GEOGRAPHY IS KNOWING WHERE THE SURF IS PUMPING

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BEACH PROFILE CHANGE
AT
ST. CLAIR BEACH
DUNEDIN

A thesis
submitted in partial fullfillment
of the requirements for the Degree
of
Master of Science in Geography
in the
University of Canterbury
by
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University of Canterbury

1994

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ABSTRACT

This thesis examines the nature of changes that occur within the beach profile at St. Clair Dunedin on the south coast of the Otago Peninsula. The profile changes are linked to variations in the wave and wind environments, and the results are compared to both previous local work and to the relevant theory and models accepted in the literature.

Erosion at St. Clair occurs during extended periods of strong southwest winds which are associated with increased wave heights, decreased periods and enhanced longshore currents. Under these conditions sand is transported both offshore and alongshore to the east, away from the western St. Clair corner, resulting in a lowering of the beach profiles. Erosion is accentuated at St. Clair by the presence of a sea wall, resulting in exceptionally low profiles which may allow fill to be eroded fom behind the concrete seawall face.

While erosion is shown to be associated with predominantly steep waves, (> 0.09) accretion at St. Clair was shown to often be unrelated to wave steepness. Within the significant accretion periods the longshore current direction was considered to be of greater importance. Thus currents moving to the west under the influence of easterly quarter swells transport sand in to the western St. Clair corner. The presence of the western headland blocking these currents results in rapid deposition, and accretion of the St. Clair profiles.

Allen (1985) showed that the critical wave steepness equation of Dean (1973) applied for a medium sand beach. The equation was shown not to apply to inshore data for the south coast of the Otago Peninsula. This was considered to be due to the higher wave energy experienced on the Otago Peninsula. The failure to gain a critical wave steepness was considerd to be due to the inconsistent survey base, and the fact that at St. Clair the accretional periods were influenced primarily by longshore sand transport over wave steepness.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The aim of this thesis is to assess the nature of the changes that occur within the beach profile at St. Clair beach, to subsequently link these profile changes to variations in the wave and wind environments, and to compare the results both to previous local work, and to those predicted by the theoretical models of profile change accepted in the coastal geomorphic literature.

Most of the theory of beach profile change is based on results from two-dimensional wave tank experiments. The applicability of the results of these experiments to natural coastal environments is often restricted due to the problems of scale and the fact that in reality the problem of profile change is actually three-dimensional. Thus while this type of experimental research continues there is also a need to back this up with analysis of natural coastal environments, based on field work, to assess the validity of the theoretical models. Theory developed in the laboratory is not of much use if it does not apply to the "real world". The findings of field based research can also point to inadequacies in the theoretical models therefore indicating areas where further research needs to be directed.

Also when dealing with local coastal problems, such as erosion and accretion patterns at St. Clair, the diverse range of coastal environments necessitates that local field work be carried out to gain an understanding of the local processes at hand. Most coastal environments have their own unique geomorphic characteristics. While the theoretical context on which the study is based, outlined next in Part 2 of this chapter, is not new the study is unique in that it is the first detailed investigation of short term coastal geomorphic change on the south coast of the Otago Peninsula.

In fact the greater part of the Otago coastline has remained relatively unstudied from a physical coastal point of view. This is in sharp contrast to its northern neighbour, the Canterbury coast, which has been extensively researched and is very well understood due mainly to research undertaken within the Geography Department at the University of Canterbury.

Within Otago land based geological research has been extensive, mostly in part due to work within the Geology Department at the University of Otago and the area has been extensively mapped and is well understood (eg. McKellar, 1966, 1990). Also the adjacent continental shelf and its hydrology have also been the subject of numerous investigations (Jillet, 1969; Heath, 1972; Andrews, 1973, 1979; Carter & Ridgeway, 1974; Williams 1979; Carter *et al* 1985; Carter, 1986; Carter & Carter, 1986) and as a result the sedimentologic and hydrologic regimes of the continental shelf are both reasonably well understood. Thus it is somewhat ironic that the boundary between these two extensively researched environments, that is the coastline, has received some what less research attention, especially within the Dunedin area.

The first Otago coastal geomorphologic papers were by Elliot (1958) and Hodgson (1966). They presented contrasting views on the evolution and origin of the various sandspit complexes within the Otago Peninsula area, but neither actually carried out any detailed geomorphologic investigations. Bardsley (1977) used mineralogic evidence to show that the beach sands of the Otago coast, from the Otago Peninsula south, had a dominant Clutha source.

The other types of coastal investigations that have been carried out in Otago have been primarily concerned with coastal management policies and practices, implemented by the local body authorities, most recently by the Dunedin City Council (1985, 1992, 1993) and the Otago Regional Council (1992a, 1992b). A point of interest among the local body papers is the reiteration of the need for monitoring of the coastline and of the coastal processes operating. After all, informed coastal decision making can only be brought about in the presence of a detailed understanding of the local coastal processes at hand, such as local coastal geomorphic change. This is not a new idea. For the area concerned within the present study it was recognised as early as 1904 in an engineer's report to the then local body authority, (the Dunedin Ocean Beach Domain Board), that in considering conservation of the St. Clair - Ocean Beach sand dunes, and the protection of St. Clair, with respect to the design of the now emplaced seawall :- *"It is to be regretted that no full and complete survey embracing observations on the force and directions of inshore currents and sand movements, etc, is available as preliminary to the formulation of any improvement scheme."* (Mason, 1904, *p5*).

Given this early recognition of the need for information concerning geomorphic change within the St. Clair - Ocean Beach system it is somewhat surprising that the research presented in this thesis is the first of its kind for both St. Clair and the south coast of the Otago Peninsula. This is clearly an area of local research that has been long overdue.

Within this introductory chapter the theoretical context on which the research is based is discussed next in Part 2. From this the main aims of the research are presented in Part 3, and finally in Part 4 the structure of thesis is presented.

1.2 THEORETICAL CONTEXT

A beach is an accumulation of loose sediments situated at the interjunction of the air, land and large water bodies, such as lakes or oceans. The single most fundamental force operative on beaches is that of waves, and as a result beaches and their nearshore environments act as buffers to wave energy. Thus the secret of beach geomorphic behaviour is that they may quickly alter their shapes in response to changes in the wave energies arriving at coasts, thereby maintaining a dynamic equilibria with the environment, through the mobility of the loose sediments. As a result beaches are sensitive to change over time scales ranging from a few seconds to several years, and longer.

In order to examine changes within beach systems, the three-dimensional environment is usually reduced to one of two two-dimensional forms. These are the plan shape, (shoreline configuration), or the beach in profile, that is at a normal to the shore, (90°). While the research conducted here is primarily concerned with the two-dimensional profile variation, it must always be remembered that the problem of beach profiles is in reality still three-dimensional.

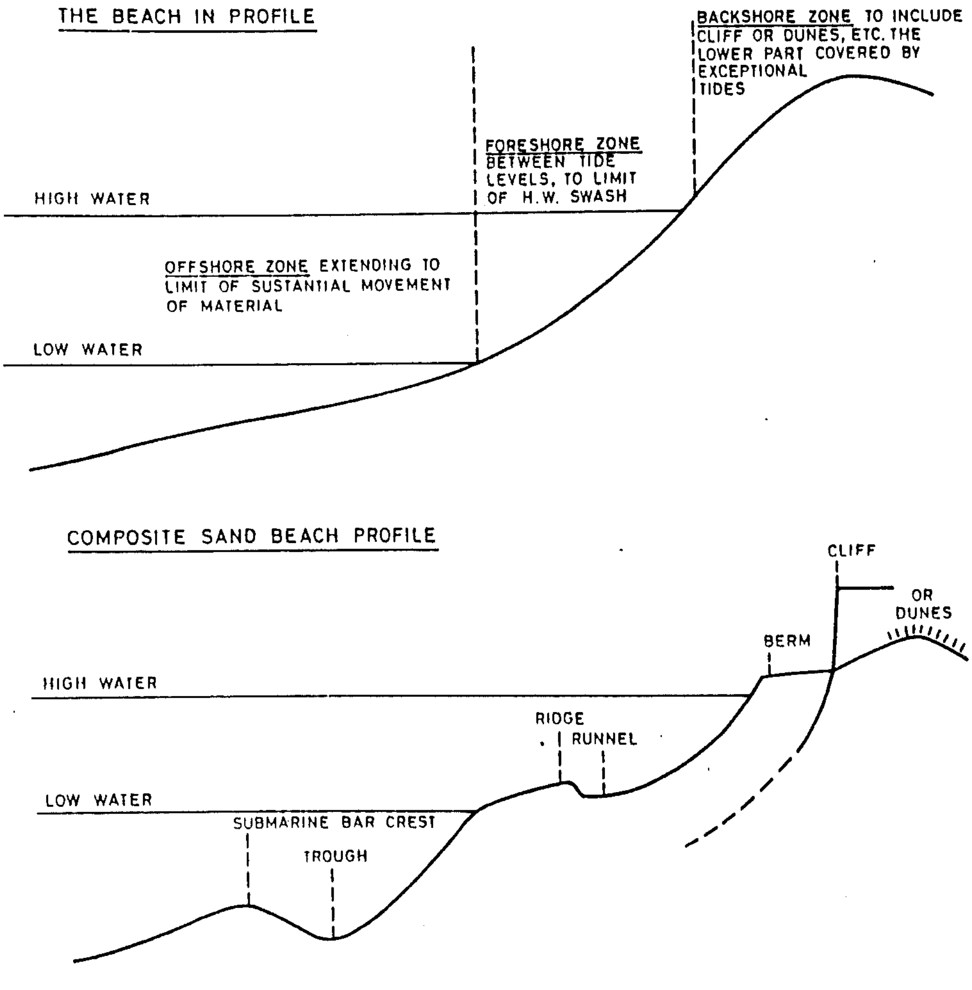


Fig. 1.1: The beach in profile, showing the three main zones, and the accepted terminology for the morphological features of the sandy beach profile. (source; King, 1972)

King (1972) divides the beach in profile into the three main zones, Fig. 1.1, of backshore, foreshore, and offshore. The offshore zone extends seaward from low water to the limit at which sediments are no longer moved by wave action. The foreshore zone extends between the low and high tide levels, to the upper limit of high tide swash. The backshore zone extends from landward of high tide to include the cliffs or dunes. Fig. 1.1 also shows the accepted terminology for the various morphological features of the sandy beach profile.

Pethick (1984) considers that there are three main factors that control profile variations. These are

1) waves: variation in wave, energy, steepness or breaker type.
2) sediment variability
3) interaction of waves and sediments: sediment transport processes

Early work on the changes of beach profiles within California (Shepard & La Fond, 1940; Shepard, 1950; Bascom, 1954) showed that low flat waves of summer resulted in accretion of the beach profiles, and the building up of a prominant berm. In winter high steep storm waves eroded the beaches, transporting the sand offshore to be deposited within a longshore bar, thus widening the beach profile and reducing its gradient. These findings led to the 'winter profile' and 'summer profile' terminology reflecting the seasonality of profile changes within California. Additional research however at other various locations around the globe showed that similar changes occured but not necessarily on a seasonal basis. Komar (1976) applies the terms of 'storm profile' and 'swell profile', to describe the two main variations of the beach profile, Fig 1.2.

The changes in the beach between the storm and swell profiles are related to the water motions as these are what move the sediment. Outside the breakpoint all unbroken waves move sediment landward (King, 1972). Steep waves move sediment seaward inside the breakpoint. Thus a build up of sediment occurs at the break point to form the longshore bar. Under flat wave conditions sediment is moved landward at all depths. Thus sediment is deposited at the landward limit of the swash runup to form the berm, and the height of the berm is controlled by the swash runup height. King (1972) considers the variation in the direction of sediment movement within the break point in relation to steep and flat waves to be related to the swash and backswash velocities. Swash has a high velocity for a short period, while backwash has a lower velocity for a longer period. When backwash velocities are below the critical velocity for sediment transport sand moves landward under the influence of the higher swash velocities. If the wave period stays constant however while the wave height increases, (the wave steepness also increases), the amount of water lost by percolation remains constant while the volume and velocity of the swash and backswash increase. If the backwash velocity increases to be above the critical velocity for sediment transport then sand will move seaward due to the longer duration of the backswash.

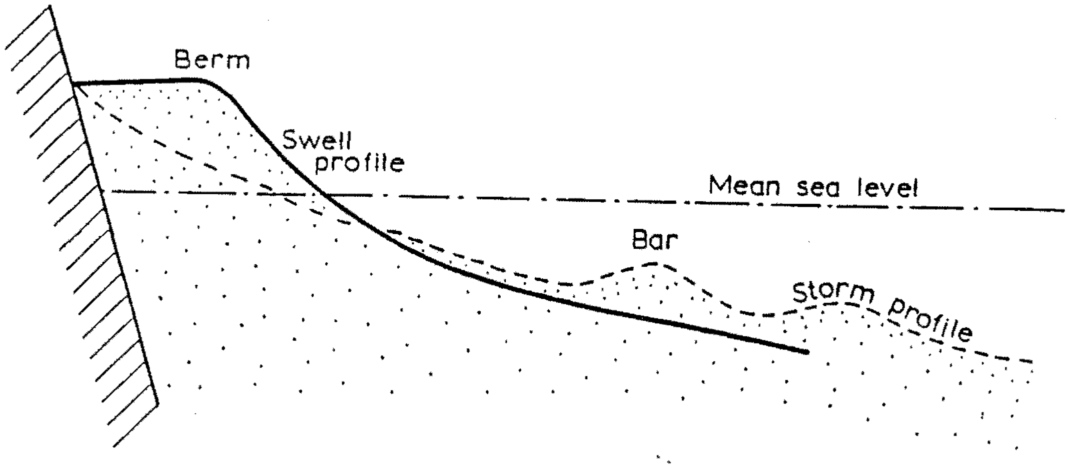
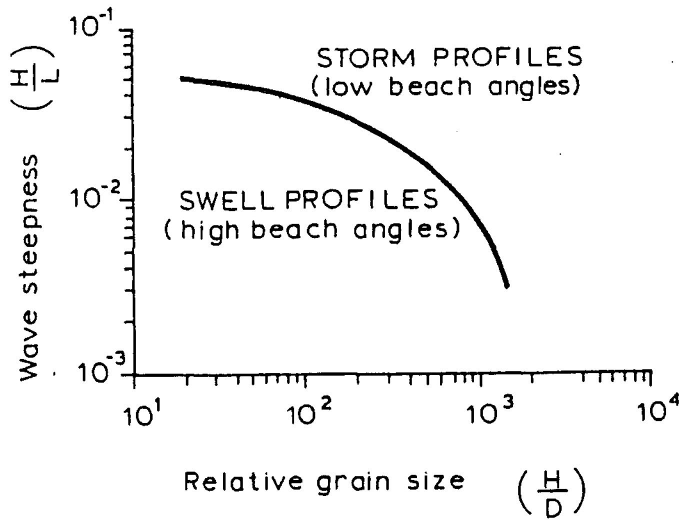


Fig. 1.2: The steep beach profile characteristics of swell waves contrasted with the shallow profile of storm waves. (source; Pethick, 1984).

Johnson (1949) first applied the terms 'storm' and 'normal' to profiles to eliminate seasonality in what was to be one of the first of many wave tank experiments examining the onshore-offshore shift of sand associated with profile changes from storm to swell conditions. The basis behind these experiments was the fact that the change from storm to swell conditions is generally correlated to changes in the ratio of deep water wave height to deep water wave length, that is H/L, or the wave steepness. Steep storm waves having greater heights and shorter wavelengths, than flat swell waves with smaller heights and longer wavelengths. Thus the thrust of these experiments was to find a critical wave steepness, above which the beach erodes and below which it accretes. Johnsons

(1949) results showed the critical steepness to lay between 0.025 - 0.003. Scott (1954) found a critical steepness of 0.019, while Rector (1954) and Watts (1954) both gained critical steepness values of 0.016. King and Williams (1949) results showed the critical wave steepness to be 0.012. King (1972) considered that the variation was due to different sized sediment used in the experiments and also due to the variations in the initial gradient of the profiles.

All of the above results were gained under conditions of small waves. Saville (1957) used much larger waves in an attempt to simulate real beach conditions and gained a critical wave steepness of 0.0064. From this Saville (1957) concluded that the deformation of the beach under wave attack was as much a function of wave size as wave steepness. Also the marked difference between the results for the large and small waves showed that variation could result from the scale of the experiment.



<u>Fig. 1.3: The critical wave steepness required for the transition from swell to storm profiles is dependent on the relative grain size of the beach sediments in relation to the wave height. (after Iagaki & Noda, 1963; *in* Pethick, 1984)</u>

Taking this idea further Iwagaki and Noda (1963) showed that the sand size used in wave tank experiments affected the beach processes with respect to the scale of the waves. By keeping the ratio wave of height to sediment size constant Iwagaki and Noda (1963) found that variations in the wave steepness altered the beach profiles as expected, but that when holding the sediment size and the wave steepness constant, that increased wave heights eroded the beach while decreased wave heights were associated with accretion. It was thus concluded that the critical wave steepness was highly correlated to both the mean sediment size and the wave height. Fig. 1.3 shows this relationship.

In the field deepwater wave height is substituted for breaker height and the wavelength can be calculated from the wave period through equation 1.

$$L = \frac{gT^2}{2\pi} \qquad (1$$

where: L = wave steepness; T = period; g = gravity

Field studies tend to also show the effects of scale with the critical wave steepness tending to be lower than those of the models, Komar (1960). Komar (1976) however notes that although many field investigations show erosion during times of storm and accretion during quieter weather that none have obtained satisfactory wave data from which a critical wave steepness could be determined. This is considered to be partially due to the irregularity of profile change, and possibly that variation in wave height is also more important than wave period variations. King (1972) also suggests that the critical wave steepness varies in relation to the intial beach gradient, with reduced gradients, having lower critical wave steepness values. Also field observations are often difficult due to the large number of uncontrollable variables which complicate the problem (King, 1972). This idea is backed byWright and Short (1984) who suggest that the actual mechanisms which cause beach change and the wave energy required to induce beach change varies with the beach state. Thus it must be remembered that the beach profile adjusts so as to maintain a dynamic equilibrium with its environment, and that the changes that the beach must make to reach this equilibrium must also partially depend on the state of the beach before the change is induced. It is suggested that there is a "*need for additional field studies which carefully tie the onshore-offshore shifts in profiles to the nature of the waves*" (Komar, 1976, p293).

Later however Allen (1985) noted that both Allen (1973) and Psuty *et al* (1980) gained critical wave steepness of 0.008 in the field for medium sand beaches. Allen (1985) also tested the Dean (1973) equation, equation 2.

$$critical\ H/L = \frac{2\pi\omega_s}{gT} \qquad (2$$

$$where:\ \omega_s = grain\ settling\ velocity$$

It should be noted here that Allen (1985) used a constant of 2 as opposed to 1.7 given in Komar (1976). Komar (1976) suggests that this correctly predicts the onshore-offshore transport of sediment in 87.5% of all cases. Comparing the critical wave steepness given by the equation to changes in beach profiles above low tide Allen (1985) found that it predicted 98% of the erosional events but only 45% of the depositional events. The low accuarcy for the depositional events was considered to be due to a time lag for the accretional changes to show up on the foreshore profiles. From this it was suggested that the equation could be more widely used for local planning and engineering design by identifying which wave parameters would result in erosion of the beach concerned.

More recently morphodynamic studies have formed links between waves, breakers and the beach gradients. Reviews of morphodynamics can be found in Wright and Short (1984) and Carter (1988). In morphodynamics it is considered that the sandy beach has two morphodynamic extremes with a range of morphological states between. Fully dissipative states are analogous to the storm profile, being characterised by flat shallow beaches with large subaqueous sand storage. At the other end of the scale highly reflective states are characterised by steep beaches with small subaqueous sand storage and exclusively surging to collapsing breakers. Intermediate states contain elements of both the dissipative and reflective states across the profile. The morphodynamic state of a beach is considerd to be controlled by the surf scaling parameter of Guzza and Bowen (1975), equation 3.

$$E = \frac{a\varpi}{(g \tan^2 \beta)} \qquad (3$$

where: E = *surf scaling parameter*; a = *breaker amplitude*

ϖ = *incident wave radian frequency* = $\frac{2\pi}{T}$

β = *beach slope*

Complete reflection occurs when E < 1. Reflection will continue to some degree when 2 < E < 2.5. Dissipation begins when E > 2.5 and complete disspation occurs when E > 20.

The dimensionless Dean parameter, equation 4, is considered to determine the thresholds at which a beach moves from one state to another (Wright and Short, 1985).

$$\Omega = \frac{H}{\omega_s T} \qquad (4$$

where: Ω = *dimensionless Dean Parameter*

Wright and Short (1985) also note that the actual mechanisms that cause beach cut and fill, and the wave energy required varies with the beach state; that the contributions of the incident waves, net surf zone circulations and resultant sand transport also varies with beach state; and that the modal beach state represents a response to the modal breaker characteristics. They also note that the range of beach morphologies is dependent on the range of wave conditions in relation to the size of the beach sediment. Low mobility is associated with high wave energy on fine grained sediments, thus maintaining highly dissipative states, and low wave steepness on coarse grained beaches which maitain highly reflective states. The greatest mobility is considered to be associated with intermediate but highly changable wave conditions and medium grained sediments with the beach alternating between intermediate states.

While it has been shown above that there are links between the waves, sediments and beach profiles it should also be noted that there is also a direct link between the sediment size and the beach gradient. The classic study of this was by Bascom (1951) in Halfmoon Bay in California, Fig. 1.4. With distance south around the bay the beach gradient steepens as the sediment size increases. The link between sediment size and beach gradient is believed to be related to the percolation rate (Pethick, 1984). Thus as the sediment size increases the percolation rate increases reducing the backwash velocities and increasing gradients due to the greater landward movement of sediment by the swash. Locally in New Zealand McLean and Kirk (1969) showed that poorly sorted sediments have lower gradients, which was attributed to lower percolation rates.

