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Low-energy Morphodynamics of a Ridge and Runnel System

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ABSTRACT

A field experiment was carried out over a period of five weeks on an intertidal ridge and runnel system on the Northumberland Strait coast of Nova Scotia, Canada. The area is microtidal with a spring tidal range of just under 2 m. The main purpose of the research was to examine the effects of changing water depth and bar emergence on the morphodynamics of the system and to determine the controls on the stability of the ridges during non-storm conditions. The system is developed on a gently sloping platform over 300 m wide at spring low tide with an average gradient of 0.004. It is characterised by the presence of 5 or 6 ridges in the intertidal zone and 2 bars in the subaqueous zone. The ridges are 0.35-0.50 m in height, 50-60 m in wave length, and the continuity of the ridges alongshore is broken by drainage channels. The system at Linden Beach is similar to others that have developed in a number of areas along this coast on platforms resulting from recession of relatively weak sandstone cliffs. Topographic surveys were carried out along 10 profiles spaced 25 m apart using a total station and the position of the ridge crests and troughs was also mapped using a GPS system. Measurements of wave transformation, water motion and suspended sediment concentration over individual tidal cycles were carried out along a profile across the second ridge and associated troughs using electromagnetic current meters, resistance wave staffs and OBS nephelometers. There were no major storms during the monitoring period but there were a number of days with significant wave heights >0.4 m and the measurements spanned the full range from neap to spring tides. During the five week period the ridge crests exhibited a high degree of stability with maximum movement <5 m. The effects of tidal currents were isolated through measurements made during calm conditions with light winds. Measurements indicate that wave shoaling and breaking across the ridge crest at mid to high tide have the potential to transport large quantities of sediment landward and thus to induce landward migration under non-storm conditions. The stability of the bars appears to be controlled by a combination of offshore flows across the bar crests due to undertow and tidal currents near high tide, and through the transport of sediment alongshore in the troughs and offshore in the drainage channels on the ebb tide. The dynamics of the system more closely resembles that of sub-tidal multiple parallel bars than that of intertidal swash bars.

ADDITIONALINDEXWORDS: *Intertidal zone, swash bars, nearshore bars, non-storm waves, tidal currents*

INTRODUCTION

Sand bar systems acted on by waves and wave-generated currents, are found along many sandy coasts in a wide range of environments and the morphology of the bars assumes a variety of configurations in which the form, size and number of bars vary (GREENWOOD and DAVIDSON-ARNOTT, 1979; AAGAARD and MASSELINK, 1999). The morphological and dynamic characteristics of the bar systems vary spatially as a function of controls such as nearshore slope, sediment characteristics, wave climate and tidal range and they vary temporally at any location in response to changing wind and wave conditions, and water levels (SHORT, 1978; GREENWOOD and DAVIDSON-ARNOTT, 1979; WRIGHT AND SHORT, 1984; DAVIDSON-ARNOTT, 1988; LIPPMAN and HOLMAN, 1990; SHORT and AAGAARD, 1993; LEE *et al*., 1998; RUESSINK *et al*., 2000). Bars are generally absent from sandy coasts dominated by low swell waves and where strong onshore winds and short period storm waves are rare (e.g. most low latitude coasts), and they may be seasonally absent as a result of onshore sediment transport and bar migration during prolonged periods without storms (SHEPPARD, 1950; WRIGHT AND SHORT, 1984; LEE *et al*., 1998).

In effect the many attempts at classification and development of conceptual models of bar systems (and non-barred conditions) all implicitly assume that it is possible to define a characteristic or equilibrium bar morphology that is largely determined by a few controlling variables. Furthermore, it may be possible to quantify the limits on the occurrence of some bar systems based on some simple quantitative expressions that make use of the variables identified above. Thus, WRIGHT and SHORT (1984) introduced the dimensionless fall velocity parameter (Ω) to characterize the beach profile:

$$\Omega = \frac{H_b}{W_s T} \tag{1}$$

where H_b is breaker wave height (m), W is sediment fall velocity (ms^{-1}), and T is wave period (s). They found that when Ω<1 beaches tended to be steep and barless, when Ω>6 they tended to be flat, dissipative and multi-barred and where Ω = 2-5, they were intermediate between the two end member types and were characterized by one or two bars. The three classes were originally defined primarily to microtidal beaches in eastern Australia. The effects of tidal range were later incorporated through the relative tidal range parameter RTR (MASSELINK and SHORT, 1993):

$$\text{RTR} = \frac{TR}{H} \tag{2}$$

where TR is the tidal range (m) and H is the wave height (m). This parameterisation thus assumes that the role of tidal range and processes associated with tidal currents will become increasingly significant in determining the form of features in the intertidal zone as the tidal range increases relative to wave height. MASSELINK and SHORT (1993) recognized three profile types associated with high tidal ranges - low tide terrace, low tide bar/rip and ultra dissipative with no bars, corresponding to the reflective, intermediate and barred dissipative of microtidal coasts.

SHORT and AAGAARD (1993) introduced a bar parameter (B*) to predict the number of bars on a nearshore profile:

$$B^* = \frac{x_s}{gT^2 \tan\beta} \tag{3}$$

where xs is the distance from the shoreline to a constant depth. The formulation is based on the premise that standing infragravity waves are responsible for the formation of the bars. SHORT and AAGAARD suggested that no bars occurred for values of B* < 20 and that 1, 2, 3 and 4 bars were associated with values of 20-50, 50-100, 100-400 and > 400 respectively.

Where the nearshore profile is developed entirely in sand the form and nearshore slope may be determined primarily by the interaction between wave characteristics and sediment size. However, in many areas the sand in which the bar systems form may be developed in a layer overlying a hard substrate of clay or bedrock, and in this case the beach profile may be controlled in part by the substrate slope. In these areas slope then becomes a significant control on bar development (DAVIDSON-ARNOTT, 1988; SHORT and AAGAARD, 1993) and it may also be an important determinant of the width of the intertidal platform. Thus, while macro tidal coasts can generally be expected to have a wide intertidal platform, relatively wide platforms can also occur on micro tidal coasts where the profile is very gentle and tidal processes and changes in water depth can be expected to play a significant role in controlling the morphodynamics of that intertidal zone.

While much of the focus over the past three or four decades has been on bar systems that are found primarily in the nearshore or sub-tidal zone, it is also recognized that some bars are found in the intertidal zone and are thus partly or wholly exposed during periods of low tide. Indeed some of the earliest work on bars was carried out on intertidal bars on Blackpool Beach, England (KING and WILLIAMS, 1949) and they used the term ridge and runnel to distinguish these intertidal bars from those found in the sub-tidal zone. In the classification system of GREENWOOD and DAVIDSON-ARNOTT (1979) these were grouped as Type 1 bars. The intertidal profile described by KING and WILLIAMS consisted of 2-6 bars with intervening troughs aligned roughly parallel to the shoreline and broken in places by drainage channels. Similar features have been described from a number of other locations in Britain and western Europe (KING, 1982; KING and BAINES, 1964; PARKER, 1975; MULRENNAN, 1992; VOULGARIS et al., 1998) as well as the west coast of Canada (HALE and McCANN, 1982) and the Queensland coast of Australia (MASSELINK and TURNER, 1999, Fig. 8.16f). These bars are found generally in meso to macro tidal areas where there is a wide intertidal zone and where the fetch length is relatively short. They appear to form in the intertidal zone itself, rather than migrating into it from offshore. While studies have shown that the number and position of the bars responds to changes in wave conditions and over the spring-neap cycle, as do similar bars in the nearshore zone, they appear in most instances to be a constant feature of the intertidal zone equilibrium profile (KING and WILLIAMS, 1949; PARKER, 1975; MULRENNAN, 1992), and they do not migrate landward and weld onto the swash slope or berm.

Another form of bar and trough system, also termed ridge and runnel by a number of authors, is commonly found in the intertidal zone (DAVIS et al., 1972; DABRIO and POLO,1981; MICHEL and HOWA, 1999). These bar systems are generally characterized by the presence of a single bar and trough in the intertidal zone which is often attached to the shoreline and rhythmic in form alongshore. They initially form in the subtidal zone during and immediately after a storm and may migrate onshore onto the low tide terrace under the influence of low waves following a storm. They thus form a part of the cycle of erosion of the upper beach during a storm and post-storm beach recovery and berm building due to the collective onshore migration of sand bars and welding to the beach face. This process has been described from many parts of the world, including: the Great Lakes (DAVIS and FOX, 1972; DAVIS *et al*., 1972; STEWART and DAVIDSON-ARNOTT, 1988), western Europe (VAN DEN BERG, 1977; DABRIO, 1982; AAGAARD *et al*., 1998), Australia (SHORT, 1978; WRIGHT AND SHORT, 1984), and the east and west coasts of North America (DAVIS *et al*., 1972; OWENS and FROEBEL, 1977). A number of studies have emphasized the role played by swash bores in transporting sediment across the bar crest and onto the landward dipping slip face when the water depth over the crest is small (DAVIS *et al*., 1972; VAN DEN BERG, 1977; DABRIO and POLO, 1981) and the bars are sometimes referred to as swash bars (AAGAARD *et al*., 1998). This form of intertidal bar is often highly rhythmic alongshore with the troughs leading into well-defined rip channels that may be perpendicular or oblique to the shoreline. In the Australian beach state model (WRIGHT AND SHORT, 1984; MASSELINK and SHORT 1993), the form is associated with the Low Tide Bar/Rip state and the role of flows in the rip current channels under low wave conditions is well-documented (AAGAARD *et al*., 1997).

