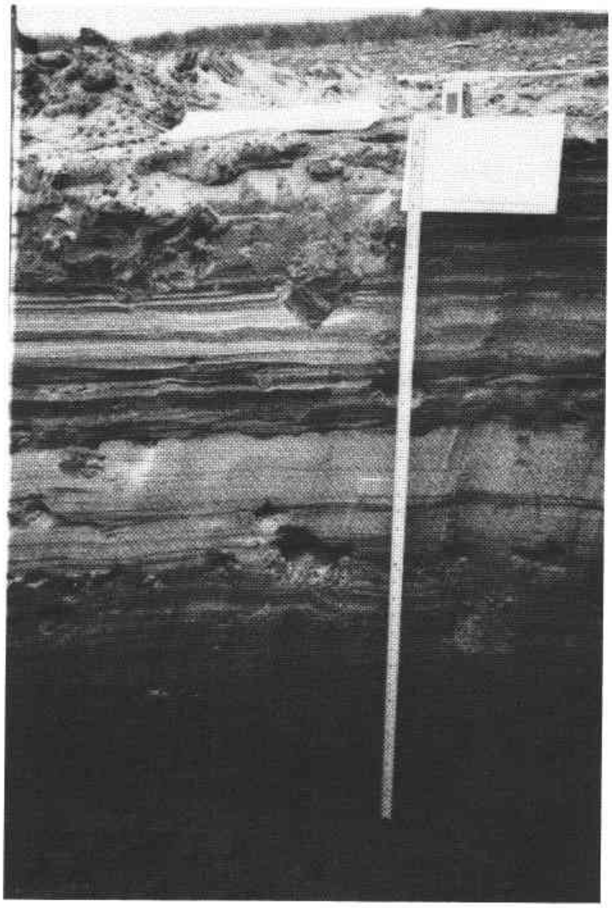


FIG. 14. (A) Sediments exposed in a pit on the mid-fan surface. The upper unit, which is about 0.3 m thick, consists of sediments deposited during the latest phase of overwash. Pebble concentrations at 0.3 and 0.5 m probably reflect deflation surfaces developed on earlier fan surfaces. Pebble lag development on the modern fan is visible at the top right.

with sufficient intensity to generate overtopping of the barrier. There may be some cyclicity present, related to cycles in storm-event frequency, and this will also be the case in the Great Lakes environment. However, because storms with a return frequency in the order of 1–3 times per year can produce overwash during the peak of the lake-level cycle, extensive overwash of the barrier is essentially a certainty during this period, and in fact it is likely that there will be several overwash events during a 2 or 3 year period. Conversely, during the low-level phase, even the most intense storm will generate overwash over only a very few highly vulnerable points. Thus, as water levels fall from the peak of the cycle, the washovers enter the passive phase simultaneously, and the processes related to washover healing (Cleary and Hosier 1979) can be expected to continue largely without interruption until the beginning of the next high-level phase.

The essential features of the overwash cycle developed for Long Point should be applicable to other barrier features in the Great Lakes, most notably on lakes Erie and Huron–Michigan, where the magnitude of the long-term cycle is greatest and where there is limited regulation. It is clear that the long-term lake-level cycles are an important control on the dynamics of all sandy beaches and barriers in the lakes, and these effects have been explicitly recognized, for example, in relation to the movement of nearshore bars (Hands 1983), to foredune development (Olson 1958; Saunders and Davidson-Arnott 1991), and in the dynamics of wetlands vegetation (Keddy and Reznicek 1986). Recognition of the overwash cycle depicted here as part of the dynamic response of the barrier to the long-term water-level cycle is thus an important element in developing management strategies for Great Lakes shorelines.

The absence of tides means that the impact of a particular storm is not influenced by timing with relation to the diurnal tidal cycle or the 2 week lunar cycle of spring and neap tides, as it is on marine coasts. In contrast, the seasonal variations in water level do have some influence on the magnitude of storm impact. Water levels during late March and April are 0.10–0.15 m lower than in May and June, and thus this tends to reduce the potential impact of spring storms. More importantly, water levels in the fall are also generally well below the midsummer peak, and this again tends to reduce the impact of storms during this season. However, in many years there is a secondary maximum in lake levels in November and December due to increased runoff during this period, and thus overwash events often occur at this time, just before freezeup.