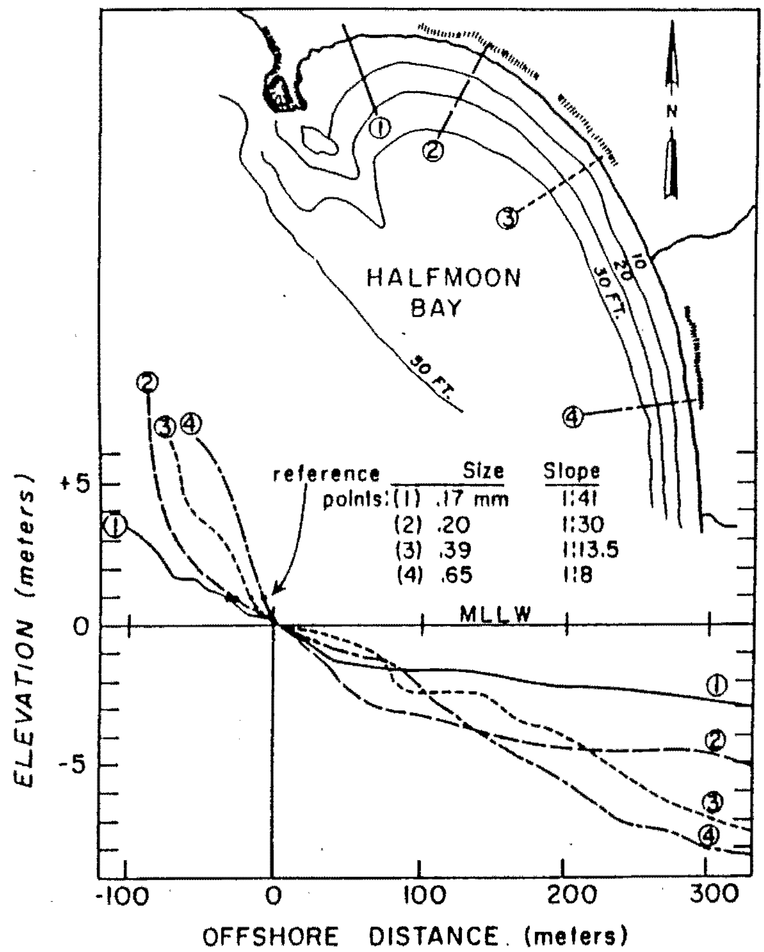


Fig. 1.4: Systematic changes in the beach profile slope along the length of Halfmoon Bay, California.
(after Bascom, 1951; *in* Komar, 1976).

Although the variation of beach profiles is most easily observed in the two-dimensional form Komar (1976) notes that the problem of beach profile variation in reality is still three-dimensional. Thus the variation of longshore transport direction must also be monitored. King (1972) considers longshore transport to be an important cause of coastal erosion as destructive waves acting normal to the coast will only move material a short distance off shore from where most of it can be returned under quieter conditions where as the transport of sediment alongshore out of the area is likely to result in more permanent erosion. The downdrift side of groynes and headlands is especially prone to this form of erosion with sediment being moved away from the headland or groyne. The importance of longshore transport was first observed in southern California (Shepard, 1950) where in winter northwesterly storms built out the southern ends of some beaches while maintaining an erosional storm profile. In summer with southerly swell waves the southern end of the beaches were cut back while maintaining an accretional swell profile.

The key to this is the beach alignment with respect to longshore transport. Longshore current velocities are generated within the surfzone when waves approach the shore at an oblique angle. Within a pocket beach where there is no influx or outflux of sediment through longshore drifts the beach will try to realign itself to be parallel to the crests of the incoming waves, in an attempt to reduce the longshore transport rates to zero. This form of alignment is termed swash alignment (Pethick, 1984). On the open coast beaches also attempt to reduce the angle between the waves and the beach but only to the point at which the sediment transport rate is that needed to prevent local erosion or deposition. This form of alignment is termed drift alignment (Pethick, 1984). Thus accretion may take place if more material is moved into an area along the shore than that which is eroded due to steep wave conditions (King, 1972).

With respect to seawalls Pethick (1984) notes that the object of coastal defences is usually to dissipate wave energy, but that the seawall actually concentrates and reflects the wave energy leading to enhanced erosion of the beach infront of the seawall. Komar (1976) also notes that as the beach erodes that progressively larger waves can move closer to the seawall therefore accelerating the erosion problem. Plant and Griggs (1992a) also consider that the erosion of the beach in front of a seawall is due to seawall reflection of the wave energy, which results in reduced swash action, increased turbulence, and higher backwash volumes and velocities. Barnett and Wang (1988) however consider that wave reflection is not significant but that the water depth is. The two are probably interrelated as when the water depth increases the potential amount of reflection must also increase, with larger waves being able to move into the seawall.

The discussion above has reviewed the accepted theoretical models as to how and why beach profiles change. These models will be used to help assess the changes that occur in the profiles at St. Clair. From this both the similarities as well as any unique variations that occur within the processes and responses of the St. Clair profiles can be assessed in relation to those processes and responses as predicted by the accepted theory and models.

1.3 THESIS AIMS

Within the main aim of examining the nature of beach profile changes at St. Clair the research in this thesis has several objectives which are.

1) To record, observe and quantify the two main process elements, the wave and wind environments, and from this assess their potential influence on geomorphic change at the coast in relation to the accepted models and theory discussed above.

2) To determine and quantify the nature of the fluctuations of the beach profile at St. Clair Beach.

3) To relate the beach profile fluctuations at St. Clair to changes within the wave and wind energy environments. Are the earlier observations of Elliot (1956) that erosion and accretion is controlled by the modification of the predominant southerly swell by the local winds correct? Does the Dean (1973) critical wave steepness equation apply to the St. Clair beach, and can a critical wave steepness be determined above which the beach erodes and below which the beach

accretes? What role if any does variation in the direction of longshore transport play in the erosion accretion cycles at St. Clair?

4) To compare the St. Clair profile fluctuations to those of the other nearby sites of St. Kilda, and Tomahawk beaches.

1.4 THESIS OUTLINE

Chapter 2: This chapter introduces the study area. First the influence of the local geology is explained. This is followed by a review of the adjacent south Otago continental shelfs hydrodrologic and sedimentologic features. The importance of the nearshore sand wedge with its influence on the beach and dune deposits of the Otago coast is outlined here. A review of the general features of the Otago coastline from the Taieri River mouth north to include the Otago Peninsula, is then followed by detailed look at the two beaches on which the research was undertaken, the St. Clair - Ocean, and Tomahawk beaches. The impacts of human actions, and the management policies and practices implemented over the last one hundred plus years on these two beaches has been of particular importance here in influencing the nature of the coast as it is seen today.

Chapter 3: This chapter examines the nature of the local Otago wind environment. It does this by comparing wind speed and direction data collected during the study period with the long term Otago Peninsula wind record. Firstly however, the general Otago climatic setting is reviewed. This is followed by a review of the previous findings on the long term Otago Peninsula wind record as collected from Taiaroa Head. The influence that local winds have on geomorphic change both indirectly, through their influence on the nearshore environment and directly, through aeolian transport is then explained. The methods of wind data collection and analysis is then set out and the results presented. The results are then discussed in relation to the long term record and their influence on coastal geomorphic change.

Chapter 4: This chapter examines the nature of the local Otago wave environment. It does this by comparing offshore swell data forecast by the N.Z. Met. Service to daily shore based observations, and also to the findings of previous works. Firstly the previous findings of investigations on the Otago wave climate are reviewed. The methods of wave data collection and analysis are then set out and the results presented. The significance of the results in terms sediment transport and coastal geomorphic change are discussed.

Chapter 5: This chapter examines the nature of the profile changes that occur on St. Clair Beach, and links these changes to variations in the wave and wind environments. Firstly previous Otago geomorphic investigations are discussed. The methods of profile data collection and analysis with respect to the wave and wind environments is then set out and the results presented. From the results the forces and processes acting on St. Clair Beach are discussed, in relation to the erosion and accretion events.

Chapter 6: This chapter reviews the main findings and conclusions of the research. Finally some possible avenues for future research are discussed.

CHAPTER 2

INTRODUCTION TO THE STUDY AREA

2.1 INTRODUCTION

The research for this study was undertaken on the Tomahawk, and St. Clair - Ocean, beaches which are situated on the south coast of the Otago Peninsula, Fig. 2.1, on the southeast coast of the South Island of New Zealand. First, Part 2 of this chapter discusses the geology of the area. This provides an outline of the major structural controls on which all other processes are dependent. It especially influences variations in the nature of the Otago coastline, the features of which are discussed in Part 4. In Part 3 the oceanic influences on the coast from the Continental Shelf are discussed, in particular the nature of waves and currents, ie; the hydraulic regime, and the role it plays in the transportation of shelf sediments. Also discussed is the nature of the sedimentation on the shelf. Of particular importance here is the nearshore sand wedge, of which the littoral sytem is an integral part. The nearshore sand wedge thus provides the beach sediments. Finally in Part 5 the two beaches on which the study was undertaken are discussed in light of past human influences, and with regard to the coastal management policies and practices that have been implemented.

2.2 LOCAL GEOLOGY

The underlying geology of a study area is important as it provides the major structural controls, on which all the other processes operate. Also "*The character of any shoreline must depend in the first instance on the charater of the land surface against which the sea comes to rest.*" (Johnson, 1915, p171). A

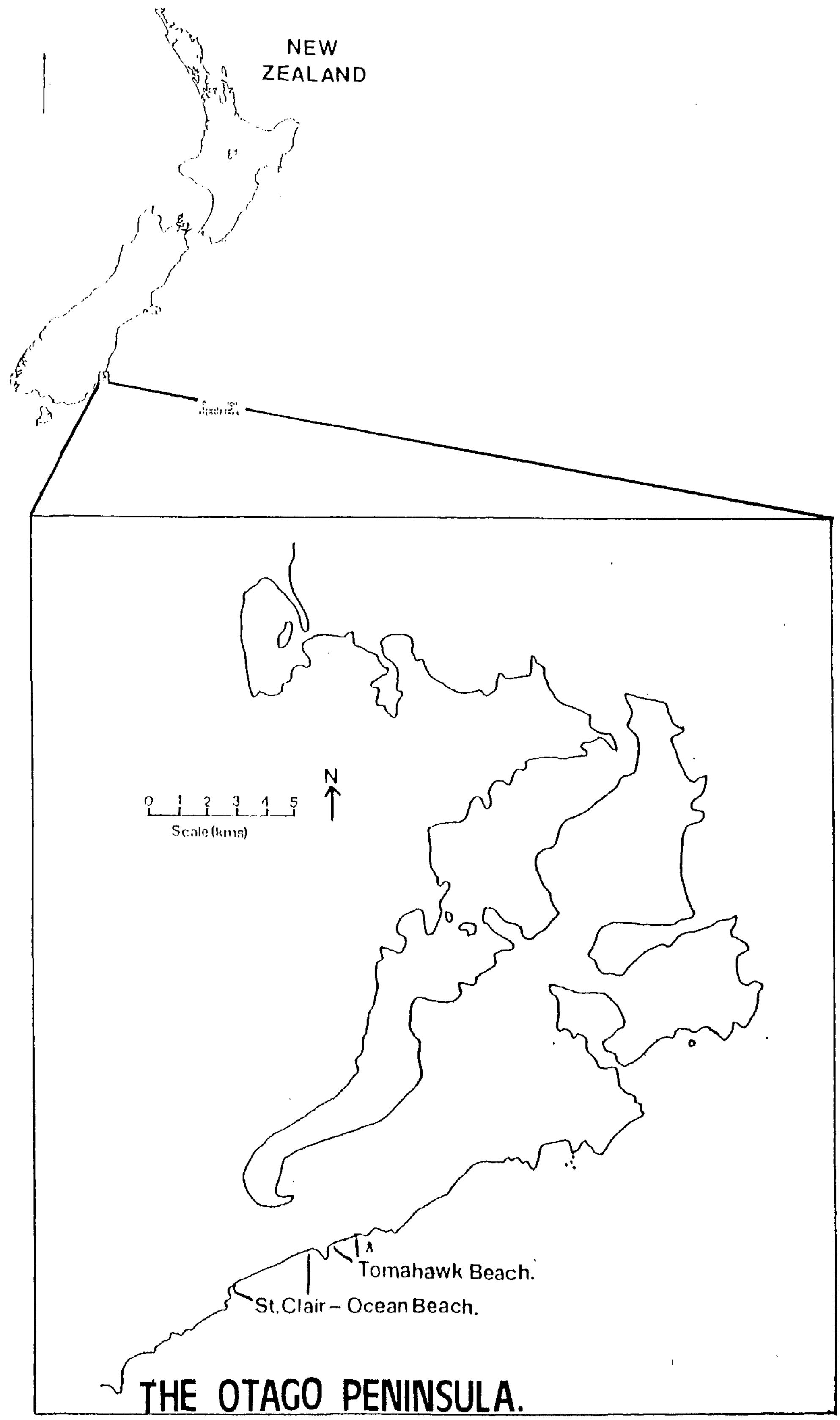


Fig. 2.1: General location of the study area. On the south coast of the Otago Peninsula, on the southeast coast of the South Island of New Zealand.

simplified map of the local geology can be seen in Fig. 2.2. The most prominant geological feature of the study area is the late Tertiary shield volcano of the Otago Peninsula, with a present day vertical relief of 700m and diameter of some 25km.

The rocks forming the metamorphosed basement of the area are the Haast Schists, which outcrop to the west of the Dunedin Volcano, and to the South, just inland along the Taieri to Brighton coastline. The Haast Schists extend westward right through to Central Otago. The Haast Schists are uncomformably overlain by the terrestrial deposits of the Henley Breccia, an Upper Cretacious fanglomerate and the quartz sands, conglomerates and coal measures of the Taratu formation. These are subsequently overlain by a sequence of Late Cretacious to Tertiary Upper Miocene, marine sediments which were deposited during a marine transgression. The marine sedimentary sequence, with a general north-easterly strike and gentle south-easterly dip, forms the immediate basement to the Dunedin volcanic complex (Coombs, 1965).

The eruptive activity of the Dunedin Volcano commenced in the upper Miocene and was comprised of four principle phases. The initial eruptive phase, centered on Portobello, opened with tranquil, or explosive, ejection of almost purely feldspathic trachytic lavas and fragmentic rocks (Benson, 1959). This is believed to have commenced before the sea had completely regressed (Coombs, *et al*, 1986) with ash of the initial eruptions found in the Waipuna Bay formation (Suggate, 1978) which is of shallow water origin (Coombs, *et al* 1960). Thus the initial eruptions may have been offshore but were mostly subaerial. It is considered that at this time there may have been "*a small volcanic archipelago, or system of peninsulas consisting of trachytic flowrocks and breccias and early basaltic cinder and scoria cones lying at the seaward edge of a coastal strip of Upper Cretaceous and Tertiary sediments, with a hinterland of Schist*" (Coombs, *et al*, 1960, p 576). Thus the coast of the Otago Peninsula was intially formed as the volcanics pushed their way up out of the seabed and rising above the ocean surface. Coombs, *et al* (1986) note evidence of both explosive erruptions and quieter effusions of basaltic lava and dome building.

The first main eruptive phase was also centered on Portobello, with

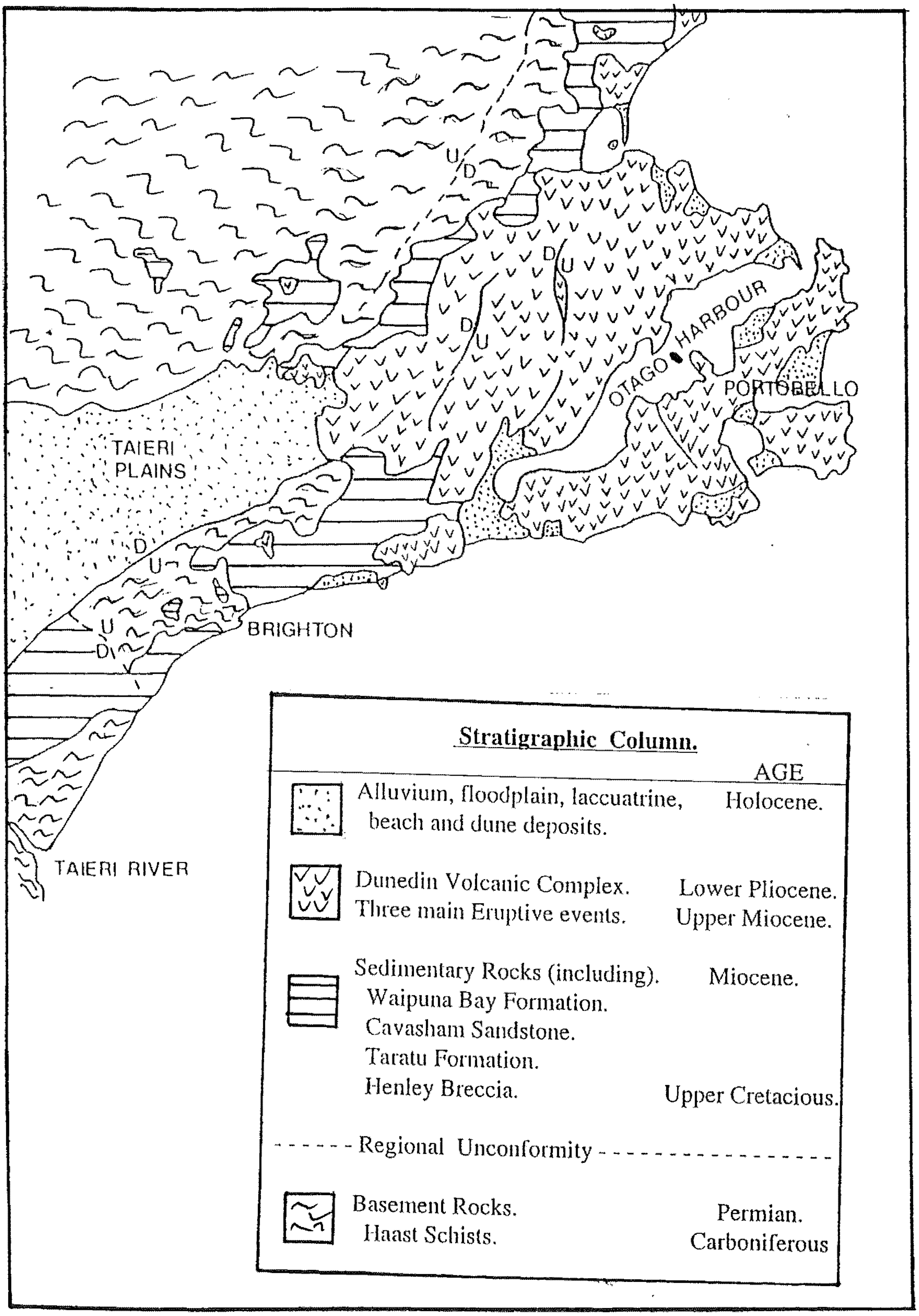


Fig. 2.2: Generalised geology of the Dunedin District. (source: Suggate, 1978; McKellar, 1990)

compositions ranging from basalt to trachyandesite and phonolite (Coombs, 1965) with flows extending further to the north and west, and becoming significantly more emergent above sea level.

The volcanic flows of the second main eruptive phase were the most voluminous, varied and widely distributed, commencing with basaltic flows, followed by rather more feldspathic and alkaline rocks and closing with massive and widespread phonolite (Benson, 1959). By the end of the second main eruptive phase, flows had reached up to 18 miles north and west of the volcanic centre (Coombs, 1965).

The third main eruptive phase was centered to the northwest of the Otago Harbour, with basaltic flows followed by voluminous phonolites.

K-Ar dating has assigned the volcanic activity to an active period of 13-10ma (Coombs, *et al*, 1960), thus allowing long periods of tranquility and subsequent erosion between volcanic eruptions over the 3 million years.

The Dunedin Volcano is situated at the northern end of the Taieri Graben, and it, along with other continental alkalic volcanism is believed to be associated with extensional tectonics. Despite the present fault-block topography of eastern and Central Otago being presently compressional, there is evidence that there was a reverse in movement and therefore extensional stresses in the crust during the period of volcanism (Coombs, *et al,* 1986). Volcanism is thought to have been shut down by the onset of the Kaikoura Orogeny which led to the present day compressional tectonics thus sealing the volcanic events around 10 ma. This also tells us that the volcanic building of the Otago peninsula was now also complete.

Since then the volcano and its newly formed volcanic coastline have had 10 million years to succumb to the forces of marine and terrestrial erosion. The Dunedin Volcano is now dissected in two via the drowned valley which forms Otago Harbour. At the coast Quarternary sediments, mainly sand, have been deposited within the many embayments formed between the rugged volcanic cliffed headlands.

2.3 THE OTAGO CONTINENTAL SHELF

The bathymetry of the South Otago Continental Shelf can be seen in Fig. 2.3. From this it can be seen that the Otago Continental shelf between Nugget Point, in the south and Karitane in the north has an average width of 30 km, the exception being adjacent to the Otago Peninsula, where it is reduced to a width of about 10 km. The break between the continental shelf and continental slope generally lies between depths of 125-150m, but may reach 105m at the heads of submarine canyons. There are 7 major canyons along with a number of minor ones. Gradients range from a steep 1;30 across the narrow shelf adjacent to the Otago Peninsula to a more usual 1;200 over the other wider areas of the middle and outer shelf (Carter, *et al*, 1985).

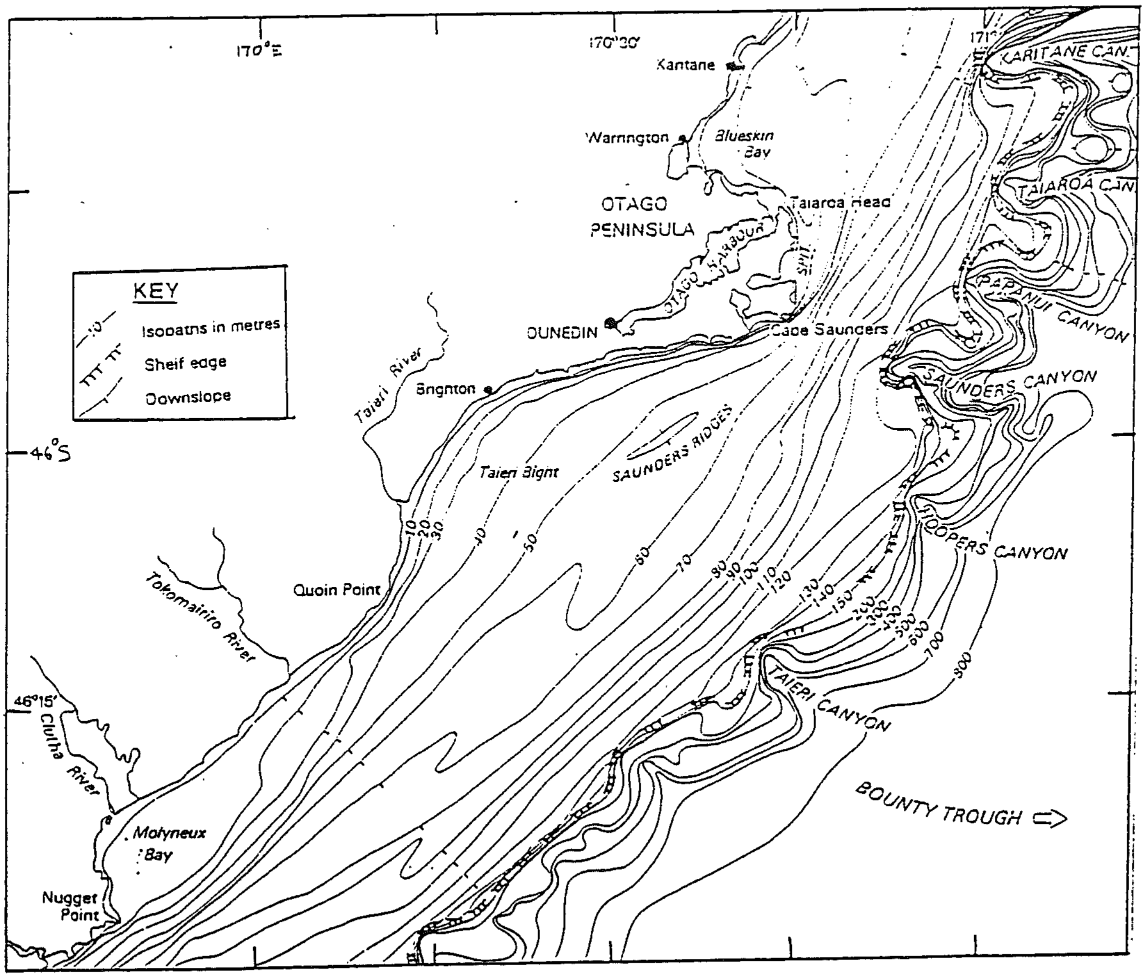


Fig. 2.3: Bathymetry of the South Otago Continental Shelf. (source: Carter, *et al* 1985).