There are clear differences in the numbers, morphology and stability of the two types of intertidal bar systems when comparisons are made between selected sites and there have been arguments made for distinguishing between the stable (British) form of ridge and runnel as described by KING and WILLIAMS (1949) and the ephemeral (North American) form described by DAVIS *et al*. (1972) - e.g. ORFORD and WRIGHT (1978), ORME and ORME (1988), and MULRENNAN, 1992. It is not clear whether the two types are end members of a continuum of forms that reflect variation in controls such as the intertidal slope, width of the intertidal zone, and wave climate, or whether they reflect more fundamental differences in the mechanisms controlling fluid and sediment motion.

There are a number of studies of the morphodynamics of ridge and runnel systems as defined by the North American terminology, or alternatively the Low Tide Bar/Rip state of MASSELINK and SHORT (1993). However there have been relatively few studies of the dynamics of intertidal bars that resemble the original (British) definition (HALE AND McCANN, 1982; SIMMONDS *et al*., 1995; VOULGARIS *et al*., 1998; STÉPANIAN *et al*., 2001). These studies have documented some aspects of flow and sediment transport associated with systems with multiple ridges and they emphasize both the role of tidal fluctuations and of wave-induced swash-surf and undertow processes. Nevertheless, there is a need for further work on these features to clarify the nature of the morphodynamic processes, especially the relative significance of waves, water level fluctuations due to tides and tidal currents, as well as the apparent stability of the features under non-storm conditions.

This study reports on a field experiment carried out primarily over a period of six weeks from May 03 to June 16, 2000 on a system of intertidal bars at Linden Beach on the Northumberland Strait, Gulf of St. Lawrence, Canada. The overall purpose of the study was to measure and describe the effects of changing water depth and bar emergence on tidal currents, waves and sediment transport over one of the bars and associated troughs, and to determine the morphological response of the bar system to a range of wave conditions. No major storms occurred during the study period and thus the focus of this paper is on assessing the controls on bar stability during non-storm conditions.

STUDYAREA

Ridge and runnel intertidal bars are characteristic of a number of reaches of the coasts of New Brunswick, Nova Scotia and Prince Edward Island along the Northumberland Strait, Canada (OWENS and BOWEN, 1977). The eastern portion of the Northumberland Strait is suitable for ridge and runnel development due to the presence of a wide, gently sloping intertidal and nearshore zone, moderate supply of sediment, and low-energy wave climate. An aerial reconnaissance of Nova Scotia's north shore indicated the systems were characterized by the presence of 2-10 ridges in the intertidal zone, broken alongshore by the presence of drainage channels orientated perpendicular to the shoreline, and by 1-2 generally linear bars in the subtidal zone (DAWSON, 2001). The selected study site located at Linden Beach, Nova Scotia is generally representative of other systems in the area (Figure 1).

The Northumberland Strait comprises the southern portion of the Gulf of St. Lawrence and lies between Prince Edward Island and the mainland of New Brunswick and Nova Scotia (Figure 1). The Strait was formed by pre-glacial erosion that separated the resistant bedrock upland that is now Prince Edward Island from the mainland. The bedrock of the Strait is comprised of relatively weak Upper Carboniferous and Permian sandstones and mudstones overlain by a thin unit of glacial drift (OWENS and BOWEN, 1977). Beach sediments are derived from reworked bottom sediments, erosion of coastal cliffs and small inputs from rivers. These sediments are fine- to medium-grained sands and availability is considered scare compared to other regions in the Gulf of St. Lawrence.

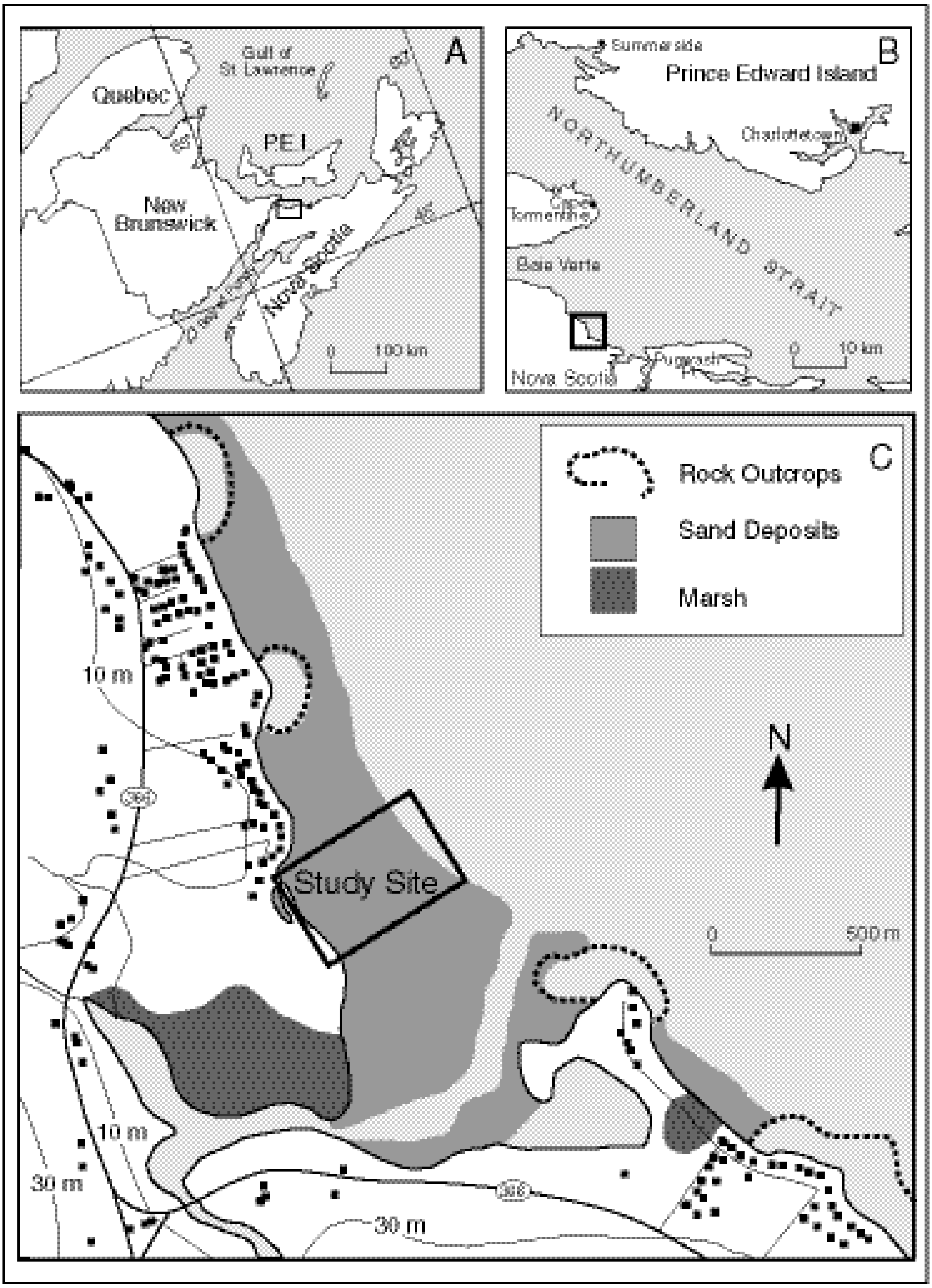

Figure 1. Location of the study site.

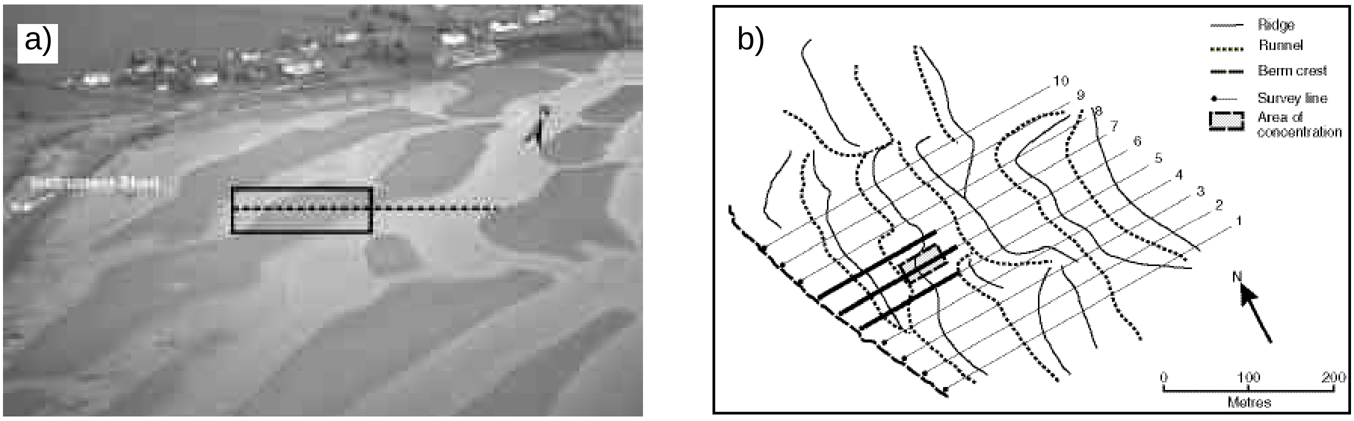

Figure 2. a) Oblique aerial photograph of Linden Beach taken on May 27, 2000 at about quarter tide. The two most offshore intertidal bars are submerged. The location of the primary study area on the second ridge is outlined; b) map of study site based on a differential GPS survey showing location of survey lines, primary study area and position of the main intertidal ridges and runnels.