Although Lake Erie is a fetch-limited environment, storms there generate significant wave heights well over 2 m, and the shallow depth results in surges that can exceed 2 m. Thus, conditions during overwash of the barrier are of comparable

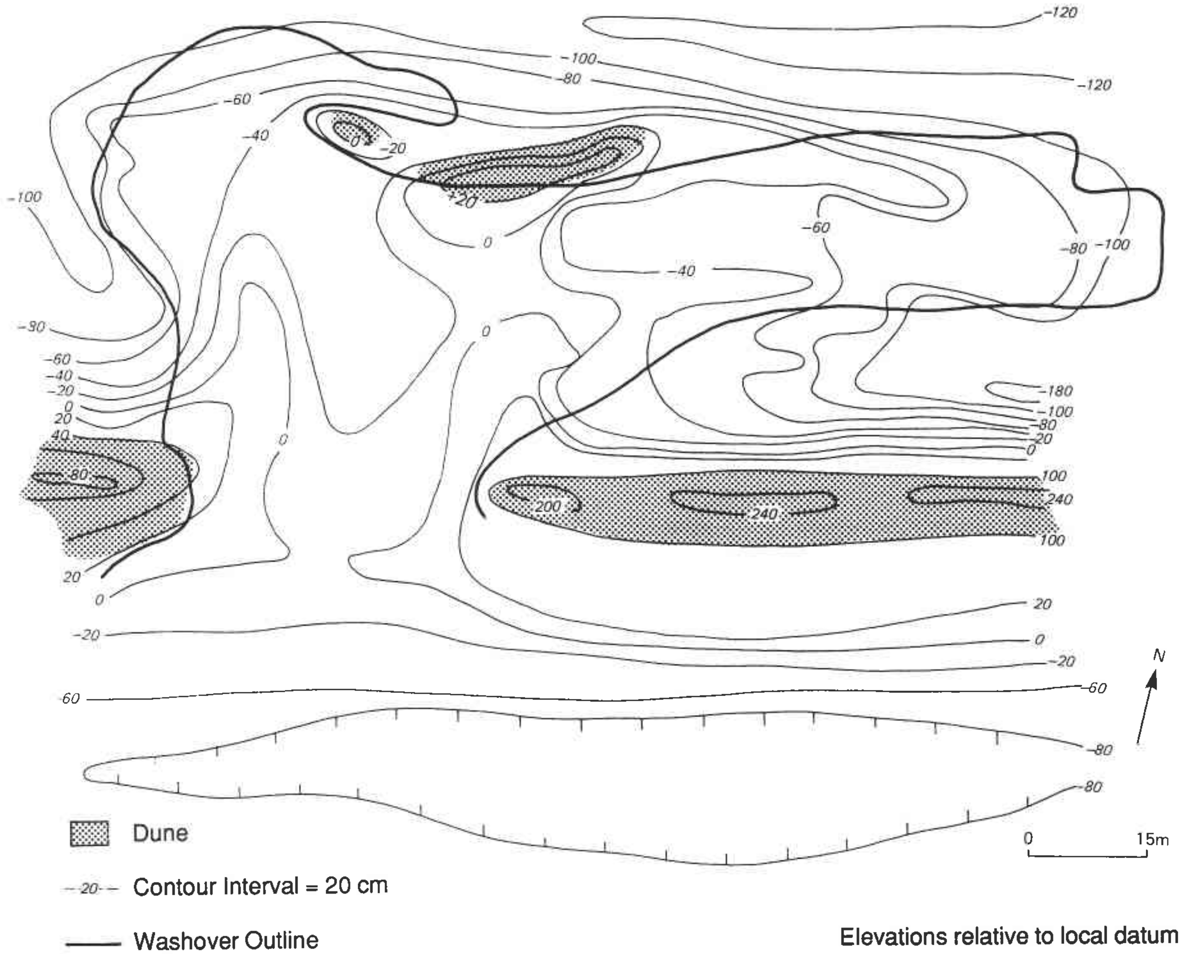


FIG. 14 (*concluded*). (B) Contour map of WSS3 based on a survey of May 13, 1987.

magnitude to those experienced on the barrier shorelines of the United States and the Gulf of St. Lawrence. Actual overwash was observed on only a couple of occasions during this study, and then consisted only of minor overtopping of the berm crest during small storms. However, evidence from site visits and overflights within days of major overwash events suggests that overwash processes and the morphology and sedimentology of the washover deposits are similar to those described from barrier systems in the Gulf of St. Lawrence (Armon 1979; Atkinson 1986) and from the east coast of the United States (Schwartz 1975; Leatherman *et al.* 1979; and many others). Washover-fan sediments consist almost entirely of the two facies recognized by Schwartz (1975): *horizontal stratification facies*, which was found over most of the fan surface and within the washover throat; and *delta-foreset facies*, which was found near the margins of washover fans where deposition took place into standing water in the bay or in interdune ponds.