There are two main factors of the continental shelf which impinge on the coast. These are the movements of waves and currents, etc, ie; the hydraulic regime, and also the nature of sedimentation on the shelf.

2.3.1 HYDRAULIC REGIME

The hydraulic regime of the South Otago continental shelf is dominated by three main influences which are the Southland Current, the local semi-diurnal tide, and a predominant southerly swell.

2.3.1.1 Currents

The Southland Current was first investigated by Brodie (1960) using drift cards and bottles, and has since been investigated in numerous papers (Jillet, 1969: Andrews, 1973: Carter and Ridgeway 1974: Heath, 1972 & 1973). It has been established that the Southland Current originates in the South Tasman and consists of subtropical, high saline water which flows in a narrow path along the coast around the bottom of the South Island, through Fovoux Strait and then northeast along the South Otago continental shelf (Heath, 1972). The outer margin of the current is separated from the offshore, colder, less saline subantartic water by the Southland front, and usually lies near the shelf edge. The inner margin always lies within 13km of the shore, but may extend at times right to the shore (Jillet, 1969). A sharp salinity and temperature front also marks the boundary between the inner margin of the current and the nearshore zone of neritic water, the physical properties of which vary considerably with the seasons and variations in rainfall. While the Southland current extends over the complete water column, hydraulic measurements (Jillet, 1969) have determined that the currents core is centered over the 100m isobath in winter and moves inshore to lie near the 40m isobath in summer. While the core is considered to coincide with the zone of maximun velocity long term quantitave measurements of current velocity have yet to be made. Heath (1973) calculated average surface speeds to the northeast to be around 7-8 cms^{-1}. However direct current velocity measurements east of the Otago Peninsula, Table 2.1, reveal somewhat increased speeds at depth.

Table 2.1: Current speeds and directions measured off the Otago Peninsula.

Depth (m)	Mean Current Speed (cms^{-1})	Direction/Bearing
35	31	N - NNE
65	36	NW - N - NE
85	24 - 67	variable
bottom depth = 100m	(source Andrews, 1979; p797).	
20	18	0 - 50
35	30.6	270 - 0 - 40
50	30.6	320 - 0 - 30
65	36	310 - 0 - 020
85	31	
bottom depth = 95m		
	(source Roberson, 1973, p92; *in* Nicholson, 1979, p53).	

It has been pointed out by Andrews (1973) however that these speeds may be higher than those experienced over the wider shelf to the south due to the constricting influence of the Peninsula, the flow being fastest where the continental shelf is narrowest. Given this and the fact that they are all one off measurements, implications for mean current speeds over the entire shelf can only be speculative.

2.3.1.2 Tides

The local Otago semi-diurnal tide has ranges varying between 1.1m-2.4m, with a spring range of 1.78m and neap range of 1.42m (Hydrographic Office, 1993). Measurements taken to the east of the Otago Peninsula show the floodtide to set initially west-northwest at 10cms^{-1}, then rotate clockwise to flow north at hightide at 51cms^{-1}, and east-northeast just before low tide at 5 cms^{-1} (Andrews, 1973). Thus the tidal current direction reinforces the Southland current off the Peninsula indicating that measurements of either may contain elements of the other.

2.3.1.3 Waves

The South Otago Continental Shelf wave regime is dominated by a persistent southerly swell (Elliot, 1958; Hodgeson, 1966; Pickrill & Mitchell, 1979). This results in a dominant north to northeast longshore drift within the nearshore zone of the inner shelf. The wave regime will be discussed in greater detail within Chapter 5 The Wave Environment.

2.3.1.4 Sediment Transport

From the above discussion it can be seen that all three of the hydraulic influences result in north to northeasterly currents across the entire continental shelf. These currents can also be further enhanced by the prevailing strong southerly winds and their associated storms. Given this strong combination of currents in the same direction the resultant movement of continental shelf sediment is also to the north to northeast.

The greatest transport of sediment is considered to occur within the littoral zone (Carter & Heath, 1975). This has also been revealed in studies of the Otago beach sands. Here there is a general agreement on a southern Clutha dominated source, with a northward transport and dispersal within the littoral zone. Early documentation of this came from Thomson (1870; *in* Kirk, 1979) and Marshall (1905; *in* Kirk, 1979). Later Bardsley (1977) used mineralogical evidence to confirm these ideas. He showed that the beach sands of the Catlins coast, to the south of the Clutha, are rich in minerals from the Foveaux Strait-Western Province suite, notably hypersthene and hornblende. Just north of Nugget Point however, in the vicinity of the Clutha River mouth, the beach becomes inundated by Haast Schist derived quartzo-feldspathic sands. These sands can be traced to the north, dominating beach and dune deposits continuously to north of the Otago Peninsula. Further confirmation of this dominating north to northeast littoral zone transport shows up in the arrival of pyroxenes and olivine, from the Dunedin Volcanics, in sand deposits some 15km northeast of the first coastal volcanic outcrops.

Further out on the continental shelf Carter and Heath (1975) considered that the role of waves was to stir up and suspend sediment, but not to cause major sediment transportation due to their oscillatory motions. It is considered that the bottom surges from the grounding of swell waves can stir sediment during calm weather to depths of about 30m (Carter, *et al*, 1985) but have the potential to stir sediments to depths of 70m during annual storms, and 130m during maximum 25 year storms (Carter & Heath, 1975). Given the uncertainty of the current speeds on the open Otago continental shelf it is unknown as to whether the tidal and Southland currents have sufficient speeds to initiate sediment transport although the general consensus is that thay can not (Carter & Heath, 1975; Carter, *et al*, 1986). An exception to this may occur on the shelf adjacent to the Otago Peninsula, with its increased current speeds. Thus sediment transport on the Otago continental shelf is considered to be less frequent than that within the littoral zone, requiring the stirring and suspension of the sediment by waves, before it can be transported north by the tidal and Southland currents.

2.3.2 SEDIMENTATION

Numerous studies have been carried out over the years with respect to sedimentation on the South Otago Continental Shelf. The earliest study (Marshall, 1931; *in* Carter, *et al*, 1986) recognised that extensive areas of coarse grained sediment were present on the shelf.

Later in a more detailed investigation of shelf sediments off the Otago Peninsula utilising bathymetry and surficial sediment sampling Andrews (1973) showed that there was a gradation across the shelf. Sedimentation graded from that of a nearshore sand, to a muddy sand, to a muddy sandy gravel. Along with sampling from other areas he showed that the pebbly gravels occurred as a continuous band on the mid shelf from offshore of the Clutha river, none being present in samples collected south of Nugget Point, to north of the Otago Peninsula, where the pebbles grade into sands. Distribution and analysis of modal size suggested a Clutha origin. The pebbly gravels were considered to be relict, (Pleistocene in origin), delivered to a submerging coastline following the last glaciation, where glacial melt led to increased runoff, and thus an increased competance and capacity of the Clutha. The gravels were subsequently distributed to the north under the influence of an early Southland Current and dominant northerly longshore drift. Epizoan coverage suggested that the gravels are rarely in motion under the present hydraulic conditions, and are thus a relict feature of the shelf. However this interpretation by Andrews (1973) was the subject of some debate (Schofield, 1976, 1977; Cullen, 1976; Andrews, 1976; Probert, 1977) after Schofield (1976) suggested that rather than a relict feature of a little modified drowned landscape, that the continental shelf is a seascape in or approaching equilibrium with the present sea level. It was argued by Schofield (1976) that given the position of the Southland Current relative to the gravels, the pebbly gravel belt could be a lag deposit in partial equilibrium with todays Southland Current, the modern hydraulic regime being responsible for the removal of finer material from this area. Other interpretations of the sedimentological characteristics of the shelf were also debated, such as whether a submarine sand spit, running north from the outer edge of the Otago Peninsula at Cape Saunders was formed during the 8 - 9ka sea level stand still, and subsequently drowned by the final phase of the post-glacial transgression (Andrews, 1976) or a modern feature formed by the deposition from north flowing currents (Schofield, 1976).

In an attempt to resolve some of the problems of this debate and to provide a clearer picture of both the modern and relict sedimentation on the South Otago Continental Shelf Carter, *et al,* (1985) utilised both sedimentological and geophysical data including high resolution continuous seismic profiles, side-scan sonographs, core sampling, surficial samples, and underwater photography. Using statigraphic, compositional, faunal and textural evidence, based on this data collection, sediments were divided into four prominant sedimentary facies which occupy a succession of shore parallel belts across the shelf; a biogenic sand/gravel facies; a relict palimpsest sand facies; a relict terrigenous gravel facies; and a modern terrigenous sand facies. The sediment map of Carter, *at al,* (1985) showing the distribution of these sedimantary facies can be seen in Fig. 2.4.

2.3.2.1 The Biogenic Sand/Gravel Facies

This facies is most widespread on the outer shelf with both relict mollusc detritus and modern living molluscan and bryozoan faunas.

2.3.2.2 The Relict/Palimpsest Sand Facies

This facies forms an ill defined middle to outer shelf belt, with diffuse landward and seaward boundaries, the sand intermingling with both the modern sand inshore and the relict gravels offshore. The advancement of the modern sand wedge has largely inundated this facies to the south of the Tokomairo mouth. Mineralogy suggests a mixed provenance of both Haast Schist and Foveaux Strait - Western Province sources. Thus sediment has been supplied

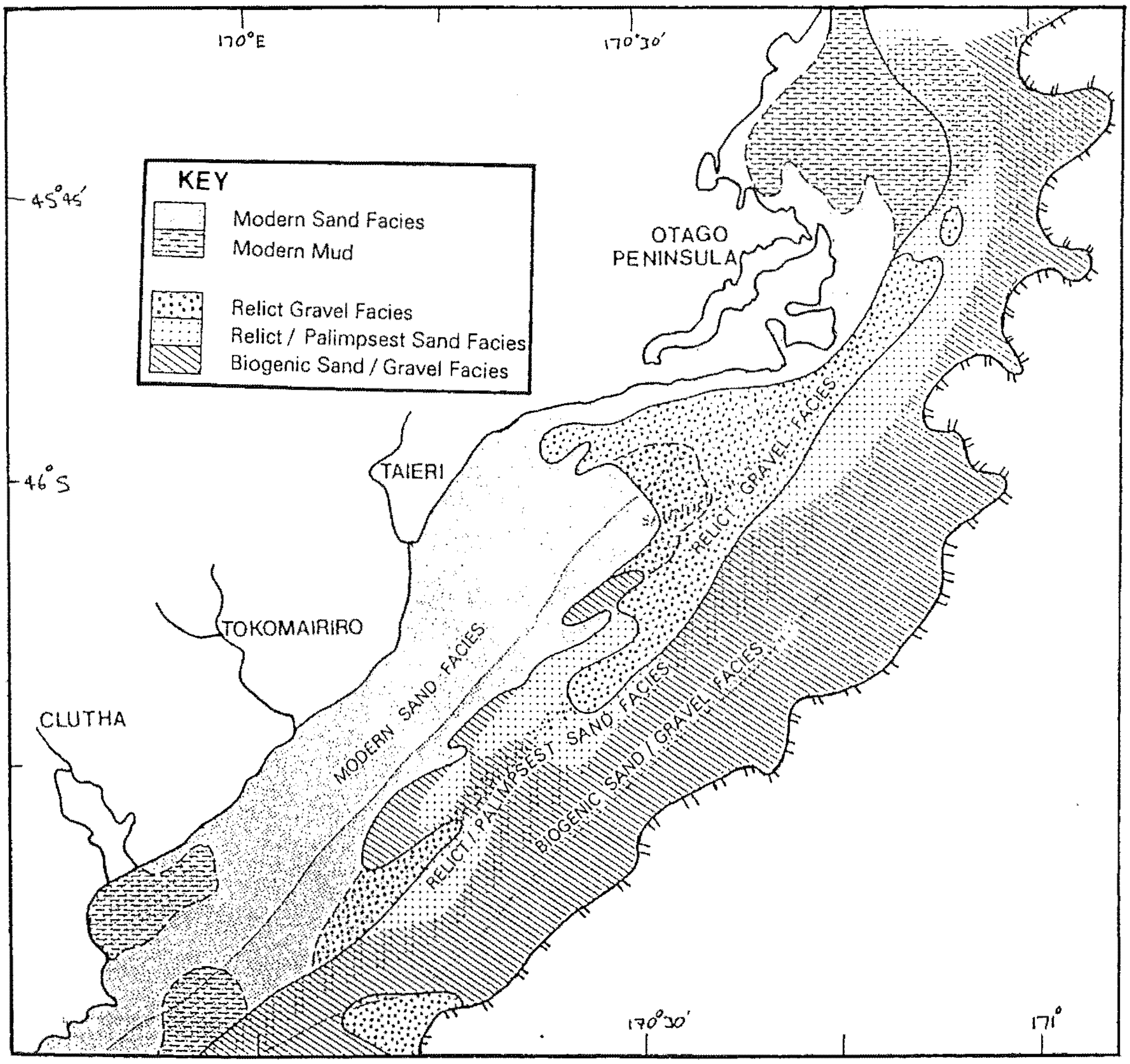


Fig. 2.4: Distribution of the main sediment facies on the south Otago continental shelf. (source; Carter, *et al*, 1985).

Note: Solid boundaries delimit main body of the facies, dashed boundaries denote areas where facies limits are indistinct, eg areas of sediment mixing (Carter, *et al*, 1985).

from both the Clutha River and the continental shelf to the south of Nugget Point, respectively. Carbon 14 dating, 10ka, of faunal elements with minor modern bryozoan encrustation were taken to establish beyond doubt the relict nature of this facies.

2.3.2.3 The Relict Terrigenous Gravel Facies

This facies forms a northeast southwest trending belt on the middle shelf. The well rounded clasts of yellow to cream vein quartz, are typically iron stained, and derived from the Haast Schists, with a dominant Clutha source. The relict interpretation supports the earlier mentioned arguments of Andrews (1973). Pebbles of less than 10mm diameter are usually clean, which is taken to imply that they are still subject to transport, unlike the larger encrusted, and therefore stationary pebbles (Andrews, 1973; Williams, 1979, *in* Carter, *et al*, 1985). However Carter, *et al*, (1985), point out that the larger encrusted pebbles are not necessarily immobile, but that they may be moved by water motions with a frequency less than that of the encrusting growth rate, such as several centimeters per year for bryozoans.

2.3.2.4 The Modern Terrigenous Sand Facies

This facies occurs as a seaward thinning wedge of fine grey sand which achieves its maximum width and thickness offshore of the Clutha River Mouth which is its dominant source. The broad belt of the wedge, between the Clutha and the Taieri rivers, narrows substantially offshore of Brighton, some 60km north of the Clutha, to a nearshore ribbon of only 2 - 3km width. This narrow inshore ribbon of sand remains fairly constant in width, continuing around the Otago Peninsula, to just north of Karitane. This marked reduction in the width of the sand wedge just to the south of the Otago Peninsula, is thought to reflect either the maximum extent of modern sand transport north along the shelf, or to be a response to local hydraulic conditions, a speculated reversal of currents against the Peninsula. The broad sand belt to the south of the Otago Peninsula can be split into two shore parallel suites by way of mineralogy. The outer suite is supplied from the continental shelf to the south of Nugget Point, with a Foveaux Strait - Western Province mineralogy dominating. The inner suite is dominated by Haast Schist derived sands, thus having a dominant Clutha source. The fining of mean grain size, to the north is in accordance with the regional dispersal patterns mentioned earlier. A slight coarsening of the mean grain size on the Otago Peninsula is accredited to the increased currents associated with the constriction of currents due to the narrower shelf width.

With respect to the Peninsula Spit it is noted that on the seismic profiles, the presence of an internal reflector, could mark the position of the earlier 8 - 9ka spit of Andrews (1973) but that the present surficial sedimentology and bathymetry are in equilibrium with the modern hydraulic regime.

It was also noted (Carter, *et al*, 1985) that a modern terrigenous mud is an important feature of the near shore sand wedge in two areas;

a) within Molyneaux Bay, offshore of the Clutha River, due to a high percentage of the rivers sediment output being mud. This is combined with the sheltering effect of Nugget Point on the dominant southerly waves, and currents, see also (Carter & Ridgeway, 1974).

b) within Blueskin Bay due to the sheltering effect of the Otago Peninsula on the dominant southerly waves and currents. The presence of a counter clockwise eddy within the bay is also important.

On the other areas of the open shelf the absence of muds is seen as a direct result of the strength of the combined currents over the middle to outer shelf, and the winnowing effect effect of waves along the inner shelf.

The evolution of the modern terrigenous sand facies, (also termed the Holocene sand wedge), is believed to have been initiated by a standstill in sea level at around 8 - 9ka, at which time the Clutha was no longer transporting gravels to the coast, due to aggradation in its lower reaches (Andrews, 1973).

Carter and Carter (1986) consider the Holocene sand wedge to have evolved in two main phases. They consider that Molyneaux Bay was favoured for the initial formation of the wedge due to a combination of an abundant sediment supply from both the Clutha and the Southland continental shelf, and the protection afforded by Nugget Point from the dominant southerly storms. As the sand built out, burying the Pleistocene gravels, it would eventually become more exposed to the north to northeast current regime, and thus begin to be dispersed to the north. A resumption in the transgression is believed to have then led to a halt in sedimentation due to a Clutha River once again within an aggradational phase, until attainment of the modern day sea level at around 6.5ka. With a stable sea level the fine sands and muds presently delivered to the coast by the Clutha were able to accumulate over the older initial wedge, being dispersed both across and along the shelf.

From the above discussion it can be seen that the nature of sedimentation on the South Otago Continental Shelf is reasonably well understood. However despite of this it is pointed out that "*there is little appreciation of the quantities of river sediment retained and removed from the shelf, and the significance of river input relative to other sediment supplies, (eg; coast, adjacent continental shelf, biogenic activity).*" (Carter, 1985, p665). To address this Carter (1985) presented a proposed sediment budget for the modern Holocene sediment in the context of the overall sedimentary regime. This proposed budget can be seen in Table 2.2.

From this it can be seen that sediment input is dominantly terrestrial, with some 85 percent coming from the combined Clutha, Taieri, and Tokomairo rivers. However it is the Clutha alone which has the single most dominant input at 70 percent. Other inputs include sediment delivered from the Southland Shelf, and sediment derived from the production of biogenic sand. The input from coastal erosion was taken to be neglible, due to the static nature of the coast. Between Nugget Point and Cape Saunders storage is dominated by bedload deposition into the nearshore sand wedge with only minor amounts stored as beach and dune deposits. The remainder of the bedload is transported north of Cape Saunders to be deposited mainly within the Otago Harbour and on the floor and shores of Blueskin Bay. Despite muds dominating sediment input, 52%, little is retained on the South Otago continental shelf south of Cape Saunders. Instead the muds are swept to depocenters north of the Otago Penisula and to the adjacent continental slope. The bedload budget deficit is seen as a discrepency between the estimation periods of the Inputs, 6.5ka, and the Storage, 9.6ka. Firstly, increased fluvial input rates during the 9.6 - 6.5ka period possibly related to the last main phase of deglaciation, if included would reduce the deficit. Also an influx of sediment eroded from a previously emergent Foveaux

Strait, along with a period of high loess accumulation around this time, not accounted for here, would have also reduced the budget deficit.

Table 2.2: Sediment budget for the South Otago shelf between Nugget Point and Cape Saunders.
(source, Carter, 1986).

	Bedload. ($Mtyr^{-1}$)	Suspended load. ($Mtyr^{-1}$)
INPUT.		
Sediment from the Southland shelf.	+ 0.40*	?
Clutha River.	+ 1.23	+ 1.91
Taieri River.	+ 0.24	+ 0.36
Tokomairiro River.	+ 0.03	+ 0.06
Production of biogenic sand.	+ 0.25	?
Total.	+ 2.15	+ 2.33
STORAGE.		
Sand wedge.	- 1.35*	- 0.02
Littoral and dune deposits.	- 0.04*	-
Total.	+ 0.76	+ 2.31
OUTPUT.		
Sand transported to beaches and inner shelf north of Cape Saunders.	- 1.09*	
Grave loss by attrition.	- 0.04	+ 0.04
Bedload budget deficit.	- 0.37	
Suspennded load transported to shelf, north of Cape Saunders, to continental slope and Bounty Trough.		- 2.35
Suspended load budget deficit.		0.00

Note: The proportion of bedload to suspended load for the Taieri and Tokomairiro Rivers is based on data from the Clutha River. Rates with asterisk apply to 9.6ka, the remainder are for 6.5ka (Carter, 1986).