Linden Beach is located in the eastern half of the Northumberland Strait in a small embayment drained by a tidal inlet and protected by two headlands (Figure 1, 2). The ridge and runnel system occurs on a wide coastal shelf with an average intertidal slope of 0.004. The system is comprised of 5 to 6 ridges in the intertidal zone and 2 bars in the subtidal zone (Figure 2a). Sediment samples taken across the system indicate that sediment is composed of fine to medium well-sorted sand (average size 0.28 mm) with a small, spatially variable silt/clay component averaging about 1% on the bars and 2% in the troughs. The cliffs and low barrier that forms the beach are retreating at a rate on the order of 0.2-0.3 m yr^{-1} in response to erosion of the cliffs and nearshore, and to sea level rise.

Linden Beach is affected primarily by waves generated within the Northumberland Strait, and is largely protected from waves generated within the larger Gulf of St. Lawrence by Cape Tormentine on the mainland to the west and by western Prince Edward Island (Figure 1). Maximum fetch is about 70 km and the fetch window is roughly equal about shore perpendicular. The closest Meteorological Service of Canada weather monitoring station is located approximately 80 km west of Linden Beach across the Strait at Summerside, Prince Edward Island (Figure 1b). Prevailing winds are offshore from the west and south-west, and large waves affecting the area occur during the passage of depressions bringing winds from the north-east quadrant.

The Northumberland Strait is a microtidal environment with spring high tides at Linden Beach occasionally exceeding 2 m and the tidal regime is mixed semi-diurnal. While ridge and runnel systems are generally associated with meso- and macrotidal areas, their occurrence here results from the very low angle platform on which the bars are developed which gives rise to intertidal areas that may exceed 400 m at spring low tide.

METHODS

The morphology and morphologic change of the bar system was measured over an area extending 225 m alongshore and measurements of waves, currents and sediment dynamics were made over a smaller area encompassing a portion of the second offshore ridge and associated troughs (Figure 2a, b). Ten shore perpendicular lines were established at 25 m intervals and surveyed offshore to the limit of wading at spring low tide (350-500 m) on three occasions between May 3 and June 16 in order to measure the morphological characteristics of the bar system and to identify changes over the study period (Figure 2b). Additional surveys of lines 5-7 out to a distance of 130 m offshore, encompassing the smaller instrumented area, were carried out on six occasions between May 13-25. Surveys were conducted with a Leica TC600 total station using standard survey techniques and tied to a local benchmark at the back of the beach. A Trimble Pathfinder Pro XR Global Positioning System with submetre accuracy was used to map the shoreline and features on the beach and back barrier as well as the positions of the bar crests, troughs and main drainage channels (Figure 2b). Additionally, a series of erosion rods were placed in a 5m x 5m grid covering an area of 40 m offshore and 20 m alongshore in the instrumented area of the second bar and troughs. The height of the rods above the bed was measured with a metre stick at low tide on 17 occasions including before and after measurements of flow and sediment dynamics.

Individual experiments incorporating measurements of winds, waves, water elevation, water motion and suspended sediment concentration were made over a complete tidal cycle on a number of occasions. Wind speed and direction were measured with a wind vane and anemometer mounted on a 2m high pole at the top of the beach. Wave characteristics were measured using 3 resistance-type wave staffs set up over the crest and landward trough of the second bar (Figure 2b). The staffs were calibrated at the site in a stilling well and are highly linear over their complete length. Flow velocity was measured using bi-directional Marsh-McBirney electromagnetic current meters. Four Model 512 current meters with 4 cm diameter heads were deployed along a line over the bar and landward trough and one Model 551 current meter with a 10 cm diameter head was deployed in the seaward trough. The current meters were calibrated in a small towing tank at the University of Guelph following the experiment. Suspended sediment concentration was measured with three D&A Instruments Model OBS-3 probes. No direct calibration of the OBS probes was carried out, in part because of the uncertainties introduced by the presence of silt in the water column during periods of wave activity. However an indirect conversion of the voltage output to suspended sediment concentration was made using a calibration curve derived by GREENWOOD and JAGGER (1995) for well-sorted sand with a mean grain size of 0.25 mm (compared to 0.28 mm for the study site) using the same instrument gain. Previous calibrations of the instruments with medium sand produced very similar curves.

In order to link the measurement of flow velocity to the amount of sediment in suspension, three of the Model 512 current meters were co-located with OBS probes. Both instruments were clamped to a horizontal brass bar held upright at 0.15 m above the bed by 2 poles secured in the bed. The remaining Model 512 current meter was individually secured in a similar format. Finally, the Model 551 current meter was co-located with a Sensit pressure transducer in the farthest offshore location to provide a general idea of incoming flow velocity with a simultaneous measurement of water depth. The location of each instrument relative to the ridge and associated runnels is indicated in Figure 5d. All instruments were hard wired to a small instrument hut set up at the top of the beach.

Experiments were conducted over individual tidal cycles for the period of time from when the instruments were submerged until they became emergent. This period varied from 6 to 8 hours depending on the position within the spring-neap cycle. Within each experiment a series of runs were performed, at roughly10 to 15 minute intervals. Data were collected at 4 Hz for either 4.26 or 8.53 minutes (1024 or 2048 data points) on a personal computer using the EasyAG™ data acquisition program.

RESULTS

System morphology and stability

The intertidal bar system consisted of five or six bars and associated troughs formed on an intertidal zone about 350 m wide at spring low tide. A further two bars are found in the sub tidal zone and are similar in form and spacing to those in the intertidal system. The bars occur on a gently sloping platform (average slope 0.004) and are formed in a relatively thin cover of sand overlying a rock platform resulting from erosion of the low sandstone and mudstone cliffs. The upper part of the intertidal zone consists of a steep berm about a metre high with a seaward slope of 0.05 and which grades into the low dunes of the barrier on its landward side. There is an abrupt junction between the swash slope and the intertidal platform on which the bars are developed. The plan form of the bars can be seen in the oblique aerial photograph of the system (Figure 2a) and from the GPS survey of the bar crests and troughs (Figure 2b). The bars are broken in places alongshore by drainage channels and their orientation changes somewhat from east to west as a result of changes in the shoreline configuration. The profile form of the bars is illustrated from three surveys of profile 5 (Figure 3a) and the general characteristics of the system based on a survey carried out on May 03, 2000 are given in Table 1. The bars range in height from about 0.35-0.5 m and have a wavelength of about 50-60 m (Table 1). Bar height does not appear to change significantly with distance offshore and there is only a slight tendency for an increase in the spacing.

Table 1. Morphometric characteristics of the intertidal bar system at Linden Beach based on a survey of the ten lines carried out on 03/05/00.

Ridge No.	Height (m)	wavelength (m)	shoreward slope	Seaward slope
1	0.42 ( )	50 ( )	0.027 ( )	0.015 ( )
2	0.38	54	0.016	0.017
3	0.49	55	0.021	0.017
4	0.42	59	0.024	0.015
5	0.35	61	0.014	0.013
6	0.39	50	0.014	0.018
all	0.41	59	0.019	0.016