The spatial pattern of overwash occurrence reflects the zonation of Long Point into a narrow, transgressive proximal end and a wide, progradational distal end. This is typical of most flying spits (e.g., Carter 1988, p. 278) and arises from the fact that as the spit progrades, the proximal portion becomes sheltered from waves that tend to counter the net sediment transport towards the distal end. The negative sediment budget that then develops in the proximal zone leads to transgression of the barrier through aeolian processes, overwash, and inlet formation. This pattern is characteristic of other large barrier spits in the Great Lakes (e.g., Presque Isle on the south shore of Lake Erie; Toronto Island in Lake Ontario) and has been described for many marine spits. In extreme cases breaching of the proximal zone may lead to complete detachment as has been described for Spurn Head in England (deBoer 1964).

Landward sediment transfer leading to barrier transgression takes place primarily through three mechanisms: (*i*) sedimentation on flood tidal deltas of both ''permanent'' and temporary tidal inlets; (*ii*) deposition on washover fans, including direct overwash sedimentation and secondary deposition related to aeolian sediment transport through the washover throat; and (*iii*) aeolian transport from the beach and shoreward face of the foredune and deposition on the lee slope and back-barrier surface. A number of studies of barriers on marine coasts have examined the relative significance of these in effecting barrier transgression (e.g., Pierce 1969; Armon and McCann 1979; Fisher and Simpson 1979). There are no permanent tidal inlets on Great Lakes barriers, but inlet breaching does occur at Long Point (Fig. 3B), and some landward sediment transfer occurs through the infilling of these inlets and development of features similar to flood tidal deltas. However, the length of shoreline breached by inlets is small compared with that characterized by washover fans, and rapid closure and absence of true tidal flow prevent the accumulation of large volumes of sediment. Thus, it seems likely that the overall contribution of inlets to the transgression, though