The sediment budget of Carter (1986) decribed above was estimated for a dam free Clutha river given that the effect of the dams would be small in the context of the 9600 year history of the wedge. The presence of the dams do however affect the present day sediment budget. This is important given the dominance of the Clutha in providing sediment to the system. The effect of a dam is to trap the sediment upstream therefore reducing the input of sediment to the coastal system. For the Roxburgh dam which has been in place since 1961 bedload has been trapped at a rate of $0.61 Mtyr^{-1}$ (Jowett and Hicks, 1981, *in* Carter, 1986) which is about 50 percent of the Clutha bedload of the above sediment budget. The Roxburgh is not the only dam on the Clutha, but was the largest until the 1992 completion and filling of the Clyde. Thus the estimated 50 percent reduction in bedload input at the coast could possibly be taken as a minimum. Whether or not the shelf and coastal sediment systems have had sufficient time to respond to these reductions is at present unclear, and is something that only future research may address.

However under an assumption of an unchanged hydraulic regime the potential to transport sediment to the north would remain unchanged. Thus any reduction in the sediment input would possibly lead to reductions in both the sand wedge and beach and dune deposits, and therefore increase the possibilty for erosion along the coastline. Also the beach and dune deposits could possibly be seen as landward extensions of the sand wedge, rather than that of a separate entity. Thus any changes in shelf sedimentation affecting the sand wedge are most probably likely to also effect beach deposits, and thereby induce coastal changes.

2.4. FEATURES OF THE OTAGO COAST

The major structural control on the Otago coastline is the geology, and the dominant feature is the protuberance of the Otago Peninsula. The presence of the Dunedin Volcanic Complex which forms the Otago Peninsula results in an interruption to the general northeast - southwest trend of the Otago coastline. The types of rocks that outcrop at the coast influence the nature of coastal features that are seen along the shore. A map of these varying coastal features can be seen in Fig 2.5.

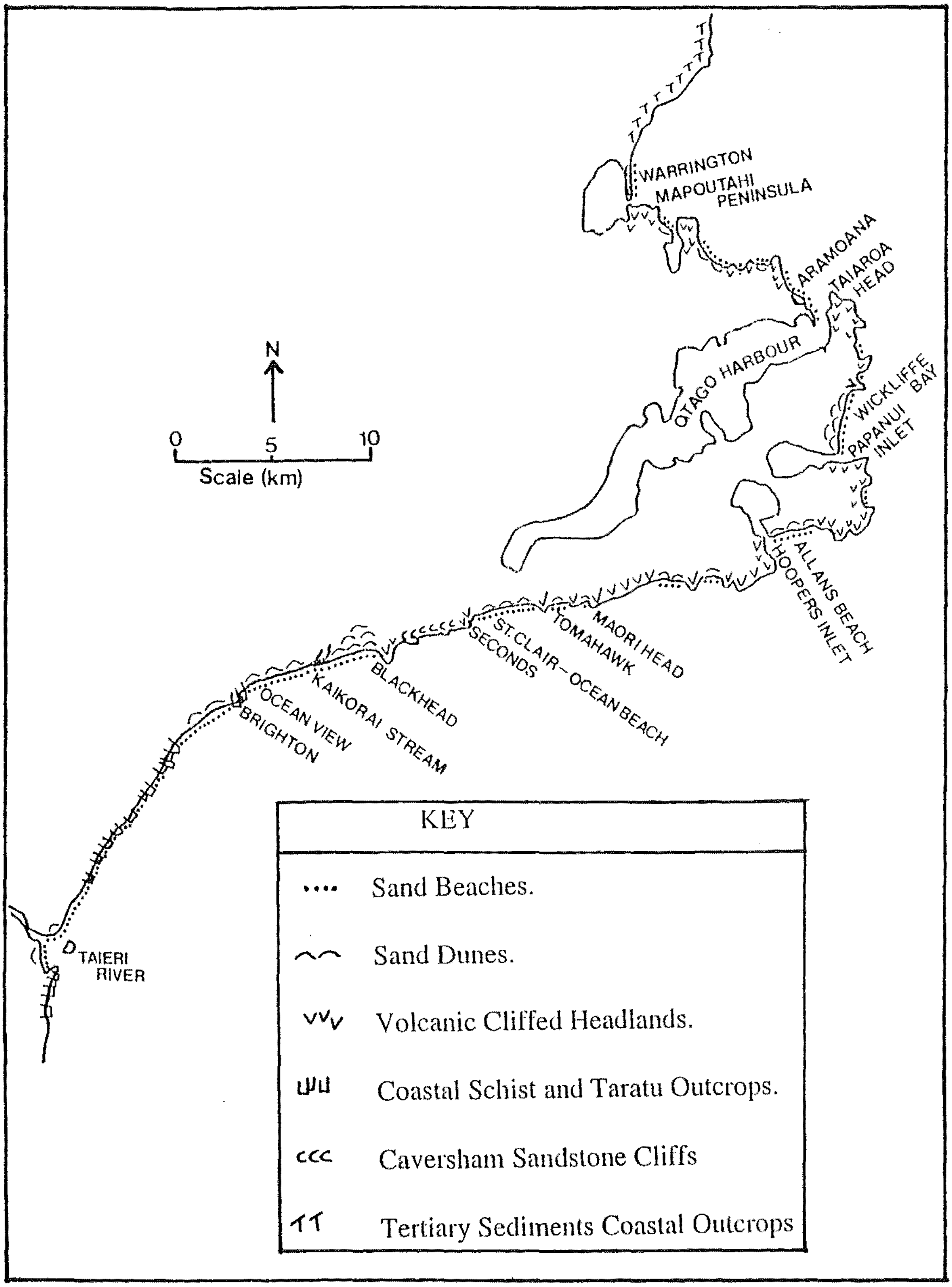


Fig. 2.5: Features of the Otago Coast.

From the Taieri river north coastal outcrops of Haast Schist and Taratu Formation result in a coastline consisting of pockets of sandy beaches between the rocky outcrops. Erosion of the Taratu measures has lead to a coarser, more rounded than normal, beach sand along this stretch of coast (Elliot, 1958; Hodgson, 1966). There is little accumulation of sand within dunes along this coast for some 11- 12km. Then here where the coast begins to trend more to the east, a broader stretch of continous beach backed by narrow vegetated dunes runs some 3.5km to Brighton (Otago Regional Council, 1992a) where schist once again outcrops at the coast. From these schist outcrops which form the Brighton headland a sandy beach backed by broad well vegetated dunes runs some 8.5km to the first coastal volcanic outcrop, the columnar basalts of Blackhead. The only interruption to the beach is at the mouth of the Kaikorai Stream. South of the stream dunes extend inland for 50 - 100m, while to the north they extend inland up tp 600m attaining heights of some 60m (McKellar, 1990). From the Kaikorai lagoon a 7m high raised marine beach can be traced through Ocean View, inland of the modern dune deposits, and then continuously from Brighton to the Taieri mouth, (McKellar, 1990). On the beach at Blackhead along with the beach sands the sediments include volcanic boulders derived from the headland, and some larger boulders of Caversham Sandstone which outcrops on the beach. Between Blackhead and the basalt headland at Seconds, Caversham Sandstone outcrops forming cliffs of up to 30m. Seconds beach, composed of volcanic boulders, is separated from St. Clair by St. Clair point, on which the Hot Salt Water Pools are situated. The beaches and coastline to the west and south of St. Clair has remained relatively unstudied.

The St. Clair - Ocean beach and its eastern neighbour, Tomahawk, compose the two beaches on which the present research was undertaken, and as such will be discussed in greater detail within the next section, 2.5, The Two Study Beaches.

From Maori Head to Taiaroa Head, at the Otago Harbour entrance, is the rugged irregularly embayed coastline of the Otago Peninsula. Numerous sandy beaches are separated by steep cliffs of the Dunedin Volcanics. The two largest bays, Wickliffe Bay, and Allans Beach, contain the Papanui and Hoopers inlets respectively. Both of these inlets have their channels at the southern ends of the beaches resulting in south facing spit tips. Early physical coastal research in the Otago area was focussed on explaining the origin and evolution of these two and other similar southward pointing spit tips to the north. Eliot (1958) considered that the growth and form of the spits was related to the modification of the dominant southerly swell by the bimodally distributed local winds. The strongest southwesterly winds were considered to build up and steepen the southerly swell, making it erosional in nature. Meanwhile the lowering and flattening of the southerly swell by the diametrically opposite northeasterly wind was tentatively associated with beach accretion and therefore the construction of the spits. Hodgson (1966) brought to attention the importance a secondary northeast to easterly swell in the Otago region giving rise to a less frequent, but important, southward longshore drift. Here it was considered that the spits were constructed by the onshore movement of sand, recognised by the seaward concavity of the shoreline, rather than by longshore drift, recognised by seaward convex spit tips. The position of the inlet channels at the southern ends of the bays was seen as being due to the fact that this is where the dominant southerly swells were the most refracted and decayed. Thus the southern ends of the bays were considered to be the zones of lowest wave energy where the inlets could most easily maintain an opening to the sea.. The merits of these arguments will be further discussed later in the light of new information brought to hand by the results of this study.

The entrance to the Otago Harbour is situated between Taiaroa Head and the sand flats of Aramoana. On the western side of the entrance, in an effort to stabilise the channel, a 1.3km groyne has been constructed dividing the spit beach in two. The eastern beach is presently erosional while the western beach continues to accrete sand (Otago Regional Council, 1992a). An influx of sediment into the Harbour from the coastal littoral system results in the silting up of the harbour therefore requiring the main shipping channel to be dredged to remain operational. The dredge spoil is presently dumped off both spit beaches.

The northeast coast of the Otago Peninsula lies between Aramoana in the east and Mapoutahi Peninsula in the west. Like the Peninsula coast to the east of the Otago Harbour the northeast coast is characterised by embayed sandy beaches interrupted by volcanic headlands. Due to its location the northeast coast recieves only extremely decayed and refracted waves from the dominant Otago southerly swell. It is however more open to waves from the northeast with a slight to moderate northeast sea running about 37 percent of the time (Hodgson, 1966). The lower energy wave environment is reflected in the beach sands which are finer than those of the more exposed southern beaches (Hodgeson, 1966). Excluding Aramoana the northeast coast beaches have been shown to display a history of rapid and recent progradation of up to 3.2myr^{-1} (Nicholson, 1979).

Warrington beach, a spit separating the ocean from an estuary, also shows a recent, 1862 - 1968, accretional trend which continues today (Gibb, 1979, *in* Otago Regional Council, 1992a). North of Warrington coastal outcrops of unstable Tertiary sediments has resulted in a rugged, cliffed, unstable coastline (Otago Regional Council, 1992a).

2.5 THE TWO STUDY BEACHES

The two beaches on which the research was undertaken were the adjacent Tomahawk, and St. Clair - Ocean beaches, Fig. 2.5. The St. Clair - Ocean Beach backs directly onto the coastal suburbs of Dunedin City, while Tomahawk backs on to the residential and recreational area of Ocean Grove. Thus both beaches are backed by urban development, and have subsequently been impacted on by human actions in their most recent, 100 - 150 year, history. Therefore to understand the form and nature of the present coastal environment, the influence of past human actions on the coastal system must be taken into account.

2.5.1 TOMAHAWK BEACH

Tomahawk beach lies between Lawyers Head in the west, and the fortified headland, adjacent to the rocky Bird Island reef in the east, which separates it from the next beach, Smails, Fig. 2.6. In the early nineteenth century, the dunes were largely devoid of vegetation (Harris, 1987). Recorded observations indicate that there was a greater extent of highly mobile bare sand within the dune

Plate 2.1: Overview of Tomahawk Beach looking west toward Lawyers Head with St. Clair in the back ground.

Plate 2.2: Notification of dune conservation and sewage problems at Tomahawk.

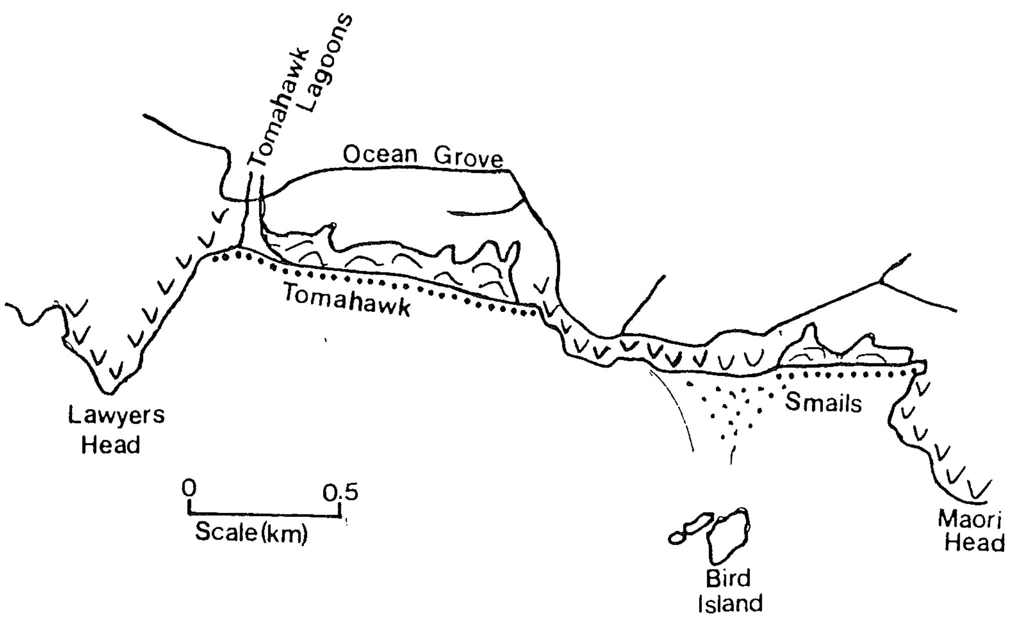


Fig. 2.6: The Tomahawk coastal area.

system around this time (Thompson, 1870, *in* Kirk, 1979). Kirk (1979) considered this to be related to the fact that the primary dune vegetation of this time was most probably the native Pingao, (*Desmoschoenus spiralis*), which tends to grow at low densities, resulting in low, flat, humocky dunes, with highly mobile sand. With the introduction and subsequent planting of Marram Grass, (*Ammophilia arenaria*), first initiated in 1890 (Morrison, 1955) Kirk (1979) considered that the most important changes in the beach system for the 1862 to 1942 period to be a direct result of this change in the type and extent of the primary dune vegetation cover. A dense coverage of Marram Grass results in a higher, steeper, and less mobile dune field. The policy of Marram planting has continued to the present day (Dunedin City Council, 1985; Harris, 1987) along with a hindune policy of planting native trees and shrubs. Also in 1984 brush fences were erected which have been sussessful in the trapping of sand and subsequently the building up of the foredune. The erection of fences around and through the dunes has restricted user access thus affording dune protection and also allowing newly seeded plants the chance to establish (Harris, 1987). Through the analysis of aerial photography Kirk (1979) showed that Tomahawk beach had prograded some 30m between 1942 and 1958 but had then shown no growth after this 1958 date. This was attributed to the mining of sand directly from the beach which began in 1952-53, the sand extration halting the beach growth. The sand extraction takes place on the western end of the beach at the outlet of the Tomahawk Lagoons. The sand removal is seen as playing an important role in maintaining the Lagoons channel outlet and therefore minimising the flooding potential within the Lagoon, and around the neighbouring residential land (Harris, 1987).

In 1971 Tomahawk beach was considered "*...unfit for a family outing or for a stroll on the sands...*" due to the beach being "*... befouled by sewage from the Lawyers Head outflow...*" (D.M.R.P.A. 1971, p16). With the installation of a new treatment plant the beach itself is no longer fouled by sewage. However the sea is still considered unsafe for surfers and swimmers (Harris, 1987), Plate 2.2.

Today Tomahawk beach is a stable sandy beach, backed by a well vegetated stable dune field, along its entire length. The exception is at the western end where sand mining prevents dune build up to maintain the Lagoon channel outlet. Present day management practices are a continuation of the vegetation planting and sand conservation policies that were reintroduced in the 1980's (Dunedin City Council, 1993).

2.5.2 ST. CLAIR - OCEAN BEACH

The St. Clair - Ocean Beach is situated to the west of Tomahawk, lying between Lawyers Head in the east and St. Clair Point in the west. This beach is the most extensively modified in the Otago area (Kirk, 1979) which is not surprising considering that it is situated adjacent to Dunedin City. The beach and its hinterland sit at the southern end of the Otago Harbour and are considered to have taken the form of a tombolo, that is a bar of sand connecting the Otago Peninsula to the mainland. The St. Clair - Ocean Beach is a steep sandy beach with a single vegetated dune running almost along its entire length. The exception is at the western St. Clair end where the dune system has been repaced by a concrete seawall in order to protect public and residential developments. West of the built up residential St. Clair end of the beach the dune is mostly backed by public sports grounds. Also from St. Kilda a road, John Wilson Memorial Drive, runs east to Lawyers Head. This road was situated for the most part on top of the foredune, which was extensively built up with rubble fill. Now a new foredune has been grown along the front of John Wison Memorial Drive thus displacing the old rubble fill encased foredune landward.

What follows is an early history of the St. Clair - Ocean beach coastline, summarised from Morrison (1955) and Aitken (1975). The early settlers along with the Maori had no use for the sandy stretch of coast for it had no trees for timber or grass for stock, while the hinterland was a swampy area covered with tussock. However by 1876 urban growth had pushed the city to the landward edge of the dunes. Sand was often removed from the dune area for the purposes of fill and reclamation. Sand was also removed to flatten land for the purposes of a park in the area which is now occupied by Tahuna Park. With numerous earlier breeches of the sea through the dunes having already occurred G.M. Barr, a civil engineer, gave a warning in 1880 that the continued removal of large quantities of sand from the dunes would increase the risk of the hinterland being inundated by the sea. With increased periodic encroachments of the sea the idea to reclaim the dunes was proposed and in 1890 lupin and marram seed was purchased with subsequent planting being carried out along the eastern end of the beach adjacent to the area now occupied by Tahuna Park. In 1891 however the sea broke through the dunes near the Central Battery and at the St. Kilda lagoon site causing extensive flooding of the residential hinterland. This extensive flooding led to an increased the demand for a safe sand hill barrier to

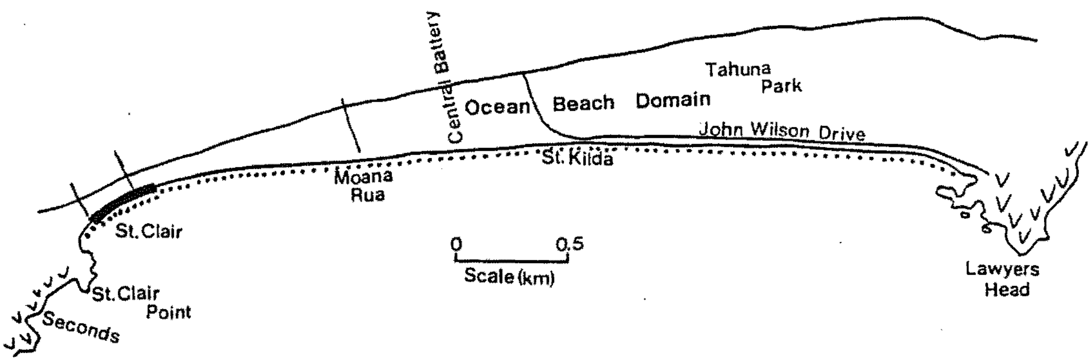


Fig. 2.7: The St. Clair - Ocean Beach coastal area.

Plate 2.3: Overview of St. Clair - Ocean Beach with St. Clair in the foreground, looking east to St. Kilda and Lawyers Head.

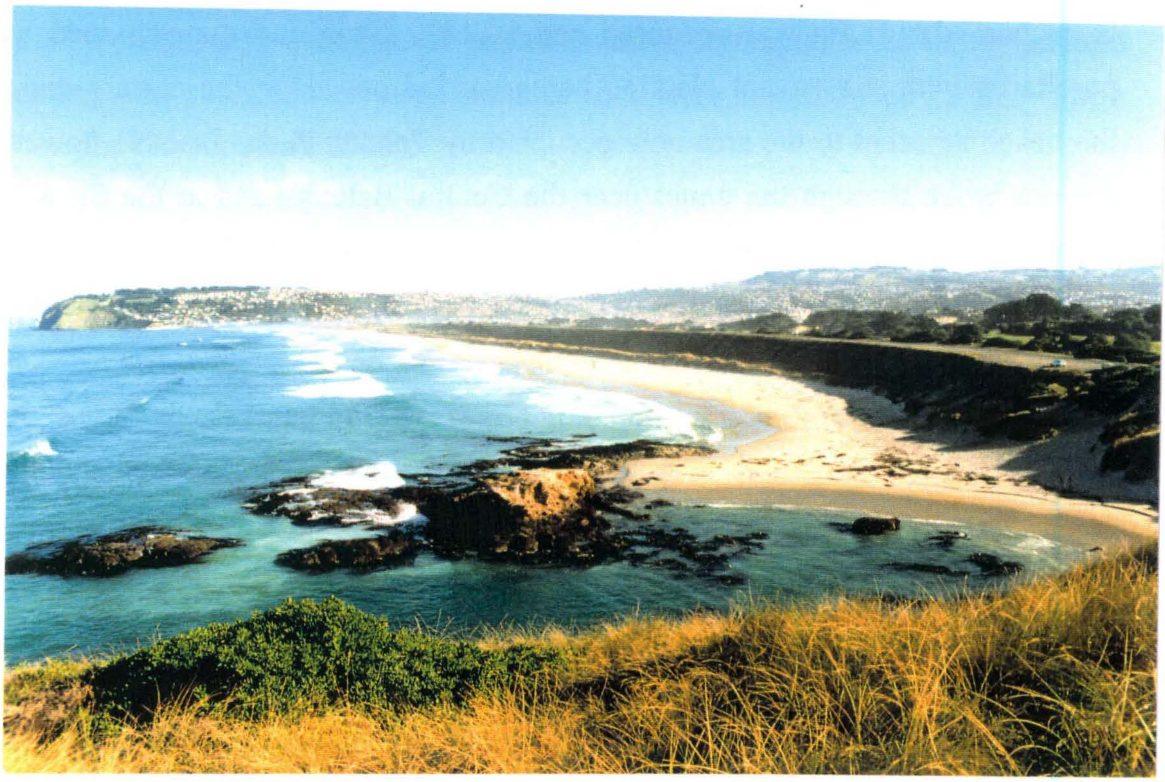


Plate 2.4: St. Clair - Ocean Beach looking west from Lawyers Head. Note recently grown foredune in front of John Wilson Drive.

hold the sea at bay. The subsequent debate that developed after the 1891 encroachments led to the formation of the Ocean Beach Domain Board in 1892. The Board introduced plans for the erection of wood and scrub fences along with continued planting of marram and lupin to build and stabilise the dunes. By 1898 however little progress had evolved with citizens often carting sand away from areas where it had been built back up. Also the defence authorities invited people to remove sand from adjacent to the Central Battery. Major inundations of the hinterland in both May and July of 1898 led to extra urgency in the planting of marram and lupin and the erection and maitenance of scrub fences. By 1902 the dunes had begun to grow in the problem areas and by 1952 the dunes had reached heights of 50 - 60 feet in places. With the dunes raised and stabilised the Domain Board set about developing the immediate strip of hinterland behind the dunes into the numerous parks and recreation areas that are seen today.