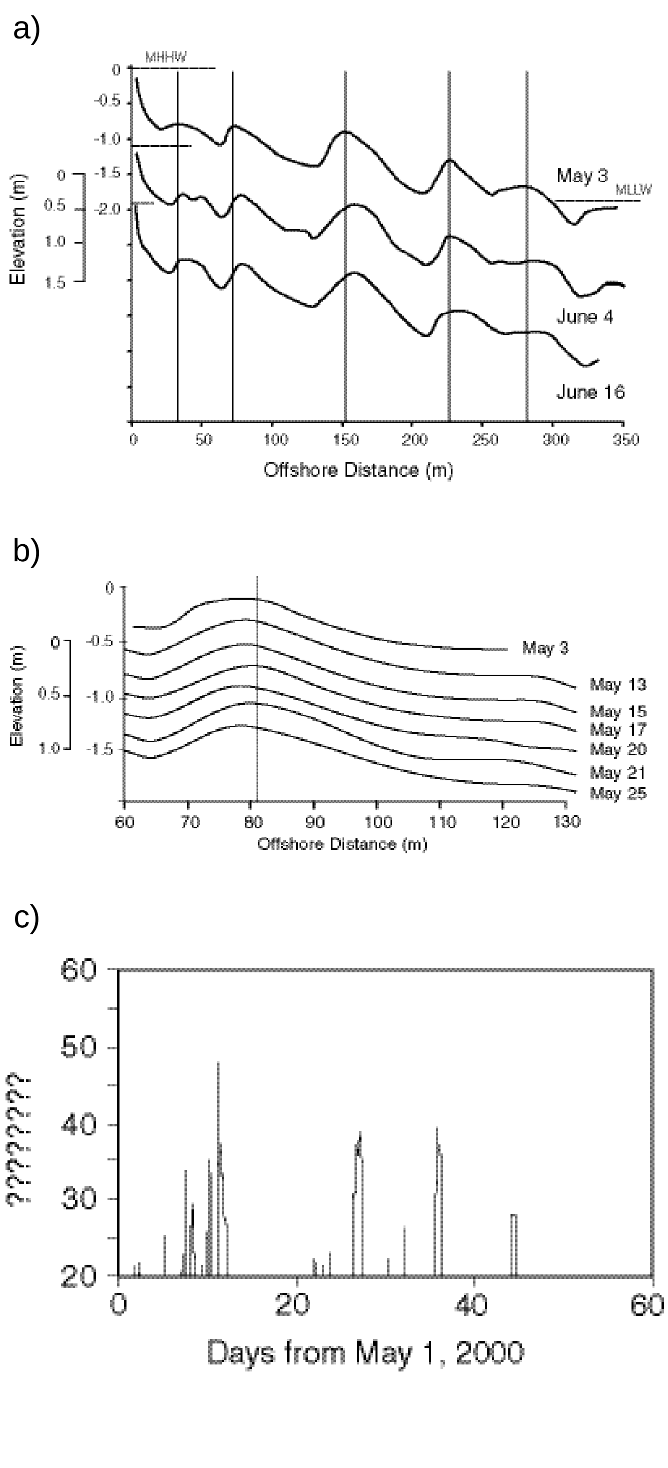

Figure 3. a) Profile of line 5 (see Fig. 2b) surveyed on 03/05, 04/06 and 16/06, 2000; b) sweep zone of line 5 over the second bar and associated troughs based on 9 surveys over the study period; c). Incidence of onshore winds exceeding 20 kph over the period 05/01-06/15 measured at the meteorological Services of Canada station at Summerside, Prince Edward Island.

Surveys of the whole system over the period 05/03 to 06/15 showed only minor changes in the form and position of the bar topography (Figure 3a). During this time there were no major storms, but winds recorded at Summerside, Prince Edward island showed a number of periods with winds exceeding 20 kph from directions that are onshore at Linden Beach and which could be expected to produce significant wave heights >0.5 m (Figure 3c). Between May 3rd and June 4th the bar crests generally moved offshore on the order of 5-8 m and this reflects somewhat greater wind activity recorded at Summerside (Figure 3c). Between June 4th and June 16 there was onshore movement on the order 2-4 m, except for the 5th bar which moved offshore. This coincided with a period with fewer incidences of strong onshore winds. There was much less movement of the position of the troughs and thus most of the change results from small changes in the position of the crest on the bar itself. Changes in the form of the second bar along the same line for the period May 3 to May 25 (Figure 3b) show the details of movement over this period.

Hydrodynamics

Measurements were carried out on six occasions over the study period. Data for May 12, 20 and 21, 2000 when measurements were obtained over the whole period during which the bars were inundated are described here. In general the bars are exposed and inundated during every tidal cycle, though the first bar is only covered to a shallow depth at neap high tide and the trough of the outer bar still maintains water during neap low tide. Currents are generated within the bar system by hydraulic gradients as water flows landward up the main drainage channels, such as the one located around line 10 (Figure 2b), and then along the troughs (runnels) on the rising tide and again as the water drains out of the system on the falling tide. In addition, as the troughs fill and the bars are covered with water, the system is also influenced by tidal flow into and out of the estuary to the east (Figure 1, 2a) and by general tidal circulation along the coast. Superimposed on the tidal influences are currents generated by wind and wave set-up as well as those due to the oscillatory motion of the waves, all of which will vary with the incident conditions and with the tidal stage. It was expected that sediment transport within the bar system would be influenced by the direct effects of wave shoaling and breaking across the bars, particularly on the rising and falling tides when water depth over the bars was small, as well as by the other mean flows.

Winds were light on May 21 and significant wave height <0.1 m. On May 12 and May 20 onshore winds produced significant wave heights over the second bar of 0.45 and 0.51 m respectively (Figure 4a, b). Thus the data from May 21 should reflect the effects of tidal inundation only, while the data from the other two days reflects the presence of

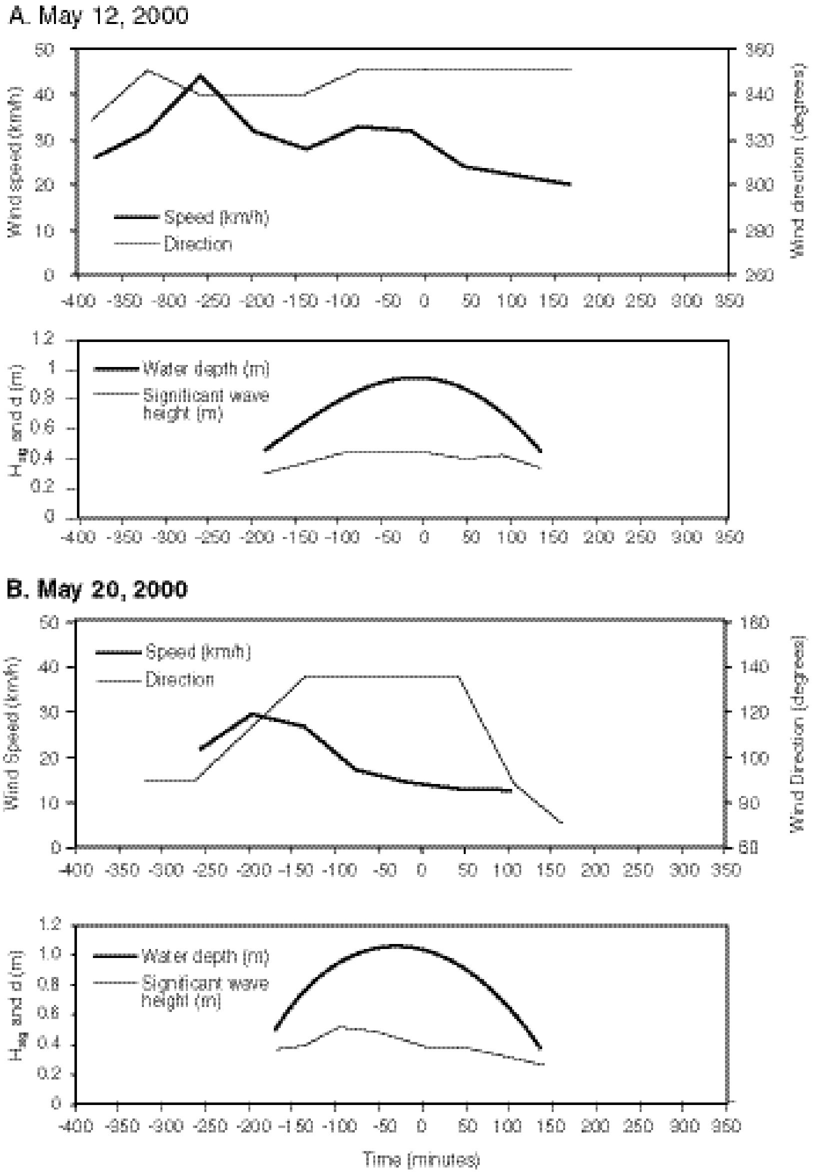

Figure 4. Wind speed and direction measured at Linden Beach and mean water depth and significant wave height measured at WS3 on the seaward side of the second bar on: a) May 21, 2000; b) May 12, 2000; and c) May 20, 2000.

winds and waves superimposed on the tidal inundation. Measurements on May 20 and 21 coincided with spring tides and those on May 12 with a neap tide.

Mean flows measured across the second bar and seaward and landward troughs over the three tidal cycles is illustrated in Figure 5. Flow vectors measured over the spring tidal cycle on May 21 when winds were light (Figure 5a) show mean flows generally <0.1 m sec^{-1} except for E-2 on the bar crest where there were higher flows just as the current meter was submerged and again as it emerged. In the landward trough (E-1) currents were very small and variable during the initial submergence, with flows generally low and directed northward along the trough over most of the rest of the period of inundation. Near the end of the ebb as the bar crest became emergent flows increased to about 0.1 m sec^{-1}. Flows on the flank of the bar (E-4) show a similar pattern with slightly higher velocities. Only in the seaward trough (E-5) is a distinct flow reversal observed, with southward flow up the trough during the early flood and northward flow towards the main drainage channel near the end of the ebb (Figure 5a). On the bar crest (E-2) flows are southeastward, obliquely offshore over much of the flood and weakly offshore during much of the ebb.