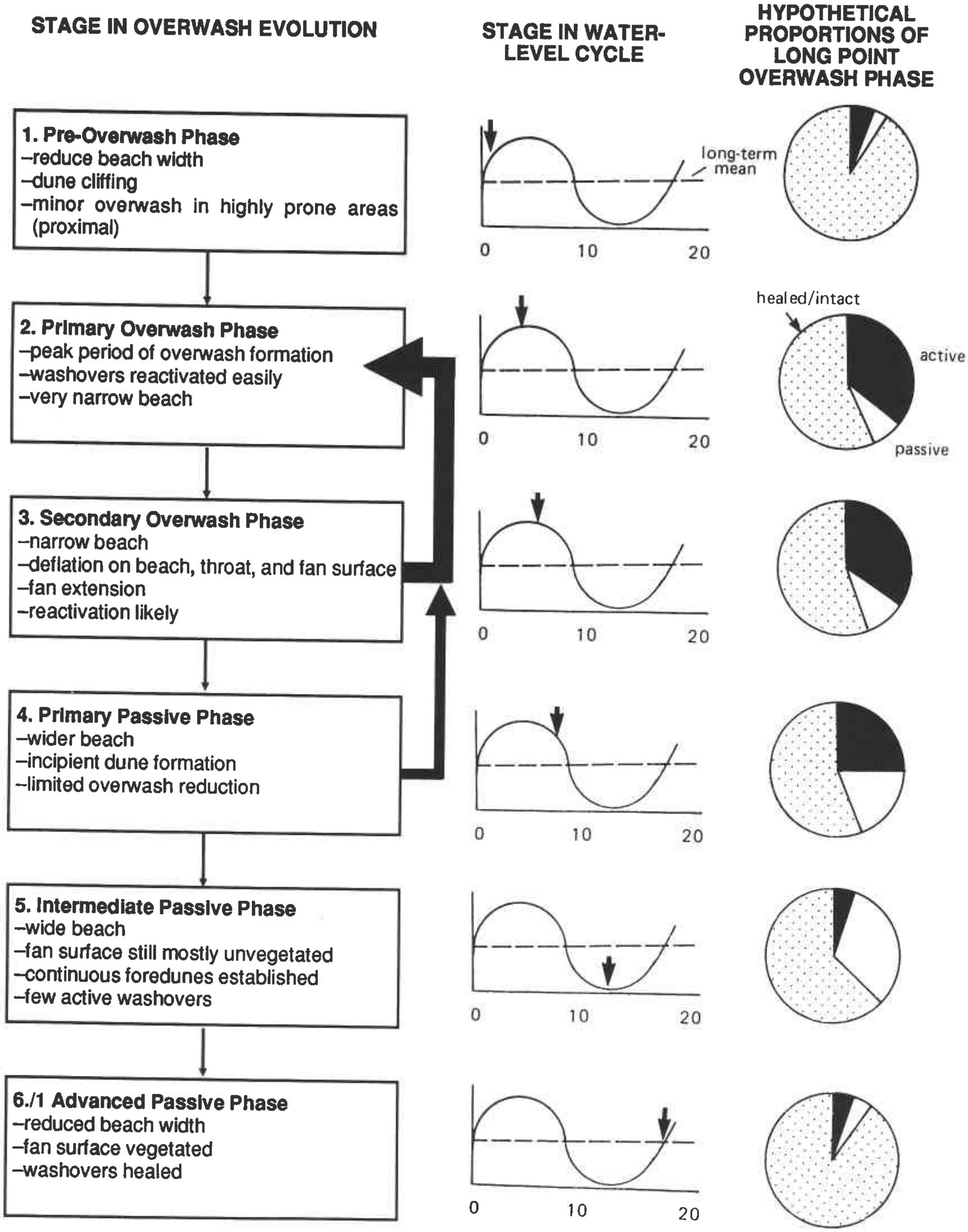


FIG. 15. Schematic model of overwash occurrence on Long Point in relation to the long-term lake-level cycle. See text for explanation of each of the stages of the model.

not insignificant, is small relative to overwash and aeolian processes.

Both prevailing and dominant winds are onshore at Long Point, in contrast with many of the barriers of the Gulf of St. Lawrence and the United States east coast, and the role of aeolian processes in landward sediment transfer appears to be correspondingly more significant. Measurements of sediment deposition in the foredune (Davidson-Arnott and Law 1990; Law and Davidson-Arnott 1991) show that aeolian sediment transport from the beach is on the order of 3–5 $m^3 \cdot year^{-1}$ per metre length of shoreline and that considerable volumes of sediment are transported over the foredune, particularly during the winter and early spring. Saunders and Davidson-Arnott (1991) showed that scarping of dunes during a high-water phase leads to destabilization of the foredune for a number of years during which time there is extensive blowout development, and large volumes of sediment are transported from the beach and the shoreward face of the dune onto the back barrier. Other evidence of aeolian activity comes from repeated surveys of profiles across the foredune at a number of sites for this study and for the studies noted above. Thus, although no detailed sediment-budget calculations have been made, these observations and measurements all suggest that the volumes of aeolian sediment transport are of the same order of magnitude as those involved in overwash sedimentation.

Finally, the proximal zone at Long Point contains a large cottage community, marinas, and a provincial park, which are all vulnerable to the effects of overwash during the high-water phases. Indeed, during the December 2, 1985, storm some 40 cottages, mostly at the western end of the community, were destroyed and many others damaged as a result of overwash. The sediment budget in the vicinity of the cottages and provincial park appears to be only slightly negative, and the presence of some small sandwaves does offer protection to the shoreline (Stewart and Davidson-Arnott 1988). However, since 1985 there has been considerable foredune erosion in this area, leading to increased shore-protection construction by cottagers. The presence of the cottages and shore protection has prevented new embryo dune development and rebuilding of the foredune, and this has increased the vulnerability of the shoreline to overwash during the next high-water phase. It is evident from the results presented here that continued transgression of the barrier in this zone will occur. It is imperative, therefore, that management plans be developed to mitigate the impact of this, while at the same time to recognize the need for overwash to continue in order to retain the dynamic stability of the barrier.

Conclusions

The major conclusions of this study can be summarized as follows:

(1) Overwash processes and washover morphology and sedimentology at Long Point are similar to those found on barrier systems on marine coasts.

(2) Overwash occurs primarily in the proximal and central zones of the spit, and this is a reflection of the negative sediment budget that is characteristic of these zones on all spits.

(3) Overwash and washover-fan evolution are controlled primarily by the long-term cycle of lake levels in the Great Lakes. Almost all overwash occurs during the few years of peak water levels, and most washovers will be reactivated several times during this period. The low-water phase of the cycle is characterized by washover healing and rebuilding of a continuous foredune ridge.

(4) Overwash plays a significant role in transgression of the proximal portion of the spit, and volumes of sediment transfer are likely of the same order of magnitude as that through aeolian processes.

(5) The cottage community at Long Point is located in a zone that is highly vulnerable to overwash, and extensive damage is likely to occur during the next high-level phase.

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