At St. Clair the first sea-wall was built in 1866 by a Mr. Smith whom by way of a survey error owned land right to the high water mark. Composed of unplastered stacked stones the structure subsequently collapsed as soon as the sand was washed out from behind it. The second sea-wall was built by the public works extending the width of the esplanade by 15 feet. This structure was undermined by storms in 1884 and was subsequently collapsed by further storms in 1886. With funding being directed at the more urgent issue of the raising and stabilisation of the dunes to the east, reconstruction of the seawall was not undertaken until some years later. In 1904 wooden groynes were erected at St. Clair with the beach rebuilding substantially by 1906. However it was not until 1912 that funding for the reconstruction of the seawall and esplanade was finalised. The new sea-wall and esplanade were oficially opened in 1913 and remain in place today.

The St. Clair - Ocean Beach also had some early pollution problems. In the nineteenth century the dunes were used for the dumping of dead animal carcasses garbage and nightsoil. Also, similar to Tomahawk, before the installation of the recently new treatment plant raw sewage from the Lawyers Head outfall was frequently washed up along the eastern end of the beach.

It can thus be seen that while the width of the dune field, now only one dune wide along Ocean Beach, has been diminished dramatically by the spread of urban development that the implacement of early management policies of planting and sand conservation has ensured that a stable well vegetated dune has remained in place. The exception to this is at St. Clair with the presence of the sea-wall. It is well recognised that the best and most efficient form of protection from the sea is that of a well vegetated dune system (Kirk. 1979).

In spite of the reasonble success of the early dune conservation strategies more recently management practices have in fact been detrimental to the health of the dune system. These are outlined in Kirk (1979, 1991) and summarised here. At the end of the sea wall magnified erosion and scour due to 'end effect' of the adjacent shore line has been attempted to be offset by the random tip of rubble. Rather than solve the problem this practice has actually tended to accentuate the erosion due to the rubble generating extra turbulence and therefore allowing more sand to be washed away. At Moana Rua the encroachment of playing fields onto the dune crest led to breaches and blowouts. The stability the beach was then further adversly affected by the dumping of both rubble and soil atop the dunes in an attempt at rebuilding them. However fine soil particles being washed onto the beach have the effect of clogging up sand pore space leading to increased backswash velocities and volumes which inturn results in enhanced erosion of the upper foreshore. Oversteepening of the fill by storm erosion also led to significant slumping in this area often leaving rubble on the beach below. The completion of the John Wilson Memorial Drive in the 1960's, which runs from St. Kilda to Lawyers Head, was seen as the accolade of the successes of the Ocean Bach Domain Board. Situated on the crest of the foredune large volumes of fill were required for its construction. Also soil and rubble fill was often tipped down the seaward slope in attempts to offset erosion of the toe which often resulted in slumping. These practices had similar consequences to those outlined for Moana Rua. However a new foredune has since been grown, in font of the drive thus displacing the fill landward of the swash zone and preventing it from entering and destabilising the beach system.

Following the report of Kirk (1991) the most recent management plans have reverted back to more sound policies of dune planting and sand conservation (Otago Regional Council, 1992b; Dunedin City Council, 1992 & 1993). Also materials detrimental to the stability of the beach system, such as soil and rubble, are to be removed, sensitive dune areas are to be fenced off, and public accessways provided.

2.6 SUMMARY.

This chapter has described the study area and its surroundings. The research was undertaken on the adjacent Tomahawk and St. Clair - Ocean beaches which are situated on the south coast of the Otago Peninsula. The peninsula coast is formed from the remains of a late Tertiary shield volcano errupted between 13 - 10ma.

On the continental shelf the northward flowing Southland Current is reinforced, at least off the Otago Peninsula, by the tidal stream. Also a persistent southerly swell results in a dominant northward longshore drift within the littoral zone. The Clutha river is the dominant supplier of sediment to the shelf system. This sediment is dispersed and transported north under the influence of the hydraulic regime. The beach sands of Otago are thus dominated by quartzo - feldspathic, Haast Schist provenance, Clutha sourced sands. The sediments of the South Otago Continental Shelf can be divided into a suite of four shore parallel belts. The inshore modern terrigenous sand facies is seaward thinning wedge of fine grey sands and could possibly be seen as a seaward extension of the beach and dune deposits. With the now dammed Clutha river delivering a much reduced bedload to the coast, possibly less than 50 percent of its original output, under a similar hydraulic regime deposition of sands into the nearshore sand wedge could possibly also be reduced which may in turn lead to future erosional problems along the Otago coastline.

The northeast - southwest trend of the greater Otago coastline is interrupted by the Otago peninsula which creates ireggularly embayed coastline with pockets of sandy beaches placed between rugged cliffed volcanic headlands.

Early physical studies of the Otago coastline were primarily concerned with the nature of the southward facing spit tips of the area. However the greater coast of the peninsula and that further south have remained relatively unstudied but are considered to be stable in nature. The north coast of the peninsula however is shown to have undergone rapid recent progradation.

The two study beaches of St. Clair - Ocean and Tomahawk have been dramatically influenced in their recent history by human activities and the subsequent management policies and practices implaced. Tomahawk is now a stable sandy beach backed by a well vegetated dune system. Sand is mined from the western end of the beach to keep the lagoon channel outlet open to the sea. The St. Clair - Ocean Beach is also a stable sandy beach. The western end is however backed by a seawall. The rest of the beach is backed by a single vegetated dune which in places now requires remedial work due to prior unsound management practices.

CHAPTER 3

THE WIND ENVIRONMENT

3.1 INTRODUCTION

This chapter concerns the nature of the winds within the study area. An appreciation of winds is important in any study of physical coastal systems for several reasons.

The location of the study area in relation to the earths atmospheric general circulation pattern influences the type of weather and winds affecting it. As winds are directly responsible for the creation of waves they thus influence the nature of the waves arriving at the coast. While the winds at the coastal site itself are often not directly responsible for the creation of the arriving waves, they do result in the modification of them. These modifications are important as they influence the way that the waves spend their energies on the shore, within the littoral zone, and thus also influence geomorphic change within the beach profile.

Winds also influence coastal currents. Winds can reinforce or mitigate longshore current velocities. They can also directly result in the set up of both onshore and offshore currents at the coast. These currents can transport sand and therefore influence profile change.

The above are examples of wind indirectly influencing geomorphic change at the coast. Landward of the water line winds can also act as a direct agent of geomorphic change in the aeolian transport of sand.

To assess the nature of the local winds at the study site wind direction and speed were recorded, analysed, and compared to local long term records. Within this chapter Part 2 looks at the general climatic setting of the study area and the resulting meteorological influences. Part 3 reviews previous local work which has centered on the analysis of long term local wind records. Part 4 reviews the influences that local winds have on the nearshore environment, while Part 5 is concerned with aeolian sand transport. An outline of methods in Part 6, is followed by the results in Part 7. The results are then discussed with respect to the long term local wind record, the influence of the local winds on aeolian sand transport, and how the local winds affect the nearshore environment in Part 8.

3.2 THE OTAGO CLIMATIC SETTING

The climate and weather of Otago, as discussed below, has been summarised from de Lisle and Brown (1968). New Zealand lies in the mid latitude belt of westerly winds. It is traversed by a succession of anticyclones tracking eastward at an average 6 - 7 day regular interval. Within Otago the weather is dominated by the passage of these anticyclones, and the intervening troughs of low pressure. The anticyclones traversing east usually pass to the north of the region leaving Otago embedded within a disturbed westerly airstream. The frequent passage of troughs of low pressure embedded within the westerly flow brings frequent rain and strong cold southwesterly winds to the region. The blocking of these troughs by the Southern Alps often leads to strong north to northwest flows, which result in warm dry weather within coastal Otago before the onset of the southwesters. Depressions which move to the east of the South Island often result in rain bearing easterly to southerly winds on the Otago coast. Sea breezes from an easterly quarter frequent the coast during daylight hours in the late spring and summer months under weak gradient flows.

3.3 PREVIOUS WORK

By tabulating annual wind direction and speed frequencies for Taiaroa Head, Fig 3.1, Elliot (1958) showed that the most frequent wind directions were southwest, (25%), north, (21%), northeast, (9%), and south, (9%). However, winds under 4 miles per hour, 1.8ms^{-1}, considered to be generally north to northeast, were not tabulated. It was also pointed out that northeast winds tended to be recorded as north at Taiaroa Head. From this Elliot (1958) concluded that southwesterlies were the strongest prevailing winds on the Otago coast, but that the most common winds were the generally lighter north to northeasterlies.

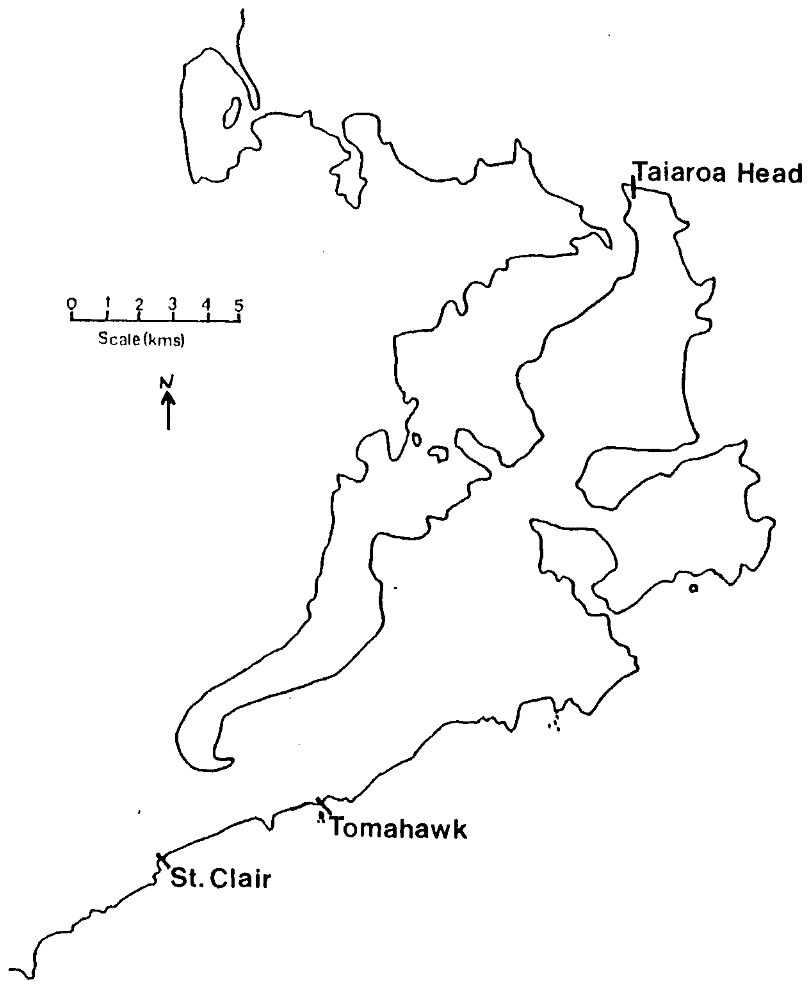


Fig. 3.1: Otago Peninsula wind data collection sites.

Using a longer data set, again for Taiaroa Head, Fitzharris (1975, *in* Nicholson, 1979) also showed a similar pattern with 37% of winds originating from the north to northeast, and 33% from the south to southwest.

Similar results were also obtained by Nicholson (1979), Fig 3.2, who utilised the New Zealand Meteorological Service Taiaroa Head 1957 - 1978 data set. Here the most frequently occurring winds were from the southwest (26.2%), north (21.2%), northeast (17.5%), and south (7.6%). This gives a bimodal north to northeast (38.7%), southwest to south (33.8%) distribution similar to that of Fitzharris (1975, *in* Nicholson, 1979). This data set also supports the earlier conclusions of Elliot (1958) in that it shows that the south west to south winds tend to attain greater velocities than the more frequent but lighter north to northeast winds.

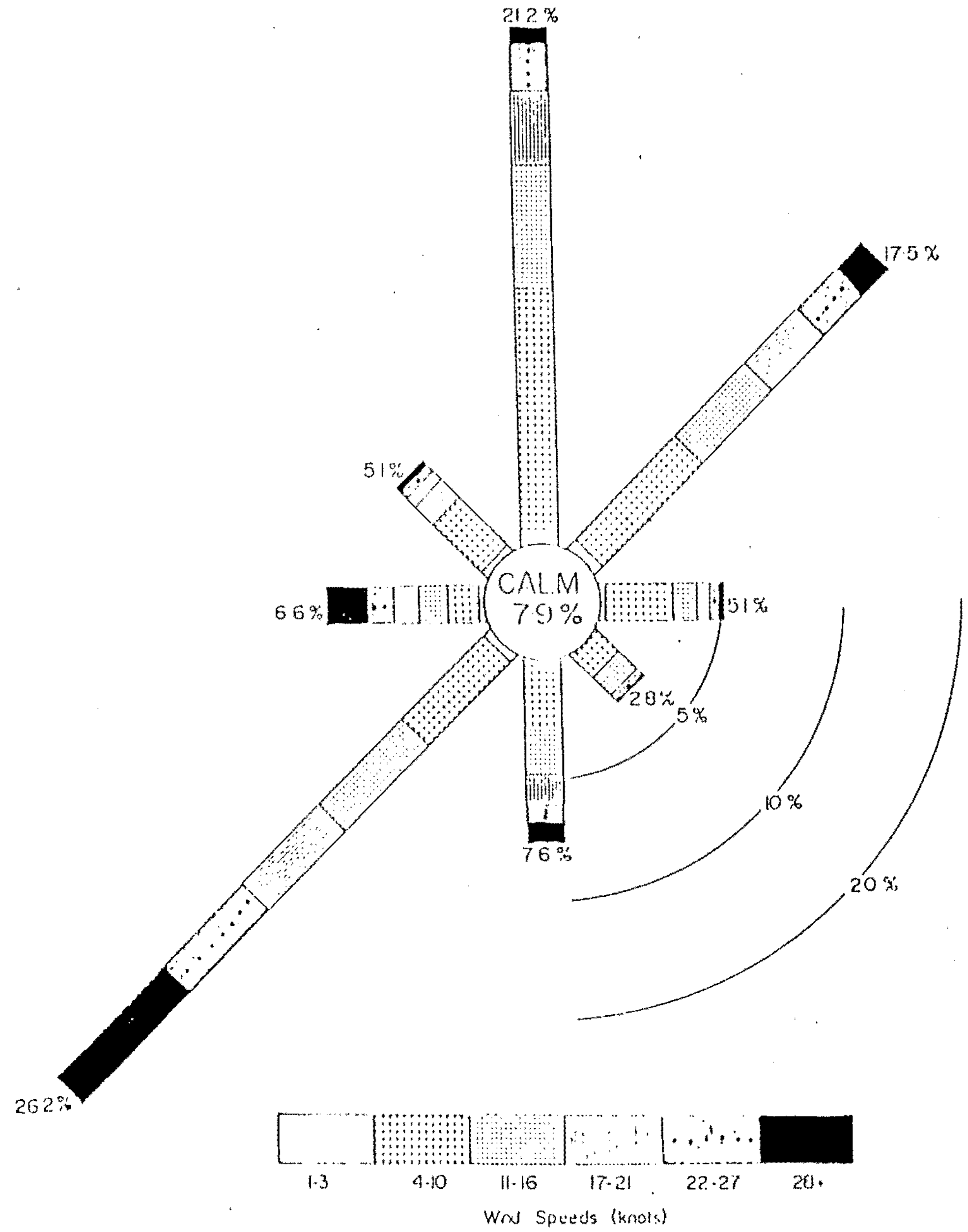


Fig. 3.2: Windrose for Taiaroa Lighthouse. 1957 - 1978. N.Z. Met. Service Data. (source; Nicholson, 1979).

3.4 THE INFLUENCE OF LOCAL WINDS ON THE NEARSHORE ENVIRONMENT

The importance of winds for the nearshore circulation remains largely unevaluated (Komar, 1976). Despite of this some general concepts have evolved with respect to the effects of local winds on the nearshore environment.

Winds blowing parallel to the coast in the longshore direction may contribute to the longshore current. King and Williams (1949) noted that there was a good correlation between along shore winds and the observed longshore current directions. Shepard and Inman (1950) noted that winds blowing along the shore were significant in generating longshore currents, but pointed out that it was difficult to assess whether it was the wind stress that was directly responsible for the currents or the short period waves generated by these winds. In the studies of Harrison and Krumbein (1964) and Sonu, *et al*, (1967) the wind velocity in the long shore direction showed only weak correlations with the resulting longshore current. Komar (1976) notes that on the Oregon Coast strong winds blowing along the shore have profound effects in increasing the longshore currents.

Wave tank experiments have shown that strong onshore winds cause offshore transport of sand under wave conditions that with no wind transported sand onshore (King & Williams, 1949; King, 1959). In the field erosional phases of beach profiles have also been associated with periods of strong onshore winds (Shepard & La Fond, 1940). The shoreward movement of surface waters under onshore winds is thus believed to be compensated by a seaward return current at depth, and vice-versa with strong offshore winds. Komar (1976) however points out that separating out the effects of these wind induced currents from the effects that the local winds have on the waves is rather difficult. This is because onshore winds tend to construct locally generated, short, steep waves that are also conducive to beach erosion, while offshore winds tend to produce flatter accretional waves, thus enhancing and masking the effects of any wind induced currents.

The local coastal wind direction can also influence the type of breaker observed at the coastline with onshore winds tending to enhance breakers of the spilling mode and offshore winds enhancing plunging breakers (Galloway, *et al*, 1989). Local South Island research has confirmed this phenomena within Pegasus Bay (Cope, 1993).

3.5 AEOLIAN SAND TRANSPORT

Winds can act as direct agents of geomorphic change at the coast through the aeolian transport of sand. As the two study beaches concerned are both composed of sand this is important.

Onshore winds are often very effective in the removal of sand from the beach, transporting it inland (Komar, 1976). Also strong onshore winds combined with an abundant sand supply and the presence of a vegetation cover provide the ideal conditions for dune growth (Pethick, 1984). The movement of sand by wind action is a complex phenomenon. The initial theory of how sand is transported by wind was developed by Bagnold (1941) and since then research has been generally based on refinement of his work (Olson, 1958; Pethick, 1984; Pye, 1993).

The distribution of wind velocity with height over sand follows a logarithmic curve, Fig 3.3. The effect of this is to create a zero velocity, produced by frictional drag, at a small but significant height above the ground. This height is related to the surface roughness and is called the effective surface roughness, or z° (Olson, 1958). The upper layer of a beach surface has a scatter of individual grains lying on it which project through the surface roughness layer, into the velocity profile, (Pethick, 1984). As the wind speed increases to exceed a critical threshold velocity the grains at or below a critical size begin to move (Bagnold, 1941). On colliding with other grains some sand grains are flicked into the air, (aerodynamic entrainment), thus beginning the process of saltation. The saltation process has four distinct but linked subprocesses which are; aerodynamic entrainment, the trajectory of the wind driven sand grains, the grain/bed collisions, and modification of the wind field by the wind driven sand,

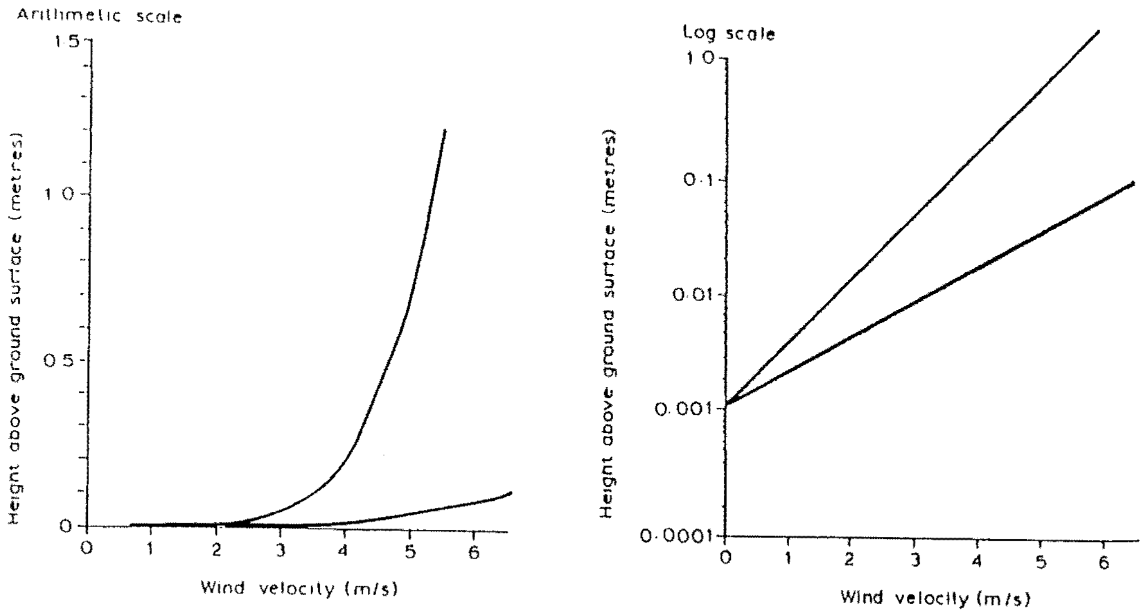


Fig. 3.3: Velocity profiles over a bare sand surface, (left), and the same profiles plotted on a logarithmic height scale, (right). (source; Pethick, 1984).

(McEwan & Willetts, 1993). Once in the air the grains are subject to increased velocities and therefore accelerate, before falling back to the sand surface. On impact with the sand surface other grains are then ejected into the air thus continuing the process. Once saltation is underway the wind velocity profile is modified, the entrained grains slowing down the air flow. Pethick (1984) suggests that the threshold velocity for average dune sands is approximately $4ms^{-1}$ and that any wind velocities below this are not capable of maintaining saltation. Saltation is probably the most imporant aeolian sand transport mechanism as it is believed to account for 75% of all aeolian sand transport (Pethick, 1984).

Small sand grains, < 0.2mm, are often suspended in the air by upward turbulent eddies. Grains too large to take part in saltation move by surface creep, in which they move along the beach surface due to the impacts of other grains.

The amount of sand transported per unit beach width per unit time is related to the cube of the wind velocity (Bagnold, 1941; Skidmore, 1965; Hsu, 1973). The importance of this cubic relationship is that a small increase in the wind velocity results in a big increase in sand transport.