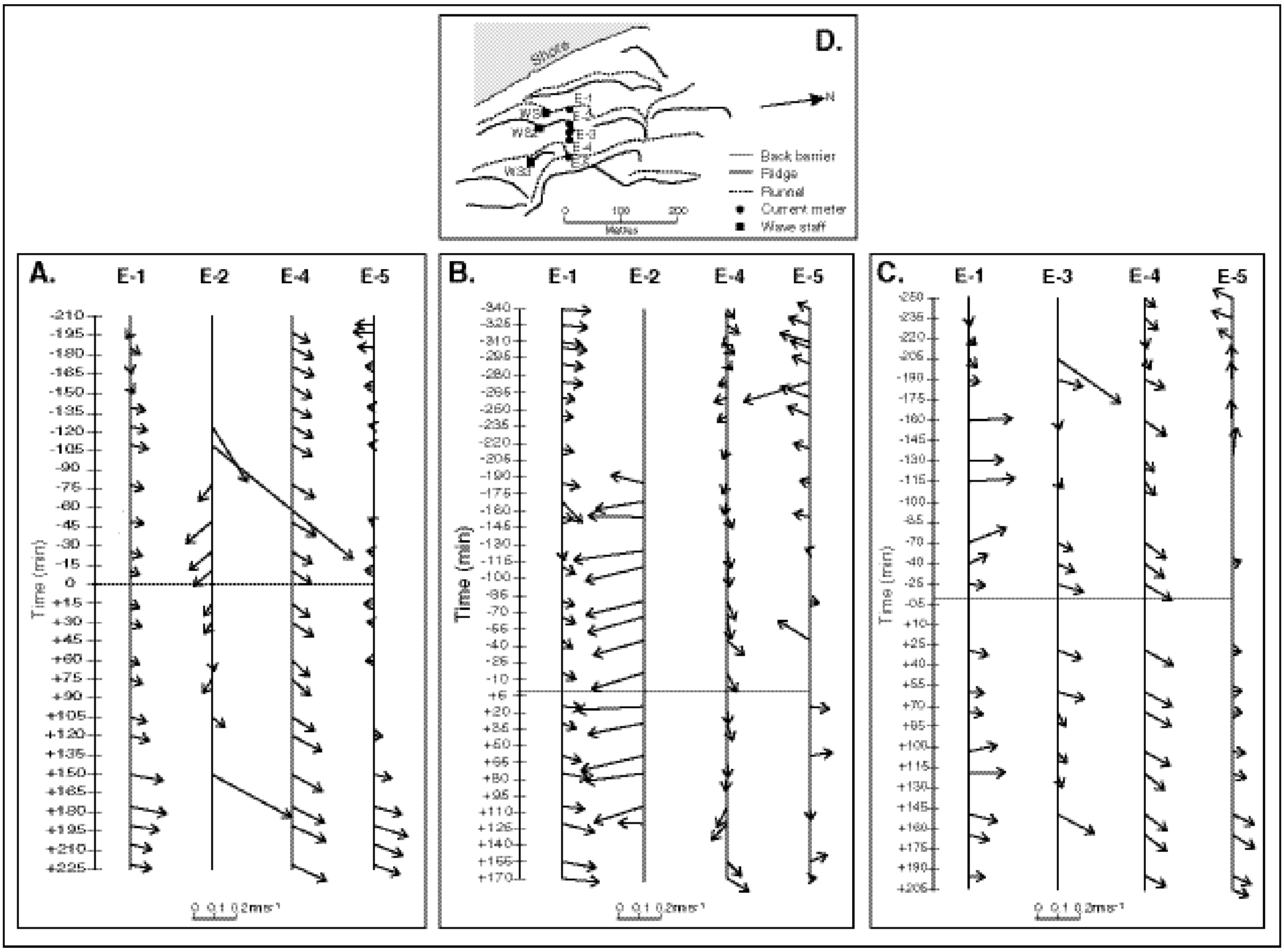

Figure 5. Mean flow vectors measured over the second bar on: a) Spring tide,May 21; b) Neap tide May 12; and c) Spring tide May 20. The time of the measurements is expressed relative to high tide. Winds were light on May 21 with significant wave height <0.1 m. Significant wave height measured over the bar at high tide reached 0.45 m on May 12 and 0.51 m on May 20. d) location of the instruments relative to the main bar crests and troughs.

Flow vectors on the days with onshore winds and waves show some differences from the pattern outlined above. On May 12 winds were from the north at speeds of 25-35 kph over much of the period of inundation, dropping to about 20 kph near the end of the ebb. Significant wave height ranged from about 0.3-0.45 m (Figure 4a). On May 20 winds were from the east and southeast with speeds around 20-25 kph during the rising tide but diminishing to 10-15 kph near high tide and during the falling tide (Figure 4b). Significant wave height measured on the seaward side of the bar ranged from about 0.3-0.5 m (Figure 4b). Flows in the landward trough (E-1) and on the seaward side of the bar and seaward trough (E-3 and E-4) are generally alongshore to the north and directed slightly offshore as they were under low wave conditions but are stronger in the presence of waves and the northward flow is more persistent over the whole period of inundation. The exception to this is at E-4 on May 12 when flow speeds were very low and primarily directed offshore (Figure 5b). The flow pattern is consistent with set-up landward of the breaker zone with flow in the trough being directed by the oblique orientation of the bar to the shoreline at this point. However, mean flows on May 12 on the bar crest (E-2) were directed primarily alongshore to the south and slightly offshore during the ebb. Flow speeds were much higher than during calm conditions on the 21st and this presumably reflects the effects of wave breaking on the bar crest. Flows at E-5 located in the seaward trough just north of a bifurcation in the bars shows a consistent pattern of flow reversal on all three days and appears to be least affect by wave action due to the greater water depth. Flows are generally onshore or alongshore to the south during the flood and alongshore to the north during the ebb.

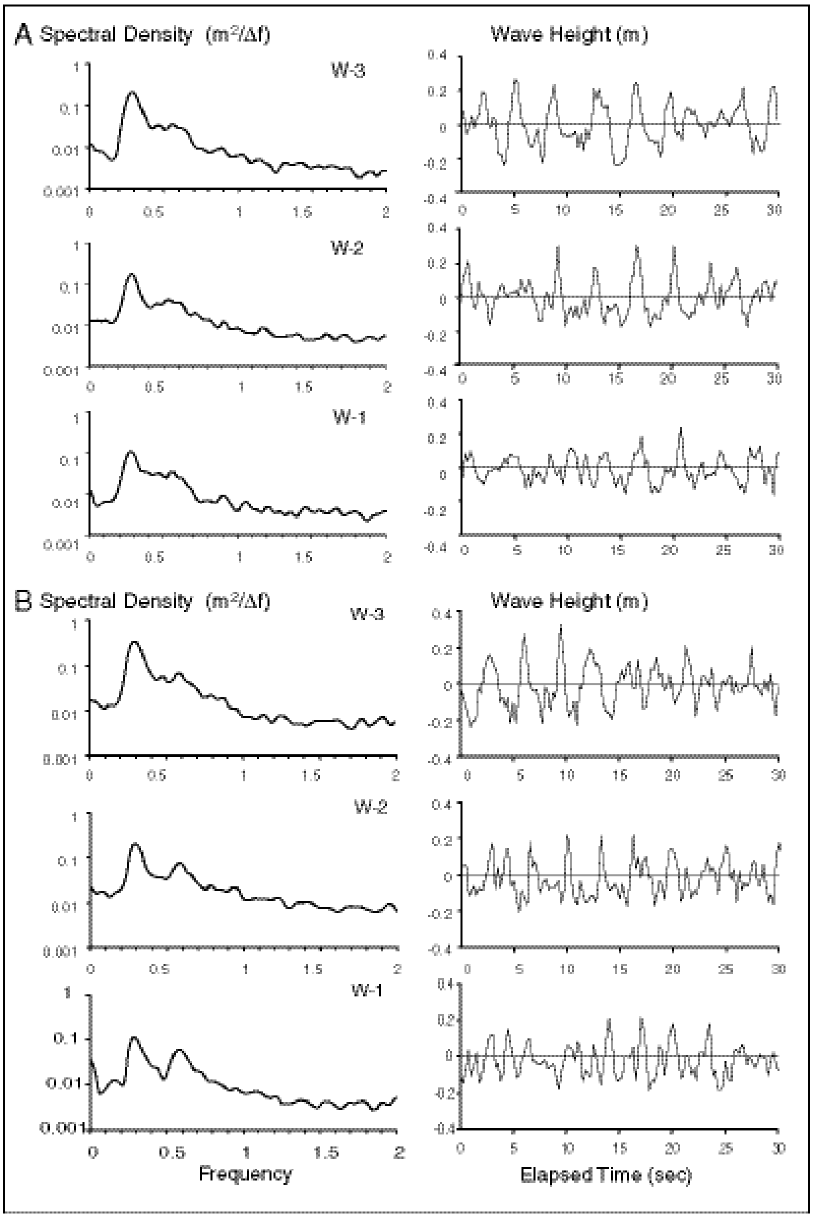

Figure 6. Spectral density and wave characteristics measured across the second bar on May 20 at a) 95 minutes before high tide and b) high tide. The examples of the water surface profile at each staff have been time shifted so that the same wave forms are shown.s.