Vegetation plays an important role in dune growth as it creates a new increased surface roughness, therefore reducing sand transport by saltation, by reducing the wind velocities near the surface (Olson, 1958). This encourages rapid sand deposition within the vegetation, and as the vegetation grows so does the dune (Pethick, 1984).

3.6 METHODS

In order to observe the nature of the winds directly affecting the study beaches a Lambrecht Anemometer was set up atop a house roof. The anemometer was situated on the headland at the eastern end of Tomahawk Beach as can be seen from Fig. 3.1.

The study period for the winds began on December 14, 1993. Unforeseen circumstances, (the vacating of the house on which the Lambrecht was situated), led to the cessation of wind data collection earlier than intended on June 16, 1994. This then left approximately six months of wind data with which to work, covering the summer and autumn months. Mechanical problems also led to a sporadic data set with some 28 days of missing data scattered throughout the six month period. A record of the gradient wind direction for the missing days can be seen in Table 3.1. The gradient wind direction was assessed visually for the Otago Peninsula area using the New Zealand Meteorological Services mean sea level analysis synoptic charts.

Lambrecht charts were analysed using the University of Canterbury, Geography Department digitizing programme (Digwind.Bas). This programme converts the raw Lambrecht chart data into date, time and hourly means of wind direction and speed. From this data windroses were created. The windroses display the distribution of wind speed and direction frequencies. The programme used, Windrose!1.5Apl. (developed by A.Dyer, 1992, Department of Geography, University of Canterbury) split wind direction into twelve, 30 degree classes. Windroses were drawn up for the individual months, Figs. 3.4, 3.5, the two seasons, summer and autumn, and the total study period, Fig. 3.6. The 16 days of June were included within the autumn windrose, despite June not actually being an autumn month.

Table 3.1: Gradient winds for the Otago Peninsula for the missing days of wind data as observed from N.Z. Met. Service mean sealevel analysis charts.

Month	Missing Days	Gradient Wind on Missing Days
December	22 (1500) - 29 (1800)	22 - 23) E - SE
		24 - 29) N - NE
January	5 (1500) - 9 (2100)	5 - 6) N - NW
		7 - 9) NW
	10 (1300) - 11 (1400)	10 - 11) Light Variable
February	23 (2100) - 28 (2400)	24 - 27) Light Variable
		28) N
March	1 (0100) - 3 (1900)	1) N
		2 -3) S
April	4 (1600) - 12 (0900)	5) W - SW
		6) S - SW
		7) Variable
		8) N - NW
		9) SW
		10) N
		11) N

3.7 RESULTS

3.7.1 INDIVIDUAL MONTHS

The windroses for the individual summer months are displayed in Fig. 3.4. For December southerly winds, (13.1%), dominated and tended to be quite strong, (7.5% >4ms^{-1}). However if the six days of missing north to northeast data, Table 3.1, had been recorded north would have become the prominant wind direction. South-southeast winds, (7.8%) were followed in importance by east-northeast (6.8%). The two southwest winds, (5.4%), west-southwest and south-southwest, tended to be alot stronger, typically greater than $4ms^{-1}$, than the other less frequent wind directions which tended to be less than $4ms^{-1}$. It should reemphasized here that the data here is only indicative of the latter half, that is the 16th to the 30th, of the month.

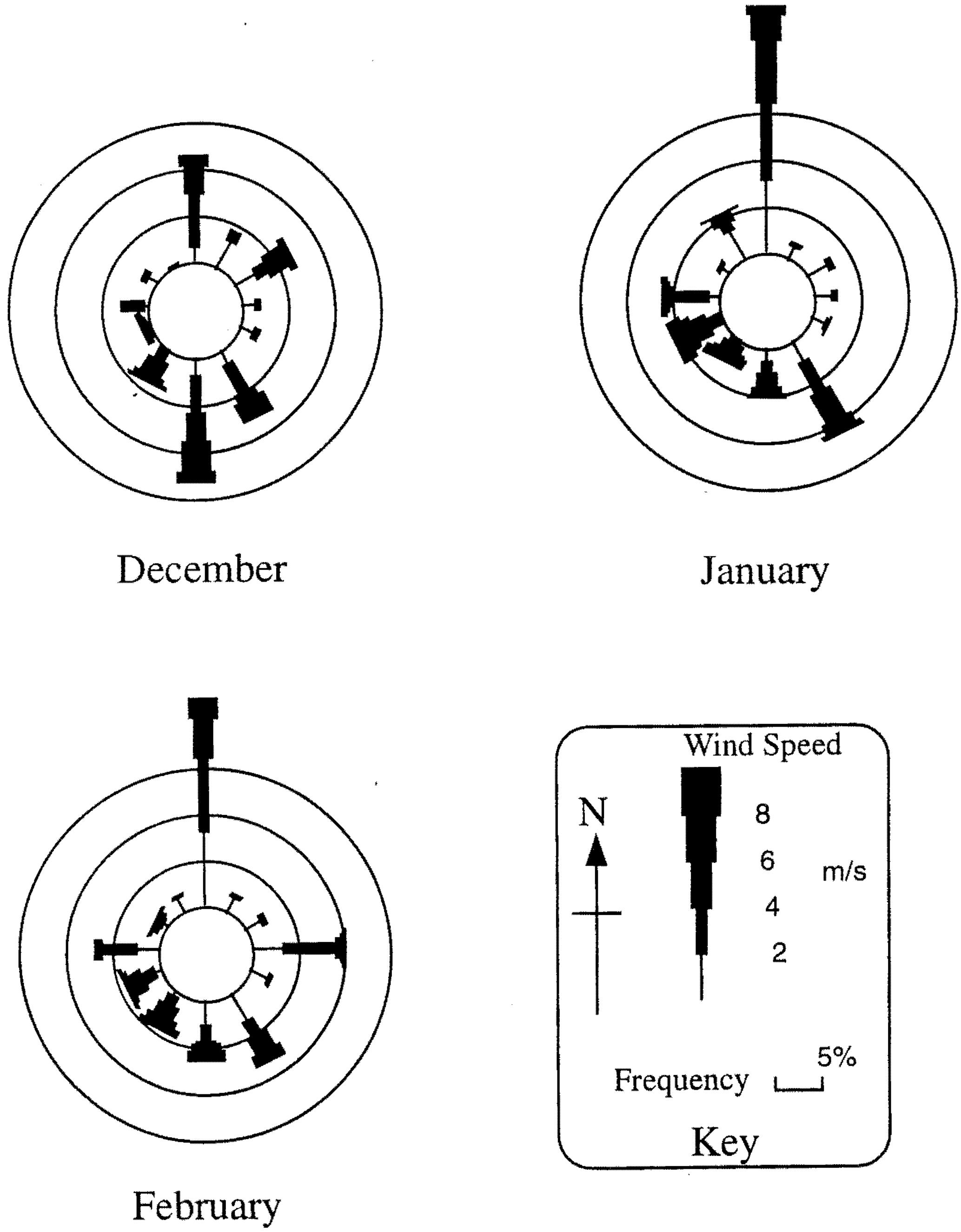


Fig. 3.4: Individual windroses for the summer months of December, January and February.

In January the northerly winds dominate, (26.3%), but tended to be light, (16.5% <4ms^{-1}). If the missing data were taken into account this would possibly increase, as would have winds from the northwest, north-northwest, (5.6%). South-southeast winds, (11.3%), were followed in importance by west, (6.1%), west-southwest, (5.8%), and south, (5.3%). The west-southwest, (5.8%, 4.1% >4ms^{-1}) and south, (5.3%, all >4ms^{-1}), however tended to have the higher windspeeds. Also the south-southwest had significantly higher wind speeds, typically greater than 4ms^{-1}, than the other less frequent wind directions that were all less than 4ms^{-1}.

In February northerly winds, (23%), dominated, but tended to be light, (17% <4ms^{-1}). This was followed by light east, (10%, 9% <4ms^{-1}), south-southeast, (8.3%, 5.1% <4ms^{-1}), west, (7.1%, 6.2% <4ms^{-1}), and southerly, (6.5%, 4.5% <4ms^{-1}), winds. The south-southwest and west-southwest winds tended to be a lot stronger, typically greater than 4ms^{-1}, than the other less frequent wind directions which were nearly all less than 4ms^{-1}.

The windroses for the individual autumn months are displayed in Fig. 3.5. In March northerly winds, (21%, 12.4% <4ms^{-1}), dominated, followed by quite strong south-southwest, (13.5%, 11.3% >4ms^{-1}), and south-southeast, (12.0%, 8.3% >4ms^{-1}), winds. Light westerlies, (9.3%, 6.9% <4ms^{-1}), were followed in importance by south, (8.4%), and west-southwest, (6.8%), winds. Quite strong east-southeast winds occurred for some 4.1%, (3.5% >4ms^{-1}), of the time. The remaining wind directions were infrequent with speeds less than 4ms^{-1}.

In April the northerly, (17.3%), dominated tending to be light, (14.7% <4ms^{-1}). Stronger winds from the west, (12.3%), were followed in importance by even stronger west-southwest, (11.3%, 9.2% >4ms^{-1}) and south-southwest, (6.8%, 6.1% > 4ms^{-1}), winds. The other less frequent wind directions tended to be less than 4ms^{-1}.

In May northerly winds, (33.4%, 23.3% <4ms^{-1}), dominate followed by west, (14.3%), and quite strong west-southwest winds (12.8%, 11.6% >4ms^{-1}). The south, (6.8%), and south-southwest, (5.6%), winds tended to be stronger,

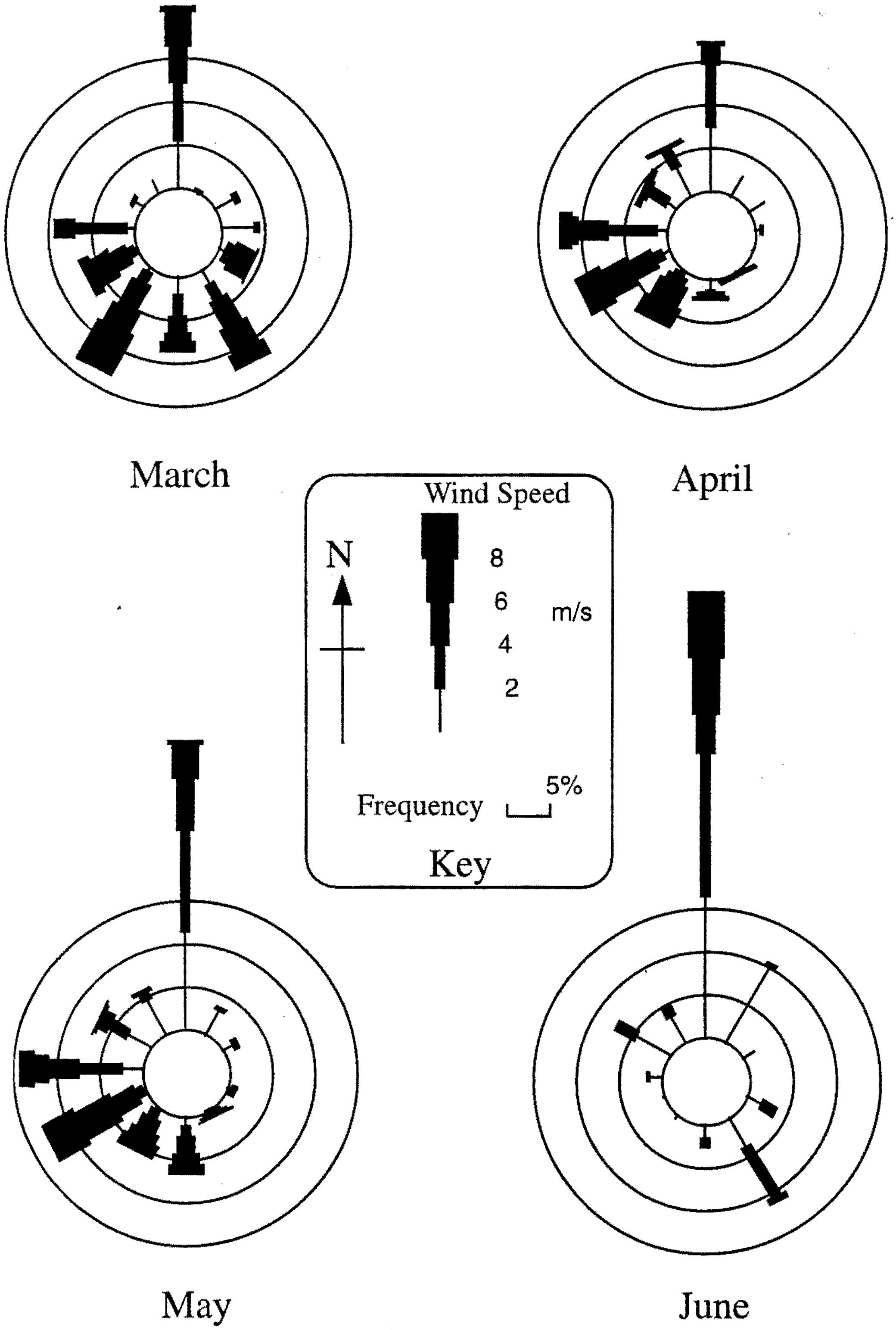


Fig. 3.5: Individual windroses for the autumn months of March, April, and May, and the half month of June.

typically greater than $4ms^{-1}$, than the west-northwest, (6.9%), north-northwest, (6%), and other less frequent wind directions which tended to be less than $4ms^{-1}$.

For the half month of June northerly winds, (51%), completely dominated, with west, southwest, and southerly directions being conspicuously absent in comparison to the other months.

3.7.2 SEASONAL ANALYSIS

The collated windroses for summer and autumn are shown in Fig. 3.6. For the summer period northerly winds, (21.4%, 14.3% $<4ms^{-1}$) dominated, followed by south-southeast, (8.9%), south, (7.5%), west, (5.6%), and east winds (5.3%). The west-southwest, (4%), and south-southwest, (4%), tended to be a lot stronger, typically greater than $4ms^{-1}$, than the other less frequent winds, which were mostly less than $4ms^{-1}$.

Northerly winds, (27.7%), also dominate the autumn period but tended to be light, (18.8% $<4ms^{-1}$). However here this was followed by west, (10.5%), and stronger west-southwest, (9%, 7.5% $>4ms^{-1}$), and south-southwest winds (7.6%, 6% $>4ms^{-1}$). South-southeast, (6%), and southerly, (5%), winds tended to be stronger, typically greater than $4ms^{-1}$, than the northwest wind components, both at 5%, and the other less frequent wind directions which were mostly less than $4ms^{-1}$.

3.7.3 TOTAL STUDY PERIOD

For the total study period of December 14 1993 to June 16 1994, the northerly wind, (25.5%), dominated but was mostly light in nature, (14.3% $<4ms^{-1}$). This was followed by a fairly even distribution of west, (8.6%), west-southwest, (7.1%), south-southwest, (6.8%), south, (6%), and south-southeasterly, (7%), winds. The west-southwest and south-southwest winds tended to be the strongest however nearly always greater than $4ms^{-1}$. The other less frequent, (<5%), wind directions, tended to be relatively light winds, mostly less than $4ms^{-1}$.

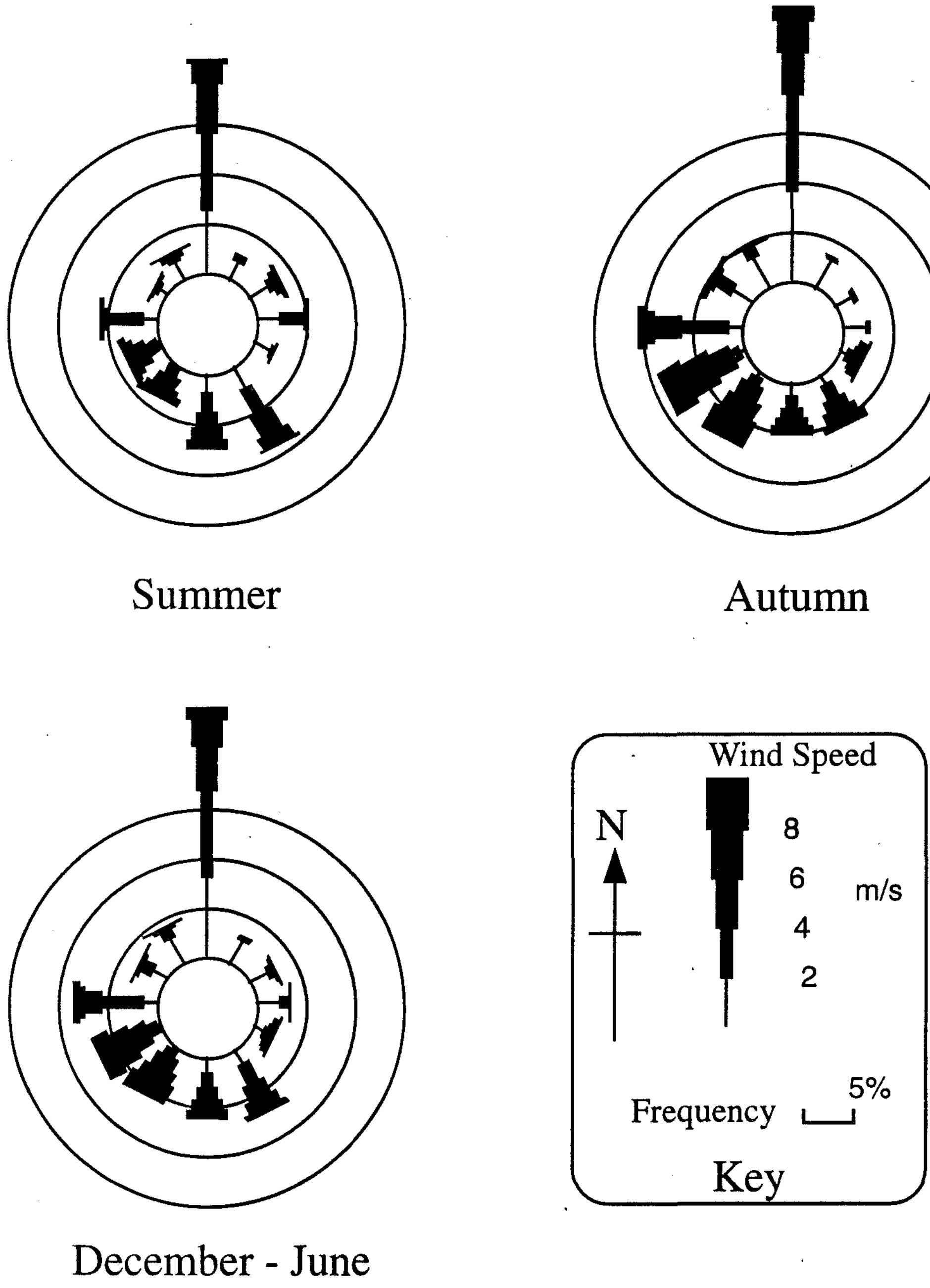


Fig. 3.6: Windroses for summer, autumn and for the total wind data collection period of December 14 to June 16.

3.8 DISCUSSION

In the data set obtained for this study there is a conspicuous absence of northeasterly winds in almost all of the windroses and especially so for the study period as a whole. However northeast winds form an intergral part of the coastal Otago wind regime as can be seen in Fig 3.2. Also it has been acknowledged (Elliot, 1958) that Taiaroa Head tends to record northeast winds as northerly. It is thus concluded here that local topographic influences at the data collection site have resulted in northeast winds tending to be recorded as northerly winds within the present data set. In all windroses the northerly is the dominant wind direction. The exception is for the December period, but here seven days of northerly data are missing, (Table 3.1). While northerly winds did attain speeds of greater than $8ms^{-1}$, speeds of less than $4ms^{-1}$ are the most dominant. These findings are consistent with the long term Taiaroa Head wind record. Thus a north to northeast wind, recorded as north at the study site used here, is the dominant wind direction on the Otago coast, but that it tends to be relatively light in nature.

For the total study period the west-southwest and south-southwest directions produced the strongest winds. However the general 'southwest' direction did not appear to be as dominant as that shown in the long term Taiaroa Head record. Several explanations arise as to why this might be.

First the windrose programme used in this study used twelve 30° increments, rather than the eight 45° increments of the Taiaroa Head record. This had the result of splitting the southwest record in two and therefore reducing its apparent influence. A 45° increment would possibly result in the southwest becoming the second most dominant wind direction for the total study period, for autumn, and for the individual months of March, April, and May.

Secondly the data collected in this study is not an annual set encompassing only the summer and autumn months. A full annual data set would tend to smooth out any seasonal influences. In the summer months south, (7.5%), and south-southeast, (9%), winds tended to dominate over the west-southwest, (4%), and south-southwest, (4%), thus giving a S - SSE/WSW - SSW ratio of 16.4%/ 8%. Also this ratio was strongest for the half December month, (21.8%/4.7%), than for January, (16.3%/8.1%), and February, (12.5%/8.9%), possibly indicating some missing 'southwest' data, from the first December half, for the complete summer period. Despite this the data would tend to indicate that depressions tracked to the east of the South Island during this period. Also the southwest winds were possibly influenced by the occurrence of sea breezes during this period causing the southwest winds to back around to southerly during the daylight hours similar to that experienced and documented on the Canterbury coast to the north, (Sturman & Tyson, 1981). This would reinforce the southerly component. In the autumn months the west-southwest, (9%), and south-southwest, (7.6%), directions became more dominant than the south-southeast, (6%), and south, (5.%), thus giving a S - SSE/WSW - SSW ratio of 11%/16.6%. This is especially so for April, (3.8%/18.1%), and March, (7.7%/ 18.4%). Thus in summer south to south-southeast winds dominated over west-southwest to south-southwest, but this is reversed in autumn. The winter months could probably be expected to reinforce this with increased periods of southwest winds although this does not show up in the data for the first half of June. Also short term data sets such as this, even if for a full year, will often tend to show deviations from that of the long term record. Climatic elements and cycles can be variable, and variability should be expected. Westerly winds were also a lot more prominant in autumn than in the summer.

Thirdly the stronger prevalence of west and south winds within the present data set, relative to the long term record could also be influenced by the locational differences of the two collection sites, Fig 3.2. Taiaroa Head is situated at the northern end of the southwest - northeast trending drowned valley which forms the Otago Harbour. The funneling effect of this valley on the west and south winds could possibly result in some westerly and southerly events being recorded as southwesters at Taiaroa Head. This would tend to reduce their importance within the Taiaroa Head record in favour of a southwest direction. The coastal site used for this study, on the south coast of the Otago Peninsula, is more open to the west and south, allowing these winds to be recorded as such and thus increasing their importance in the wind record. Obviously to assess these ideas a comparison of the two data sets over the same time period would be required. This was not possible within this study.