The effects of changing water depth on the wave form and wave spectrum are shown for conditions on May 21 when winds were from the south-east blowing over the longest fetch (Figure 6). On the rising tide (Figure 6a) the incident wave spectrum recorded at W-3 on the seaward side of the bar shows a well-defined peak at around 3.5 seconds as well as some energy in the first harmonic, presumably reflecting wave shoaling and some breaking on the 3rd bar. Individual waves are well-defined. Water depth at W-2 on the bar crest is about 0.55 m and there is strong shoaling and a considerable amount of wave breaking, resulting in the development of secondary waves as is shown by the growth in the first harmonic at W-2 and W-1 in the landward trough. At high tide when the depth over the bar crest is about 0.75 m there is reduced wave breaking and a greater amount of energy is transmitted across the bar. This is shown both by the smaller reduction in the primary spectral peak and by more limited development of energy in the first harmonic (Figure 6b).

The effects of wave action can be seen more clearly in the mean and rms x axis velocities and mean suspended sediment concentrations for May 12 and 20 (Figure 7a, b).

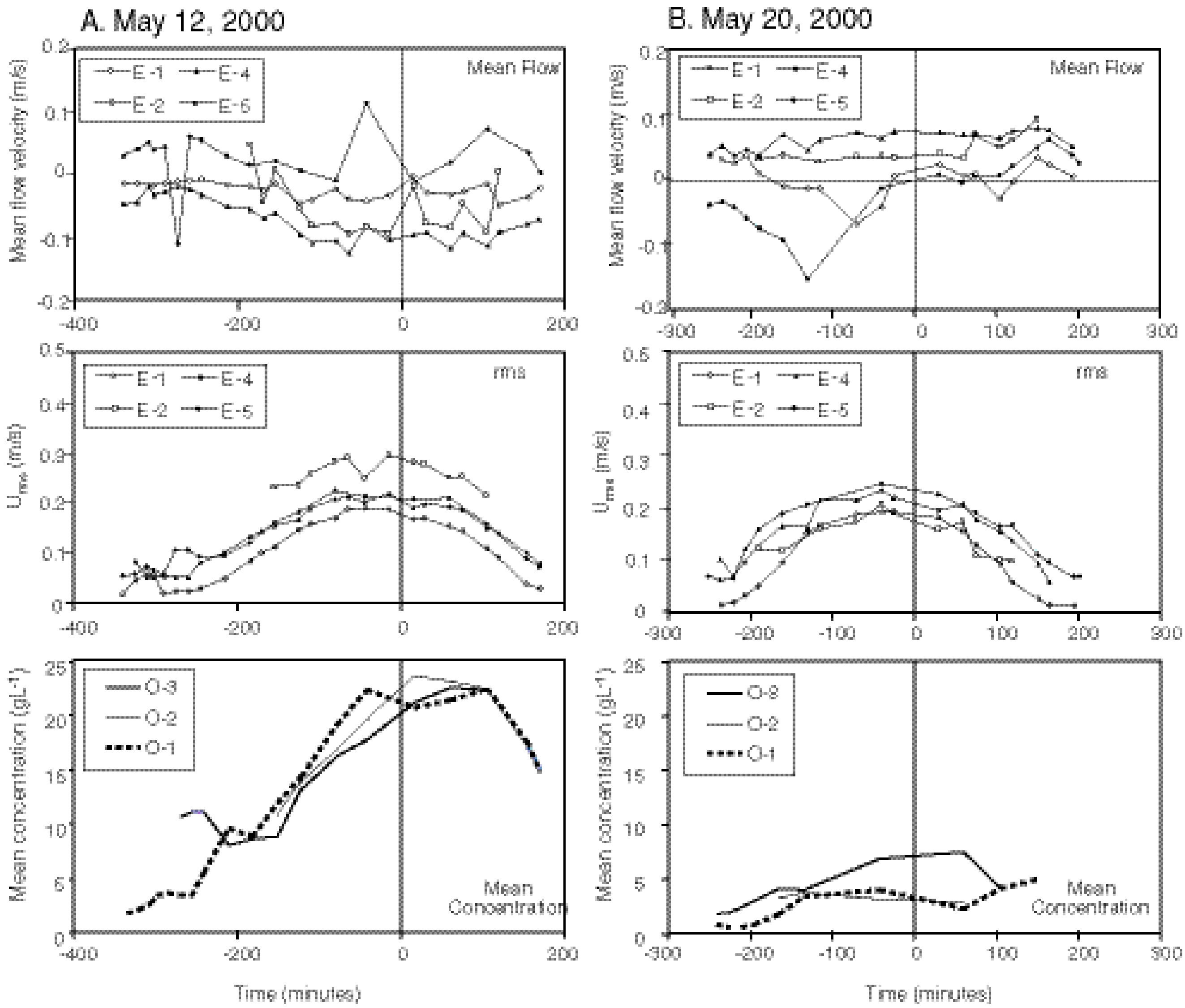

Figure 7. Mean and RMS velocity for the x axis of electromagnetic current meters and mean suspended sediment concentration measured by OBS sensors on: a) neap tide May 12; and b) spring tide May21.

Mean flows are generally onshore (positive values) at E-5 in the seaward trough and persistently near 0 at E-1 in the landward trough. However the three current meters on the bar crest and seaward slope all show offshore directed mean flows on the order of a few $cm.s^{-1}$ which is consistent with the development of an undertow. Urms at all current meters (Figure 7a, b) mirrors the change in water depth and significant wave height (Figure 4a, b) with highest values being recorded near high tide when large waves can propogate right across the bar. The magnitude of Urms at all locations is similar for the two days with the highest values being recorded at E-2 on the bar crest and lowest values at E-1 in the landward trough where water depths are greatest and there has been loss of energy through wave breaking on the bar crest.

The pattern for mean suspended sediment concentration differs somewhat from that for the mean current flows and rms velocity. Suspended sediment concentrations are low as the bars are inundated and tends to increase through the period of inundation. and to remain high during the falling tide. This appears to reflect the resuspension of fine silt trapped in the bar sands which is kept in suspension as by wave action. Mean values for concentration at high tide and on the ebb are much higher on May 12 (Figure 7a) than on

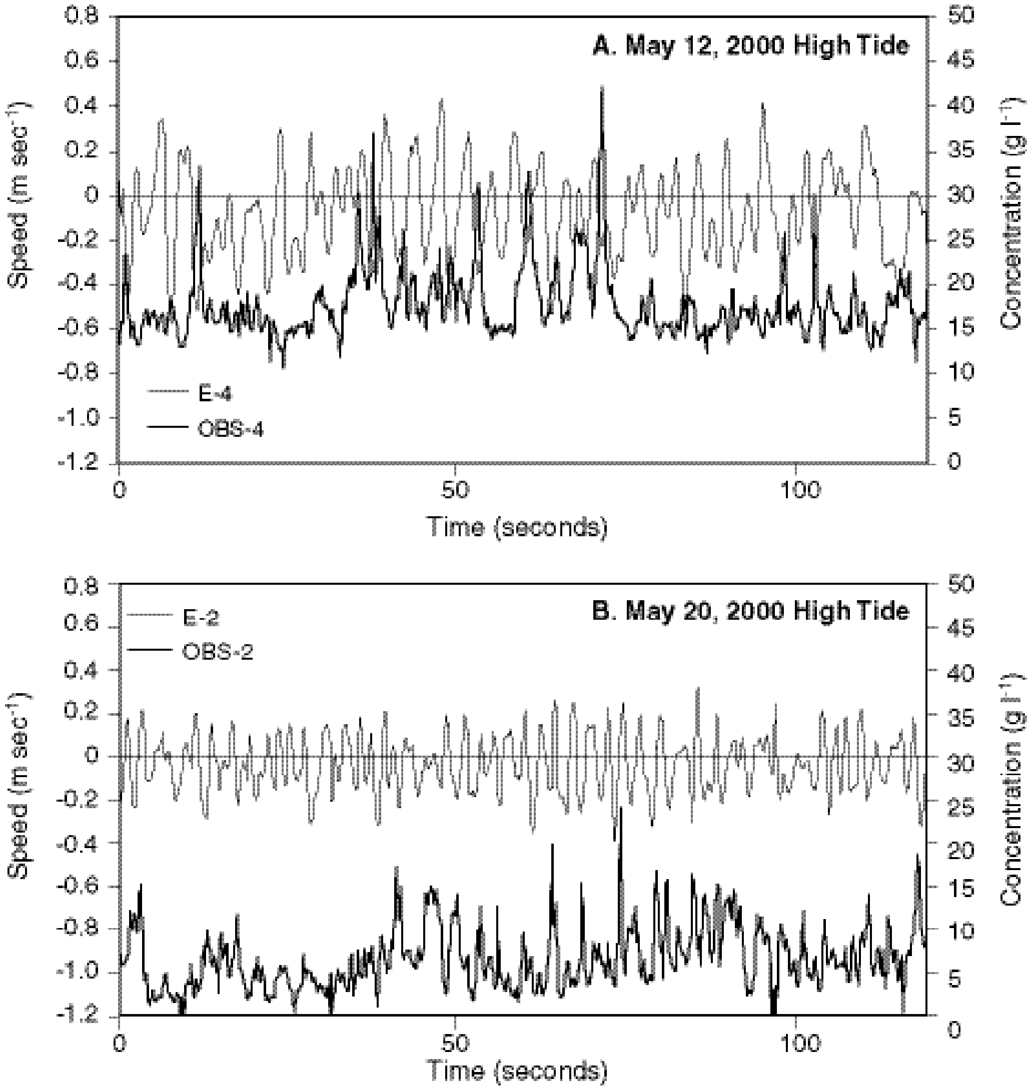

Figure 8. Instantaneous measurements of on-offshore velocity and suspended sediment concentration: a) OBS 4 and EM4x measured on May 12, 2000 one hour after high tide; b) OBS4 and EM4x measured on May 20, 2000 one hour after high tide.