Looking at what the results mean in terms of aeolian sand transport the $4ms^{-1}$ critical threshold velocity of Pethick (1984) can be taken to assess the directional influence. Thus from the total study windrose, Fig. 3.6, it can be concluded that winds from the east, east-northeast, north-northeast, north-northwest, and west-northwest, are nearly always less than $4ms^{-1}$ and would thus have little influence on aeolian sand transport. Northerly winds, (25.5%), although dominantly less than $4ms^{-1}$, (14.3%), did have speeds greater than $4ms^{-1}$, and may thus have influenced aeolian sand transport. However the northerly is an offshore wind. Examining vegetation and sand dune development at North Beach in Christchurch Bradly (1993) correlated weekly changes in dune surface morphology, (sand accumulation over a buried plate), to the rate of sand transport by the wind. The highest correlations were gained using onshore winds only, while offshore winds resulted in the weakest correlations. This led Bradly (1993) to conclude that most dune changes occurred during strong onshore winds and that there was little change when onshore winds were not present. Also looking at aeolian sand drift on a temperate beach Sarre (1989) disregarded the offshore wind directions as these were considered to have little effect on the net annual transport of sand. Strong offshore winds were seen to move little sand back onto the beach from the foredune area due to the sheltering effect of vegetation. Also beach sands are probably sheltered to an extent from offshore winds as under these conditions they are in the protected lee of the sand dunes. Thus while the northerly wind often attained speeds capable of inducing aeolian sand transport, its offshore direction, probably resulted in lower rates of sand transportation than that expected considering wind speed alone.

The wind directions with the highest frequencies of wind speeds greater than $4ms^{-1}$ are the west-southwest and south-southwest, followed by south and south-southeast winds. These winds all blow onshore and are therefore probably the most influential in the aeolian transportation of sand. The higher frequency of stronger west-southwest and south-southwest winds along with the cubic relationship of wind speed to sand transport would tend to place these winds as having the highest potential for maximum aeolian sand transportation.

Plate 3.1: Tracts of sand on John Wilson Drive having been transported off St. KIlda beach by strong southwesterly winds, through a gap in the dune vegetation.

Plate 3.1 was taken after a period of strong south to southwest winds. Not all of the sand seen here was transported by the single event, but it does show that under these conditions large amounts of sand are transported off the Beach at St. Kilda. This sand was transported on to John Wilson Memorial Drive through a gap in the dune vegetation, brought about by heavy pedestrian usage. Sand ripples were also frequently observed along Tomahawk Beach under extended periods of strong southwest winds. Other morphological evidence such as the greater width of the dune field at the eastern end of the Brighton to Blackhead coastline (McKellar, 1990) and in historical time at the eastern, Lawyers Head, end of St. Clair - Ocean Beach (Morrison, 1955) would tend support the idea that the strong onshore southwest winds are the most prominant in the aeolian transportation of sand on the south coast of the Otago Peninsula.

It should be pointed out however that the discussion above was concerned with potential rates of sand transportation in relation to windspeed alone. Sarre (1989) points out that the actual rates of aeolian sand transportation within the coastal system are usually lower than the potential rate assessed by wind speed alone due to the following variables: the meteorological variables of precipitation and the evaporation rate, the water table level, and the state of the tide. This is because of the increased weight of wet sand grains and the cohesive forces of interstital moisture, acting on wet sand grains, which result in a reduction of the ability of the wind to transport sand.

The offshore winds, principally northerlies, could be expected to produce a combination of flat accretional waves tending to be of plunging mode along with the probability of enhanced shoreward moving bottom currents. The strong onshore winds on the other hand could be expected to produce a combination of locally generated short steep waves, tending to be of spilling mode, along with the possibility of enhanced offshore bottom currents. These ideas along with the effects that the local winds had on the waves and inshore sea state will be discussed in greater detail within Chapter 4, The Wave Environment.

The strong west-southwest and south-southwest winds along with the westerlies would be expected to enhance the longshore current velocities, in the easterly direction. No actual direct measurements of longshore current velocity were taken. However from personal observations of the movements of surfers at St. Clair it was apparent that under extended periods of strong southwesterly winds eastward moving longshore current velocities were dramatically increased. The east and southeast winds on the other hand would also be expected to enhance longshore current velocities in the westerly direction, but on a less frequent basis due to their overall lower frequency of occurence. Again from personal observations at St. Clair it was apparent that extended periods of strong east to southeast winds tended to dramatically increase westward moving longshore currents.

3.9 CONCLUSIONS

This chapter has examined the nature of the winds at the study location. This was done by comparing the distribution of wind speed and direction frequencies recorded during the study period to the long term Taiaroa Head wind record. The Taiaroa Head long term wind record shows a bimodal distribution of north to northeast and southwest to south winds. The southwest to south winds tend to attain greater velocities than the more frequent but lighter north to northeast winds.

For the data set of the present study northerlies dominated followed by an even distribution of west, west-southwest, south-southwest, south, and south-southeast winds. The other less frequent wind directions tended to be generally light in nature.

Within the data set, the absence of northeast winds in favour of northerlies was taken to indicate that local topographic influences at the collection site led to the northeast winds being recorded as wind from the north. Northerly winds dominated over the study period, occasionally obtaining speeds greater than $8ms^{-1}$. However speeds less than $4ms^{-1}$, were the most common. This is consistent with the long term Taiaroa Head record.

While the west-southwest and south-southwest winds tended to obtain greater velocities than any other wind direction, as with the Taiaroa Head record, the general 'southwest' direction does not appear to be as prominant within this data set as it is within the Tairoa Head record. Here a fairly even distribution of west, west-southwest, south-southwest, south, and south-southeast winds predominate instead of just the southwest to south as with Taiaroa Head. This difference can be explained by the influence of a combination of different factors including local topograhic influences, climatic variation, the time period of data collection, seasonal variation, and the different increments, 30° verses 45°, used in windrose contruction.

The distribution frequency of wind speeds and directions, combined with personal observations, and morphological evidence would tend to suggest that strong onshore winds, most importantly the southwesterly, have the strongest impact on the aeolian transport of sand along the south coast of the Otago Peninsula. Also extended periods of strong southwesterly weather appear to enhance longshore current velocities in the easterly directions. Extended periods of strong east to southeasterly winds enhance current velocities in the westerly direction, but on a less frequent basis than for the southwesters.

Finally the effects of the local onshore and offshore winds on the waves and the inshore sea state as discussed earlier, Part 3.8, will be further advanced in Chapter 4, The Wave Environment. The difference between the erosional, short steep waves and offshore bottom currents typically set up by onshore winds and the accretional, flat waves and onshore bottom currents typically set up by offshore winds with respect to their influence on profile change will be further advanced in Chapter 5, Beach Profile Changes.

CHAPTER FOUR

THE WAVE ENVIRONMENT

4.1 INTRODUCTION

This chapter concerns the nature of the waves within the study area. An appreciation of the wave climate is important in study of the coastal system as it is the waves that provide the energy required for almost all coastal change. "*no adequate appreciation of the many problems presented by the shoreline can be gained until one is familiar with the work of waves and currents*" (Johnson, 1915, p1). "*waves are the main factor in coastal dynamics*" (Zencovich, 1967, p22). "*the driving force behind almost every coastal process is due to waves*" (Pethick, 1984, p9).

The aim of this chapter is thus to gain a better understanding of the wave climate of the two study beaches. This was based on the two pronged approach of collecting both the New Zealand Met. Services coastal swell forecasts for the Chalmers area, and by the daily collection of shore based wave observations.

First however the previous local work on the Otago wave climate is reviewed in Part 2. Methods are then set out in Part 3, followed by by the results in Part 4. The results are then discussed in Part 5, drawing comparisons between the previous local work, and the Chalmers swell reports with the shore based observations. What the results mean in terms of potential sediment transport on the two study beaches is also discussed. Finally some conclusions are set out in Part 6.

4.2 PREVIOUS LOCAL WORK

The first documentation of the Otago wave environment was by Elliot (1958). Rather than an analysis of a collected data set however, this documentation was based on a recollection of personal observations. Elliot (1958) noted that swells in the Otago area normally ran between the south and southeast with wave periods varying from 10.3 to 13 seconds. The waves arriving at the Otago coast were considered to be mainly swell waves, modified by local winds, rather than waves actually generated by these winds. The bimodal distribution of the local Otago winds was thus seen as an important factor in influencing the nature of the dominant southerly swell waves arriving at the coast. Wave heights under fresh southwest winds were observed at 6 - 8 feet, (1.8 - 2.4m), but at only 1 - 3 feet, (0.3 - 0.9m), with north to northeasterly winds. Wave periods were observed to be similar under the two opposing winds, except at extremes, with strong southwesters increasing, and strong north to northeasterly winds decreasing the wave periods. Southwest winds were thus seen to favour steeper, high energy waves, while north to northeast winds tended to favour flatter, low energy waves. It was also noted that breakers on the Otago coast tended to be predominantly of the plunging variety under all conditions.

In a more detailed study of the Otago wave climate Hodgson (1966) made use of daily observations for December 1963 to December 1964 of swell direction and wave periods recorded from Taiaroa Head, and of swell direction as observed from the Cape Saunders Lighthouse, Fig 4.1. Observations of wave height and period were also made at St. Clair and St. Kilda for three and four weeks in January and June respectively. Swell directions at Cape Saunders were considered to be more valid with respect to open sea conditions rather than those observed at Taiaroa Head since "*the direction of swell approach at Taiaroa Head is persistently affected by refraction around the Otago Peninsula.*" (Hodgson, 1966, p80). Also waves breaking at St. Clair and St. Kilda were considered to be "*less effected by wave refraction than those further north.*" (Hodgson, 1966, p80).

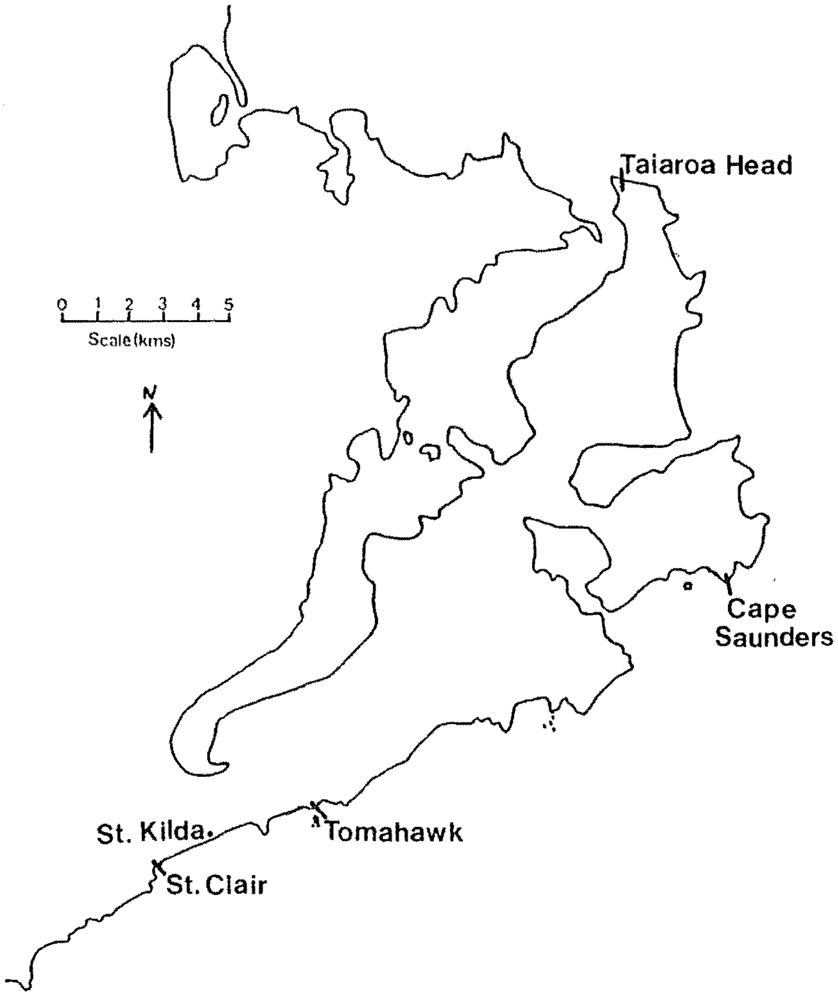


Fig. 4.1: Otago Peninsula wave data collection sites.

For the Cape Saunders data Hodgson (1966) stated that a southerly swell direction dominated, (57%), followed by southeast swells, (26%). Thus in the presentation of the Cape Saunders swell direction data, Fig 4.2, the bar length of either the south or southeast swell must be wrong. As a result the frequencies of the other directions, (not stated in the text), could be either northeast, (6%), east, (17%), and southwest, (6%), or northeast, (4%), east, (12%), and southwest, (4%), depending on whether the southeast, or south swell bar length is taken to be correct. For the purposes of later comparison a compromise distribution, of northeast, (5%), east, (14.5%), and southwest, (5%), has been accepted by the present author, Fig 4.3. It should be noted that this distribution of the Hodgson (1966) data set, Fig 4.3, is different to that obtained by Nicholson (1979) who presented the same Hodgson (1966) data set with the following distribution; south, (57%), southeast, (26%), east, (5.8%), northeast, (3.2%), southwest, (3.2%), and calms, (4.8%).

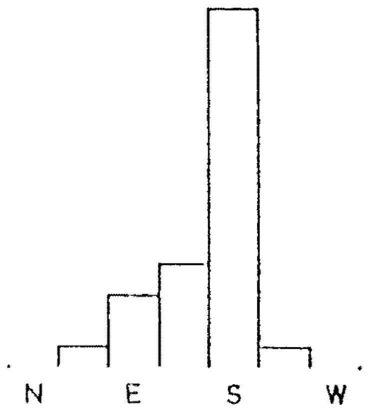


Fig. 4.2: Variation of swell direction observed at Cape Saunders as presented by Hodgson (1966).

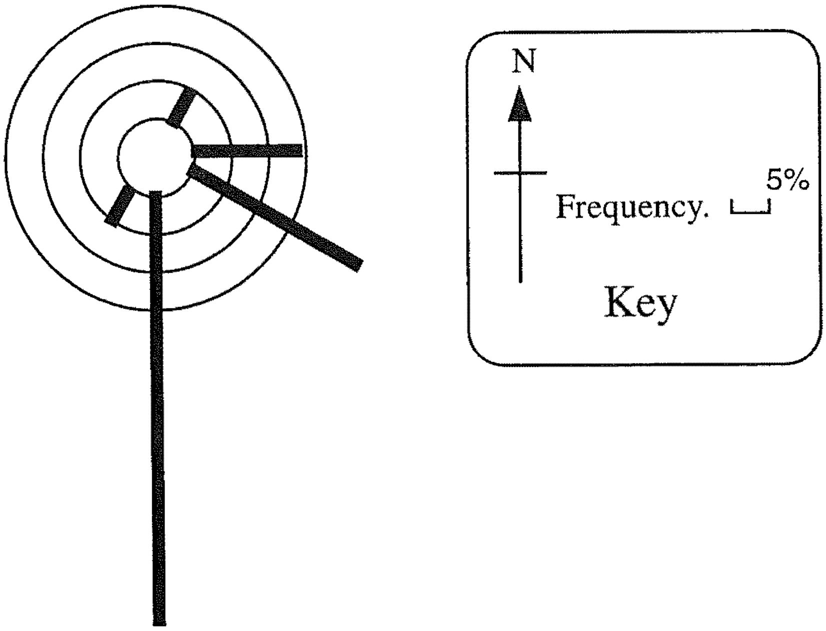


Fig. 4.3: Swell direction waverose as observed from Cape Saunders. December 1963 - December 1964. (source; Hodgson, 1966).

Hodgson (1966) also considered that the southeast swell observed at Cape Saunders was due to the refraction of south swell with periods of greater than 10 seconds. Wave heights observed at St. Clair and St.Kilda varied from 3 to 11 feet, (0.9 - 3.4m), with the mean wave height increasing from 3 feet, (0.9m), in summer to 4 feet, (1.2m), in winter. Wave periods varied from 4 to 25 seconds, but with 81% lying between 6 and 12 seconds. Lastly in contradiction to Elliot (1958) Hodgeson (1966) suggested that strong southwest winds tended to decrease rather than increase the wave period of the dominant southerly swell.

Using the New Zealand Meteorological Service Ship reports for grid square 44, (latitude 45.0° - 49.9° south, longitude 170.0° - 179.9° east), from 1957 to 1978 Nicholson (1979) gained an offshore Otago wave distribution, Fig. 4.4 dominated by south, (22.7%), southwest, (22.6%), and northeast, (13.3%) swell directions. wave periods varied from 4 to 15 seconds, but were dominantly between 6 and 10 seconds, (67.4%).

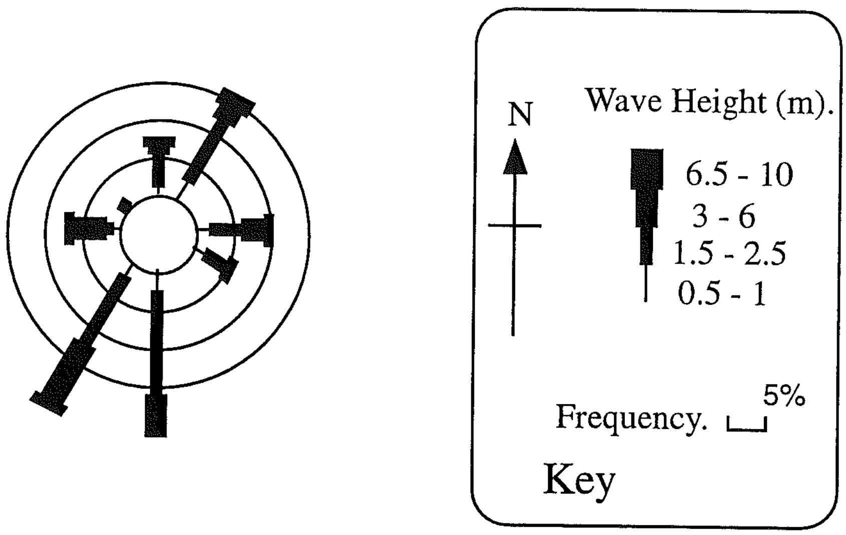


Fig. 4.4: Waverose for N.Z. Met. Service ship reports for grid square 44, (45.0 - 49.9°S; 170.0 - 179.9°E), 1957 - 1978. (source; Nicholson, 1979).

4.3 METHODS

To gain a better understanding of the wave environment of the two study beaches two forms of wave data were collected. The first was daily swell reports issued by the New Zealand Meteorological Service for the local, Chalmers coastal forecast area. The second was a series of daily shore based observations.

4.3.1 SWELL REPORTS

Coastal area weather forecasts for New Zealand coastal waters, issued by the New Zealand Meteorological Service, are broadcast twice daily on the National Programme, (680 kHz), following the 0300 and 0500 news bulletins. The second of these forecasts at 0500 was recorded daily, from which the study area forecast, (Chalmers), was extracted. The Chalmers coastal forecast area extends from Nugget Point in the south to Moeraki Heads in the north, Fig 4.5, thus taking in the Otago Peninsula, and also extends offshore for about 100 kilometers. A collection of reported swell directions, swell heights and sea states was thus built up for the Chalmers area from December 11 1993, to August 31 1994.

The frequency distribution of the reported swell directions and swell heights was analysed by way of wave roses for individual months, (Figs. 4.8, 4.9, & 4.10), for the seasons, (Fig. 4.7), and for the total study period, (Fig. 4.6). The distribution of the seasonal mean wave height, (Fig. 4.11), and the distribution of monthly mean wave heights, (Fig. 4.12), for the different swell directions was calculated to assess seasonal and monthly mean wave height variation. The distribution of the reported Chalmers sea states was also calculated, (Fig. 4.13). The sea state is a descriptive term which is applied to the state of the sea surface, (Table 4.1). The heights in Table 4.1 refer to the average size of the larger well formed waves, that is; to the average of about the highest one-third of the waves present, (Hydrographic Office, 1993).

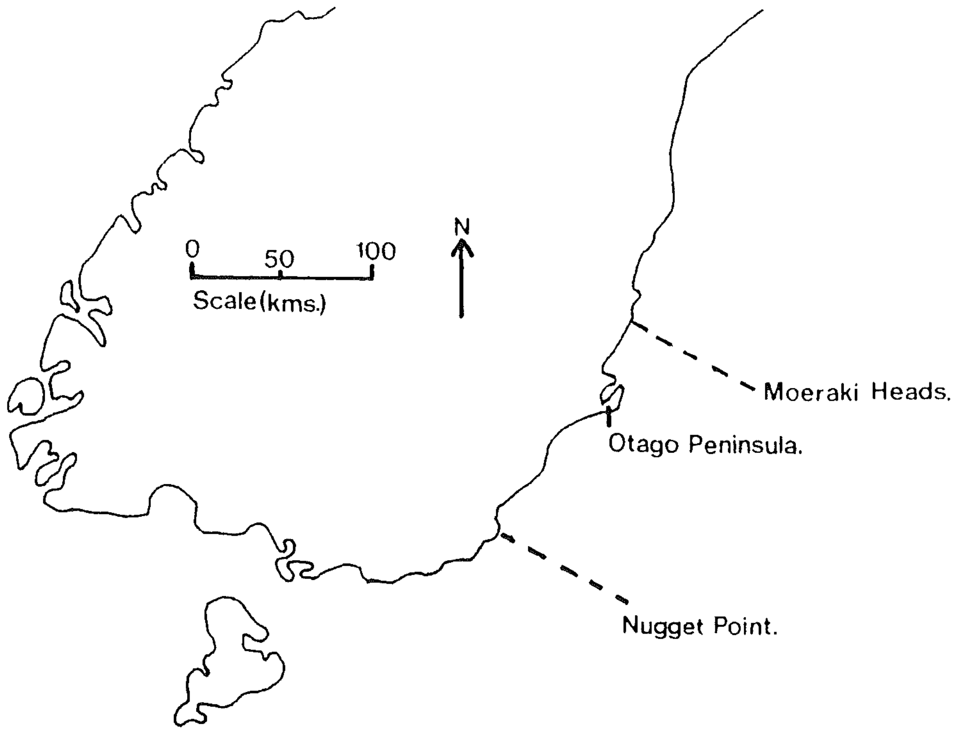


Fig. 4.5: The Chalmers Coastal Forecast Area.

Table 4.1: Sea State Descriptive Terms and Swell Heights. (source: Hydrographic Office, 1993).