May 20 (Figure 7b) and this appears to reflect the presence of a plume of fine silt eroded from the landward trough and base of the swash slope which diffused offshore across the bar (DAWSON, 2001). Examination of individual records from the OBS sensors and the x axis of the co-located current meter at station 4 on the seaward side of the bar for May 12 shows the presence of spikes related to the passage of individual waves and groups of waves superimposed on a relatively high background concentration (Figure 8a). Records for May 20 (Figure 8b) show relatively low background values and somewhat greater amplitudes attributable to sand suspension under individual waves, reflecting the greater wave amplitude on that day, particularly near high tide.

Net changes in the bed elevation within the grid established over the second bar in response to wave and tidal current action are small (Figure 9), in keeping with the small changes recorded in the overall bar form. On May 21 under nearly calm condition the small variations recorded are generally <2 cm and probably result from migration of ripple crests (Figure 9a). Over the period May 11 -13, including the wave action recorded on May 12, net changes up to 8 cm were recorded with some erosion from the seaward side of the crest and accretion on the crest and landward slope (Figure 9b). The slightly greater wave action on May 20th (Figure 9c) however produced only small changes on the order of 2 cm.

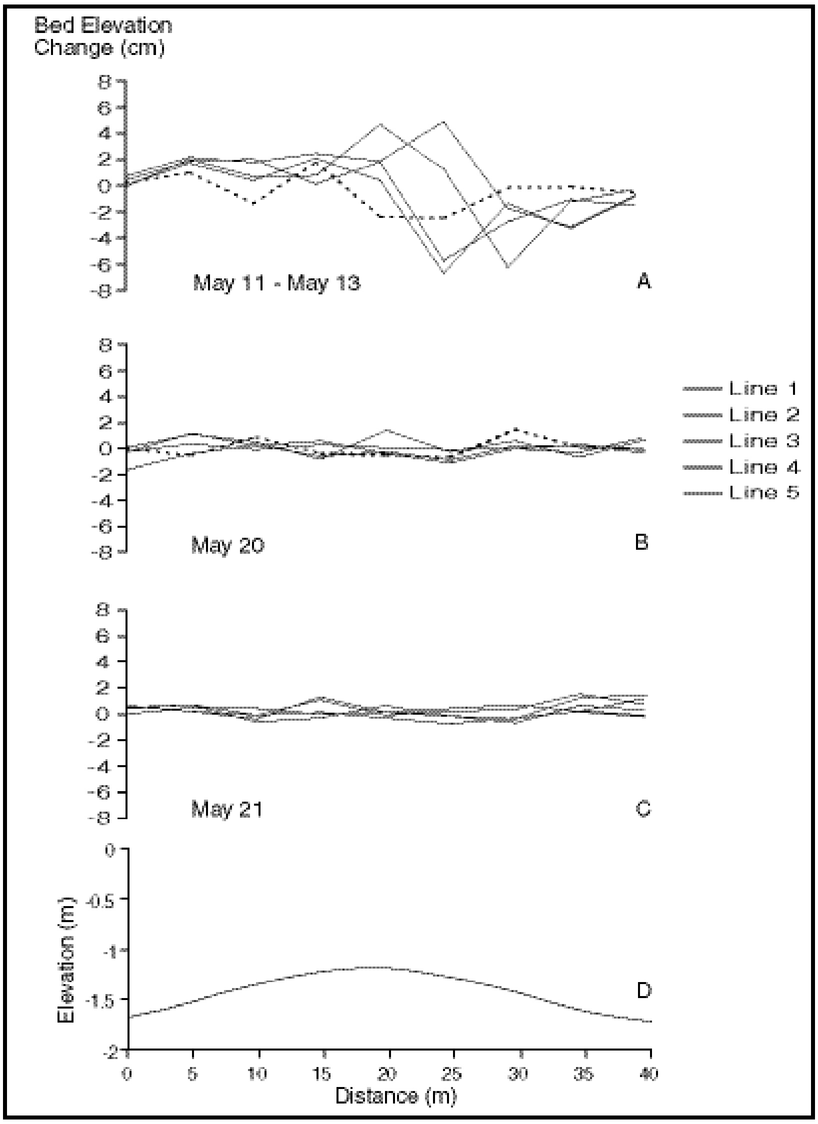

Figure 9. Changes in the bed elevation along one line of the grid over the second bar for: a) May 21, calm conditions; b) May11-13, wavy conditions; c May 20 wavy conditions. The bar profile is shown in d).

DISCUSSION AND CONCLUSIONS

The results of this study may shed some light on two questions related to ridge and runnel bar systems: 1) what are the broad factors that control the occurrence and characteristics of this bar type and how do these relate to other bar forms in the intertidal and subtidal zones; and 2) how do the morphodynamics of the system under low energy conditions produce relative stability in the intertidal bars described here in contrast to onshore migration that characterizes other forms that occur in the intertidal zone?

Morphological characteristics

Selected morphological and dynamic characteristics of the ridge and runnel system at Linden Beach are compared to those from published studies of intertidal ridge and runnel systems and sub-tidal multiple parallel bar systems in other locations (Table 2). In addition, values for the dimensionless fall velocity parameter (Ω), the relative tidal range parameter RTR, and the bar parameter B* are given, based on equations 1, 2 and 3 respectively.

Linden Beach has the lowest tidal range of all the ridge and runnel systems studied (Table 2) and this serves to

Table 1. Comparison of morphometric and dynamic components of the Linden Beach system with examples of: a) ridge and runnel systems; and b) multiple parallel bar systems. Values for the _ (equation 1), RTR (equation 2), and the bar parameter B* (equation 3) have been calculated based on values taken or interpolated from the studies referenced. It should be noted that these values are intended to be order of magnitude only. Becaue of the wide range of sediment sizes present on most intertidal beaches a single value for settling velocity corresponding to medium sand has been used. The width of the intertidal zone has been used in calculating the bar parameter for the intertidal beaches and for the multiple parallel bars the distance used is to the 1.5 m depth.

study	location	tidal-range	slope	width	nos. bars	max height	wave length	H	T	W	RTR	Omega	B*	bars predic
a) ridge and runnel														
Singh Chauhan, 2000	Solway Firth NW England	10	0.0025	2,000	3	0.3	110	1.5	6	0.05	6.67	5	2,265	4
King and Williams, 1949	Blackpool NW England	7.6	0.007	1,100	6	0.6	120	1.5	6	0.05	5.07	5	445	4
Voulgaris et al., 1998	Oostende Belgium	6.5	0.012	400	5	0.35	90	2	6	0.05	3.25	6.67	94	2-3
Stepanian et al., 2001	Normandy France	5.5	0.015	350	4	0.7	80	1.5	6.5	0.05	3.67	4.62	56	1-2
Hale and McCann, 1982	Vancouver Island W Canada	5.1	0.003	1,200	12	0.5	80	1.5	5	0.05	3.4	6	1,631	4
Orford and Wright, 1978	Dundrum E Ireland	4.9	0.01	350	5	0.8	70	1.5	8	0.05	3.27	3.75	56	1-2
Mulrennan, 1992	Portmarnock E Ireland	4	0.013	250	4	1.25	70	2	8	0.05	2	5	31	1
Dawson and D-Arnott	Northumberland Strait E Canada	2	0.004	350	6	0.5	50	1.5	5	0.05	1.33	6	357	3
b) multiple parallel bars														
Davidson- Arnott, 1988	Wasaga Beach Great Lakes, Canada	0	0	200	5	0.5	70	1.5	5	0.04	0	8.57	102	
Davidson- Arnott, 1988	Christian Island Great Lakes, Canada	0	0	180	6	0.4	25	0.5	3	0.05	0	3.33	291	
Exon, 1975	Baltic Sea Germany	0.3	0	390	10	0.5	35	0.5	3	0.05	0.6	3.33	1,767	

emphasize that a large tidal range is not a requirement per se for the development of ridge and runnel systems (ORFORD and WRIGHT, 1978; MULRENNAN, 1992) - rather, intertidal profile width is a function of tidal range and beach slope (MASSELINK and TURNER, 1999). If the profile were fully developed in sand then the beach slope would be considerably steeper and it is unlikely that there would be a significant intertidal platform. However, here and along much of this portion of the Northumberland Strait the recession of relatively weak low sandstone cliffs has produced a bedrock platform with a slope that is much flatter than would occur for one completely developed in sand.

As noted by a number of authors (KING and WILLIAMS, 1949; MULRENNAN, 1992) most ridge and runnel systems are found in areas of relatively low wave energy resulting from limited fetch conditions, and the system at Linden Beach conforms to this. It is notable that ridge and runnel systems in the Northumberland Strait appear to be confined to the central and eastern portion of the Strait which is sheltered from the higher waves and longer wave periods generated in the larger Gulf of St. Lawrence. Sandy beach and barrier systems found at the western entrance to the Northumberland Strait in Miramachi Bay (GREENWOOD and MITTLER, 1985), Kouchibouguac Bay (GREENWOOD and DAVIDSON-ARNOTT, 1975) and Buctouche (OLLERHEAD and DAVIDSON-ARNOTT, 1995) are all characterised by sub-tidal bars that fall into the Type VI category of GREENWOOD and DAVIDSON-ARNOTT (1979). It should be noted that nearshore slopes at these locations are steeper than at Linden Beach (e.g. 0.012 for Kouchibouguac Bay compared to 0.004), though this may reflect much more rapid erosion of the sandstone platform as a result of a more energetic wave climate.

The number of bars found on the intertidal profile, as well as bar height and wavelength varies considerably over the range of locations noted in Table 2. The controls on these seem to be similar to those noted for sub-tidal bars (GREENWOOD and DAVIDSON-ARNOTT, 1979; DAVIDSON-ARNOTT, 1988; SHORT and AAGAARD, 1993). In general, the number of bars increases as the slope decreases and the intertidal platform becomes wider, and decreases with increasing wave height and period. The bar parameter B* is not a good predictor of bar number, though it should be noted that it was not designed to be applied to the intertidal zone. At Linden Beach and several other sites the bars occupy most, if not all of the intertidal zone seaward of the base of the swash slope, and indeed at Linden Beach there are one or two subtidal bars seaward of the ridge and runnel. A value of 1.3 for the RTR parameter and 6 for the dimensionless fall velocity parameter (Ω) places Linden Beach in the barred dissipative regime of MASSELINK and SHORT (1993) and thus outside of the range considered for intertidal ridge and runnel. On the other hand, the site at Solway Firth (CHAUHAN, 2000), which is characterized by an extensive, flat tidal flat seaward of the ridge system, has values of 6.7 and 5 for the RTR and Ω parameters, placing it in the transition from low tide bar-rip and ultra dissipative.

Linden Beach has a calculated value for the dimensionless fall velocity parameter (Ω) of about 6 which places it at the transition from Intermediate to Dissipative in the classification scheme of WRIGHT and SHORT (1984). In practice it should probably fall much more clearly into the Dissipative regime because of the effects of the restricted fetch on limiting the entry of long period waves. In this case the use of sediment fall velocity in equation (1) may be inappropriate - it is used primarily as a surrogate for slope but in this location where the profile is determined by the underlying bedrock rather than the sediment characteristics, its use may produce a lower value for Ω than is realistic.

Comparison of the morphological features of the intertidal bars at Linden Beach with those for sub tidal multiple parallel bars (Table 2b) developed on similar slopes also suggests that there is a high degree of similarity between the ridge and runnel systems of the intertidal zone and the sub-tidal Type III and VI bars of GREENWOOD and DAVIDSON-ARNOTT, (1979; GREENWOOD, in press). Multiple parallel bars (Type III) are found primarily in low wave energy environments on gentle slopes and they are characterized by a high degree of stability(NILSSON, 1973; EXON, 1975; DAVIDSON-ARNOTT and PEMBER, 1980). Bars are near asymmetric or slightly asymmetric landward, and there is a gradual increase in height and wave length offshore. Type VI bars occur on steeper slopes and are generally exposed to higher wave energy conditions than Type III bars. They are fewer in number offshore with a greater degree of landward asymmetry and a greater rate of increase in bar height and spacing offshore (GREENWOOD and DAVIDSON-ARNOTT, 1979; GREENWOOD, in press). Linden Beach most closely resembles Type III bars but ridge and runnel systems on steeper slopes and/or in higher energy environments show features that conform more closely to the Type VI bars.

Morphodynamics

The results of this study show that the intertidal ridge and runnel system was highly stable under a range of non-storm conditions and that changes in bar form and location were minor. Such stability has been noted for ridge and runnel systems in a number of environments (MULRENNAN, 1992; STÉPANIAN *et al*., 2001) and, as noted earlier, it is a feature that distinguishes ridge and runnel intertidal bars from swash bars. In fetch limited environments such as that at Linden Beach, either bars in the nearshore zone tend to remain stable because they are in depths too great for significant wave action, or the innermost bar or bars may migrate shoreward. The rate of onshore migration depends in part on the non-storm wave climate. Where the prevailing winds are offshore and wave action between storms is limited, such as is the case at Linden Beach, the rate of migration can be very slow (e.g. GREENWOOD and DAVIDSON-ARNOTT, 1975). Where the prevailing winds are onshore, onshore migration and welding to the beach of the inner bars can occur quite rapidly in fetch limited environments (DAVIS *et al*., 1972; STEWART and DAVIDSON-ARNOTT, 1988; AAGAARD et al., 1998), and on coasts exposed to ocean swell the bar system can completely disappear (SHORT, 1978; WRIGHT, and SHORT, 1984; LIPPMAN *et al*., 1993). Onshore migration and welding of bars may be driven by wave breaking on the seaward slope of the bar and landward transport of sediment across the bar crest in shallow surf bores. Landward movement and flattening or decay may also occur as a result of waves shoaling but not breaking (LIPPMAN *et al*., 1993; PLANT *et al*., 1999; 2001).

Since the ridge and runnel bars are found in the intertidal zone it might be expected that they should migrate onshore and weld to the beach as is the case with swash bars. Under fair weather wave conditions the submergence and emergence of ridge and runnel bars should promote onshore migration during the early part of submergence and again as the bars become exposed through the first mechanism described above (VOULGARIS *et al*., 1998). As the bars are submerged to a greater depth wave breaking will occur closer to the bar crest and a higher proportion of waves will cross the bar unbroken (CARTER and BALSILLIE, 1983; MASSELINK, 1998), thus promoting onshore migration by the second mechanism. At intermediate depths, or when waves are locally generated by strong onshore winds, bars should remain stable or move offshore because of offshore directed undertow (GREENWOOD and DAVIDSON-ARNOTT, 1979; DAVIDSON-ARNOTT and MCDONALD, 1989; SALLENGER *et al*., 1985; AAGAARD and GREENWOOD, 1995; GALLAGHER *et al*., 1998). Our observations indicate that some onshore movement across the crest does occur under bores when water depths over the crest are < 0.1 m. However, once depths exceed this the measurements presented here suggest that the dominant flow in the lower half of the water column is offshore in the form of undertow and net sediment transport is probably very small and may be offshore directed. Thus, the stability of the bars may reflect a balance between onshore-directed flows at shallow depths during submergence and emergence and offshore directed flows when the bars are submerged to depths of 1m or more.

Tidal current flows in the runnels during inundation are generally too low to initiate sand movement, especially since they are cut off from wave action by the presence of the emergent bar seaward. However, drainage along the runnels and offshore through the channels breaching the bar may serve to reduce or prevent onshore migration by removing sediments brought across the bar and into the runnel. Much of this takes place when water depths in the runnels are <0.1 m and thus below the height of the instrumentation. Nevertheless flow velocities in these shallow depths are high enough to generate small standing waves and large quantities of sediment are transported through the drainage channels that cut through the bars and deposited in small ebb tide deltas near the confluence of channels (DAWSON, 2001). Thus, the landward sediment transport across the bar that can occur when water depths over the crest are shallow (VOULGARIS *et al*., 1998) may be compensated for by transport alongshore and offshore through the runnels and drainage channels.

The measurements here were carried out only under relatively low wave conditions and thus there is no direct evidence of what happens to the bars during a major storm event. Historical aerial photographs as well as visual observations over a period of several years indicate that the ridge and runnel system is a characteristic feature of Linden Beach and this is confirmed by anecdotal evidence from cottage owners at this location. If the morphodynamic controls on the behavior of the ridge and runnel bars are indeed similar to that of subtidal nearshore and multiple parallel bars then, in this restricted fetch location and with prevailing winds offshore, it would be expected that the bars would be present all the time and that the extent of profile adjustment would depend on the magnitude and sequencing of storms.

Conclusions

The main conclusions of this paper can be summarized as follows:

1) The ridge and runnel system at Linden Beach occurs in a micro tidal environment because of the restricted fetch and the existence of a wide intertidal zone resulting from erosion of a gently sloping bedrock platform;
2) The morphological characteristics and morphodynamics of the system at Linden Beach much more closely resemble those of subtidal nearshore and multiple parallel bars than those of intertidal swash bars;
3) Mean flow speeds and direction are the result of a complex interaction between tidal currents, wave-induced net currents and the morphology and orientation of the ridges and runnels;
4) The ridges and runnels are stable under the fair weather wave conditions measured during the field experiment. This stability appears to reflect a balance between onshore directed sediment transport by wave bores just after submergence of the bars on the rising tide and just before emergence on the falling tide, a near balance between onshore movement due to wave shoaling and offshore directed undertow when the bars are submerged, and offshore transport of sediment in the runnels as the runnels emerge on the falling tide.

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