Descriptive Term.	Average Height of Larger Well Formed Waves in Meters.	
Calm (glassy).	0	
Calm (rippled).		up to 0.1
Smooth (wavelets).	Over 0.1	up to 0.5
Slight.	Over 0.5	up to 1.25
Moderate.	Over 1.25	up to 2.5
Rough.	Over 2.5	up to 4
Very Rough.	Over 4	up to 6
High.	Over 6	up to 9
Very High.	Over 9	up to 14
Phenomenal.	Over 14	

4.3.2 SHORE BASED OBSERVATIONS

The shore based observations were based on the U.S. Army Corps of Engineers Littoral Environment Observation (LEO) data collection programme (Schneider, 1981). Smith and Wagner (1991) suggest that visual observations should be used for long term results rather than for single wave results, while Plant and Griggs (1992) concluded that visual observations provided a reasonable estimate of the general local wave climate. Observations were carried out on a daily basis at around 0800 hours from the headland at the eastern end of Tomahawk Beach, Fig. 4.1. The daily shore based observations were made over a six month period from December 11 1993 to May 31 1994. Wave characteristics recorded included swell direction, significant wave height at the outer most break point, wave type, wave period, and inshore sea state. The wind direction at the time of observation was also recorded.

Inshore swell direction on the south coast of the Otago Peninsula is restricted due to wave refraction to directions ranging from just west of south through to east-southeast. The inshore swell direction was thus recorded, using the L.E.O. method (Schneider, 1981) as either south, south-southeast, or east-southeast.

The significant wave height is the average height of the highest one-third waves and is equivalent to the average estimate of wave height estimated by an experienced observer (Munk, 1944; *in* CERC, 1984). In the summer months the visual estimates of wave heights were often aided by the presence of surfers within the breaker zone, thus giving a good comparison for the estimation of the wave height at break point. In the autumn months, with a lack of surfers, wave heights were recorded purely on a visual estimation basis. The validity of visually estimated wave heights to actual wave heights has been shown to be fairly accurate by sevaral authors. Schneider and Weigel (1980) compared a gauge wave height to that of shore based observations and concluded that the shore based estimates provided a good estimate of the prevailing breaker heights. Ballislie and Carter (1984), working with wave heights up to about 1m, concluded that visual estimates tended to overestimate the breaker heights. Perlin (1984) however concluded that for waves in the 0.3 - 0.9m range that there was a tendency to underestimate most breaker heights. Plant and Grigg (1992b) concluded that the heights of larger breakers tended to be underestimated, while Bowman (1979) concluded that there was a tendency for observers to overestimate the significant breaker height, especially for breakers that were greater than 1.5m. It is thus obvious that observers may visually over or underestimate breaker heights. This is most likely to vary between observers and also between different coastal sites. However as wave heights increase it becomes more difficult to estimate the breaker height because the outermost breaker line moves further offshore (Smith & Wagner, 1991). Ballislie and Carter (1984) however concluded that visually estimated breaker heights were accurate to within +/- 20%.

The two observers used in the present data collection, the author and Tane Tokona, have numerous years surfing experience on the Otago Coast, and were thus familiar with and experienced in typical wave heights, observed under most conditions.

Breaking waves were originally classified as surging plunging or spilling (Patrick & Weigel, 1955; *in* CERC, 1984). Galvin (1968) suggested that the term collapsing should be used to describe breakers in the transition from plunging to surging. Schneider (1981) identified that some waves appeared to have characteristics of both spilling and plunging breakers terming these as spill-plunge breakers. The breaker type at the two present study beaches was restricted to either spill, plunge, or spill-plunge and was thus recorded as one of these three types. Spilling breakers occur where the wave crest become unstable at the top and breaks to flow down the front face of the wave producing a foam surface, whereas plunging breakers are hollow waves where the lip of the wave curls over the front face of the wave into the trough. Obviously spill-plunge breakers share characteristics of both spilling and plunging waves.

The wave period recorded was the average of ten waves. That is the time taken for the passage of 11 consecutive wave crests to pass a fixed point was divided by ten to give a mean period. Both Perlin (1984) and Ballislie and Carter (1984) concluded that this method has a tendency to overestimate short period waves and underestimate long period waves.

The frequency distribution of the observed swell directions and heights were analysed by way of wave roses, for the total study period, (Fig. 4.14), for the seasons, (also Fig. 4.14), and for the individual months, (Fig. 4.15, & 4.16). Seasonal and monthly means of wave height for the different swell directions were calculated to assess any monthly or seasonal trends in mean wave height respectively, (Figs. 4.17 & 4.18). Mean wave periods were calculated for the total study period, and the seasons, for the different swell directions, and finally for the different wind directions. This was done in order to assess any patterns. To assess whether there was any relationship between the local wind direction and the observed inshore sea state the distribution of the observed inshore sea states was calculated with repect to wind direction, at the time of observation (Fig. 4.19). To assess whether there was any relationship between the local wind direction and the type of breaker observed at the coast, the distribution of the observed wave types with respect to wind direction at the time of observation was calculated, (Fig. 4.20).

4.4 RESULTS

4.4.1 SWELL REPORTS

4.4.1.1 Total Study Period Waverose

The wave rose for the total nine month study period, (11 December 1993, to 31 August 1994), for the Chalmers coastal forecast area can be seen in Fig. 4.6. From this it can be clearly seen that southwest was the dominant swell direction, (54.5%), followed by northeast. (31.4%), south, (15.2%), east, (11.4%), and southeast, (3.8%). Two swells were reported on 49 of the 264 days within this period, while there were 6 days of no reported swell. The southwest swells were dominated by waves in the ranges of 1.5 - 2m, (23.5%), 2.5 - 3m, (14%), and 3.5 - 4m, (11%), with a highest reported swell height of 5m. The northeast swells were dominated by 1m, (16.7%), and 1.5 - 2m, (12.1%), reported wave heights, with a highest reported wave height of 4m.

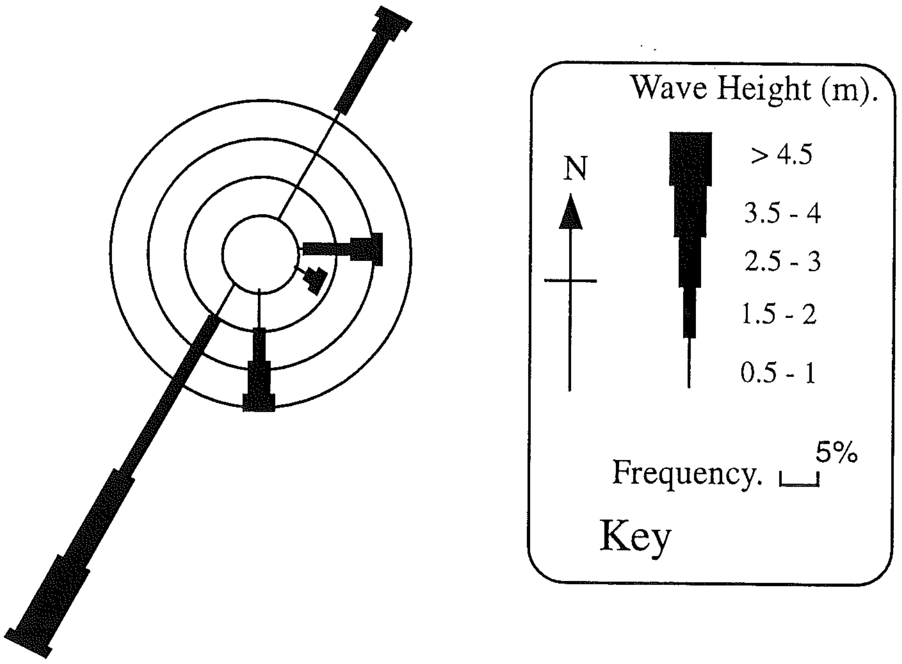


Fig. 4.6: Waverose for N.Z. Met. Service Chalmers coastal forecast area, (11 December 1993 - 31 August 1994).

4.4.1.2 Seasonal Waveroses

The wave roses for the three seasons, summer, autumn, and winter, can be seen in Fig. 4.7. For summer there were 22 days with two reported swell directions, and 3 days of no reported swell. Southwest, (50%), and northeast, (50.0%), swell directions, were the most prominant. Despite having even frequencies the southwest swells tended to have larger reported wave heights, (1.5 - 2m, 23.8%; 2.5 - 3m, 14.6%; 3.5 - 4m, 6.3%), than the northeast swells, (1m, 25%; 1.5 - 2m, 23.8%).

Autumn had two swells on 13 days with 3 days of no reported swell. Southwest swells, (60.9%), dominated followed by northeast, (26.1%), and south, (17.4%). The southwest swells peaked at 5m, but were dominated by reported by wave heights of 2m, (27.2%), 3m, (16.3%), and 4m, (10.9%). The northeast swells reported wave heights peaked at 3m, but were predominantly only 1m, (17.7%).

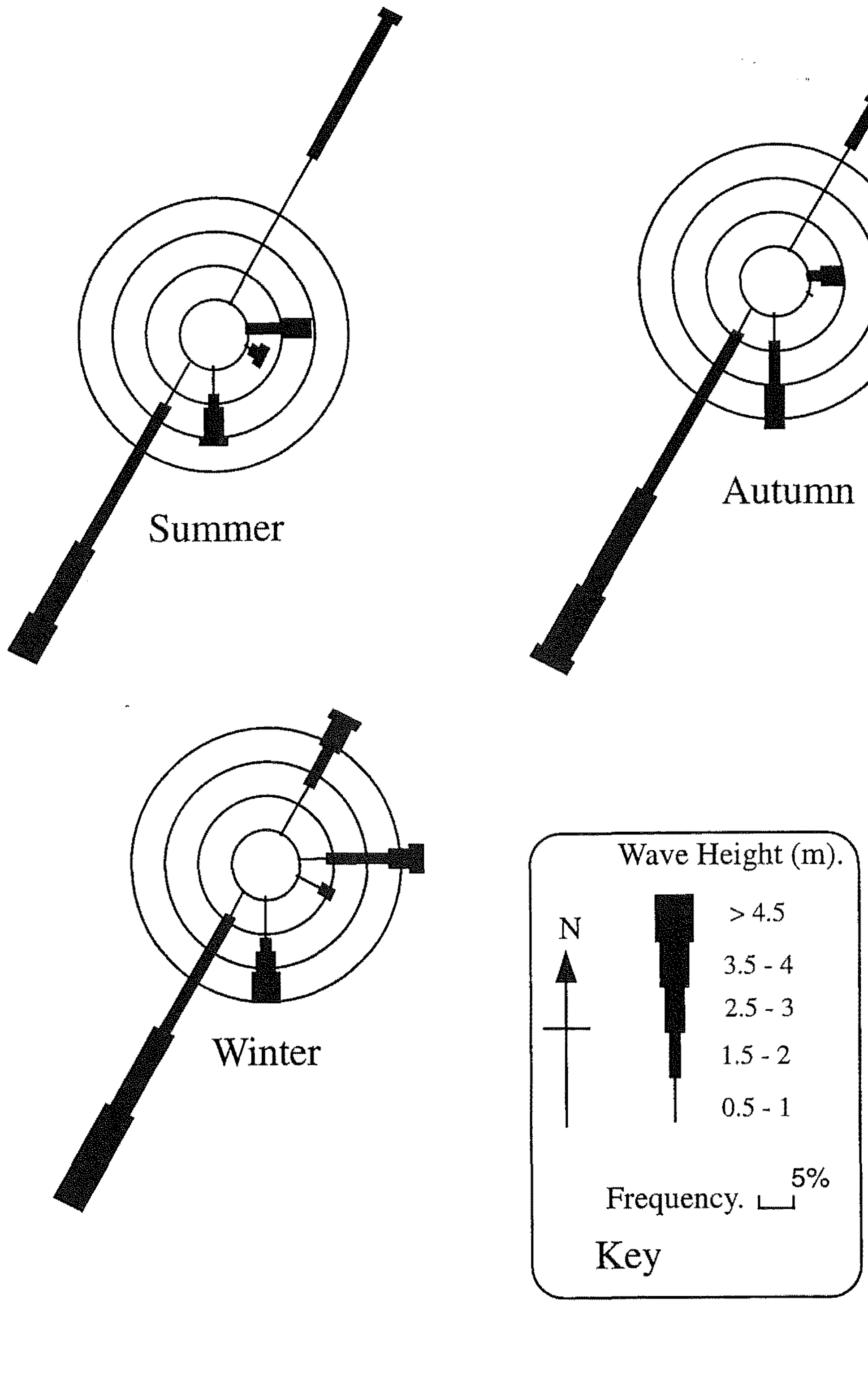


Fig. 4.7: Waverose for N.Z. Met. Service Chalmers coastal forecast area for summer, autumn and winter.

In winter there were two swells on 14 days with zero reportings of no swell. Southwest swells, (52.2%), dominated followed by northeast, (20.7%), east, (19.6%), south, (16.3%), and southeast, (16.3%). Southwest swells were dominated by wave heights of 2m, (19.6%), 3m, (13%), and 4m, (15.2%). Northeast, south, and east swells ranged from ranged from 1 - 4m, but southeast swells from only 1 - 2m.

4.4.1.3 Individual Months Waveroses

The wave roses for the individual months of summer are shown in Fig. 4.8. December had two swells on 8 days, and zero days of no reported swell. Southwest swells, (61.9%) dominated followed by northeast, (42.9%), and east, (23.8%). Southwest swells were dominated by wave heights of 1.5 - 2m, (33.3%), and 2.5 - 3m, (14.3%), peaking at 3.5m. Northeast swells were dominated by wave heights of 1.5 - 2m, (28.6%), and 1m, (9.5%), peaking at 2.5m.

In January there were two 2 swells on 12 days and zero days of no reported swell. Northeast, (74.2%), dominated, (1m, 41.9%; 1.5m, 32.3%), but did not reach the heights reported for the southwest, (58.1%), swells, (1.5 - 2m, 25.8%; 2.5 - 3m, 16.1%; 3.5m, 6.5%).

February had two swells on 2 days and 3 days of no reported swell. Southwest swells, (32.1%), dominated followed by northeast, (28.6%). Southwest swells were dominated by reported wave heights of 1.5 - 2m, (14.3%), 2.5 - 3m, (7.1%), and 3.5 - 4m, (7.1%). Northeast swells had an even distribution of 1m, (14.3%), and 1.5 - 2m. (14.3%) wave heights.

Wave roses for the individual months of autumn can be seen in Fig. 4.9. March had two swells on 5 days and zero days of no reported swell. Southwest, (38.7%), and south, (38.7%), swells dominated, but the southwest tended to be slightly larger, (SW, 2m, 9.7%; 3m, 22.6%; & 3.5 - 4m, 6.4%; S, 1m, 3.2%; 2m, 16.1%; & 3m, 19.4%). Northeast swells, (32.3%), were dominantly of the order of 1.5 - 2m, (25.8%), but peaked at 3m.

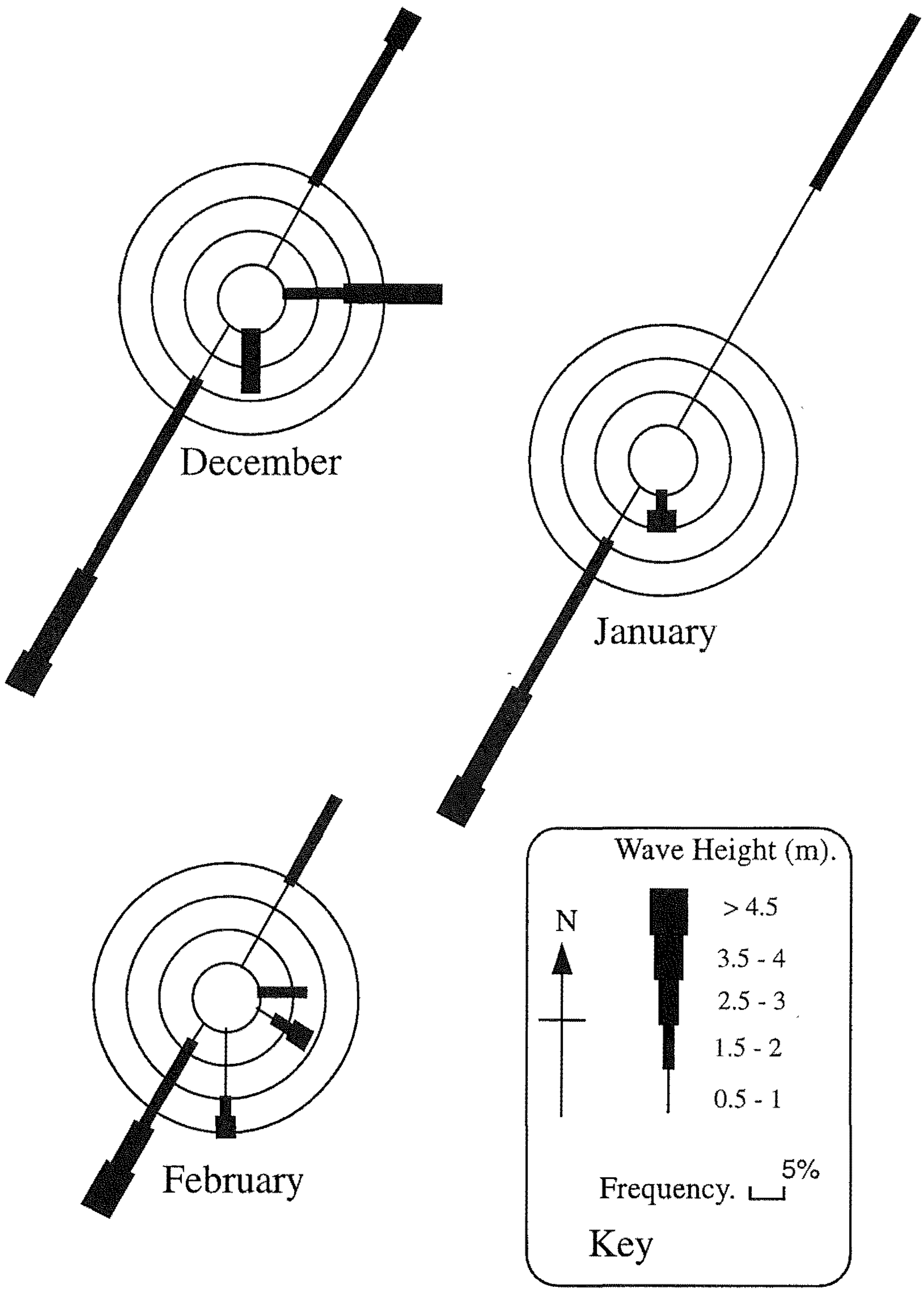


Fig. 4.8: Waverose for N.Z. Met. Service Chalmers coastal forecast area for December 1993 and January and February 1994.

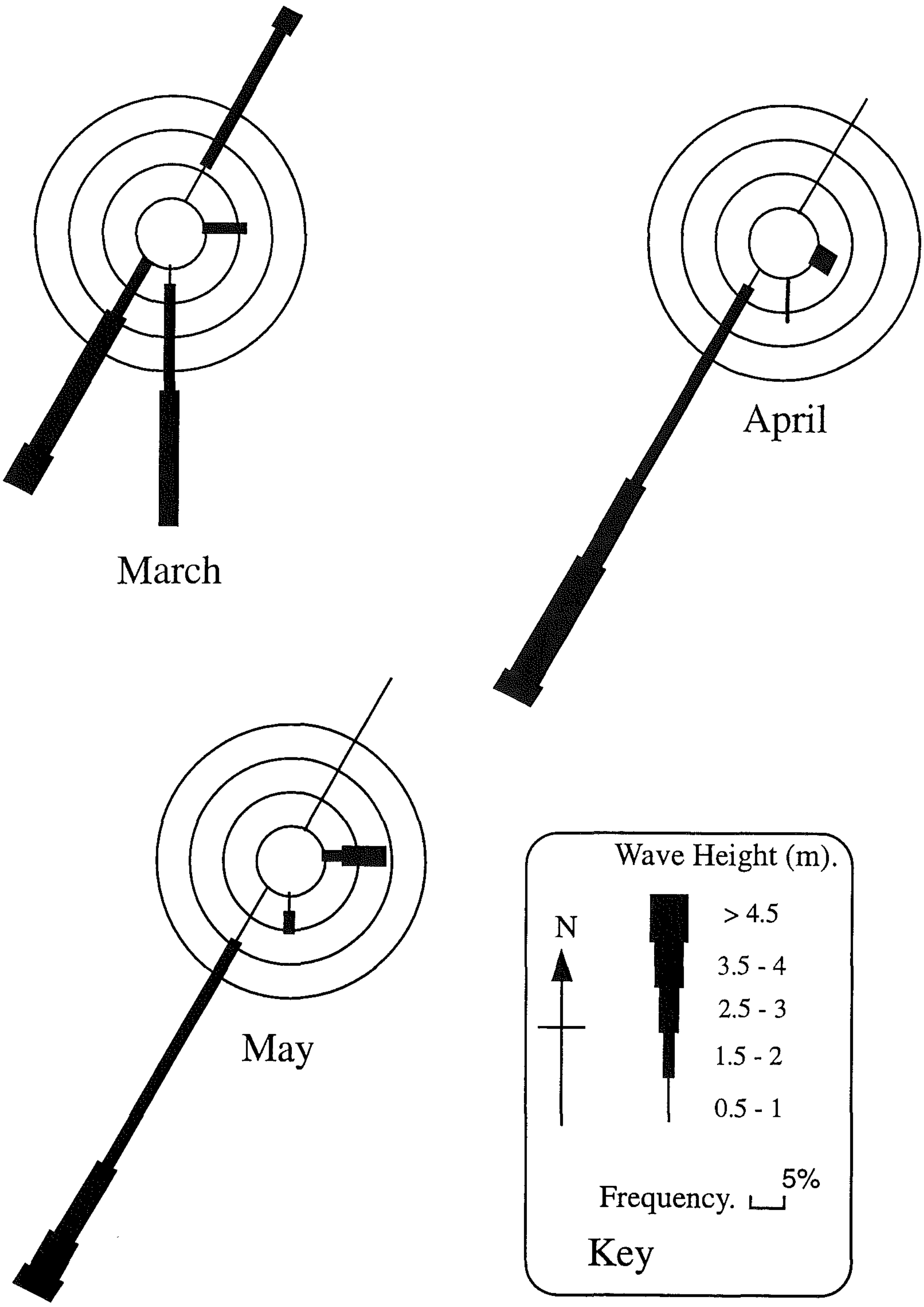


Fig. 4.9: Waveroses for N.Z. Met. Service Chalmers coastal forecast area for March, April and May 1994.

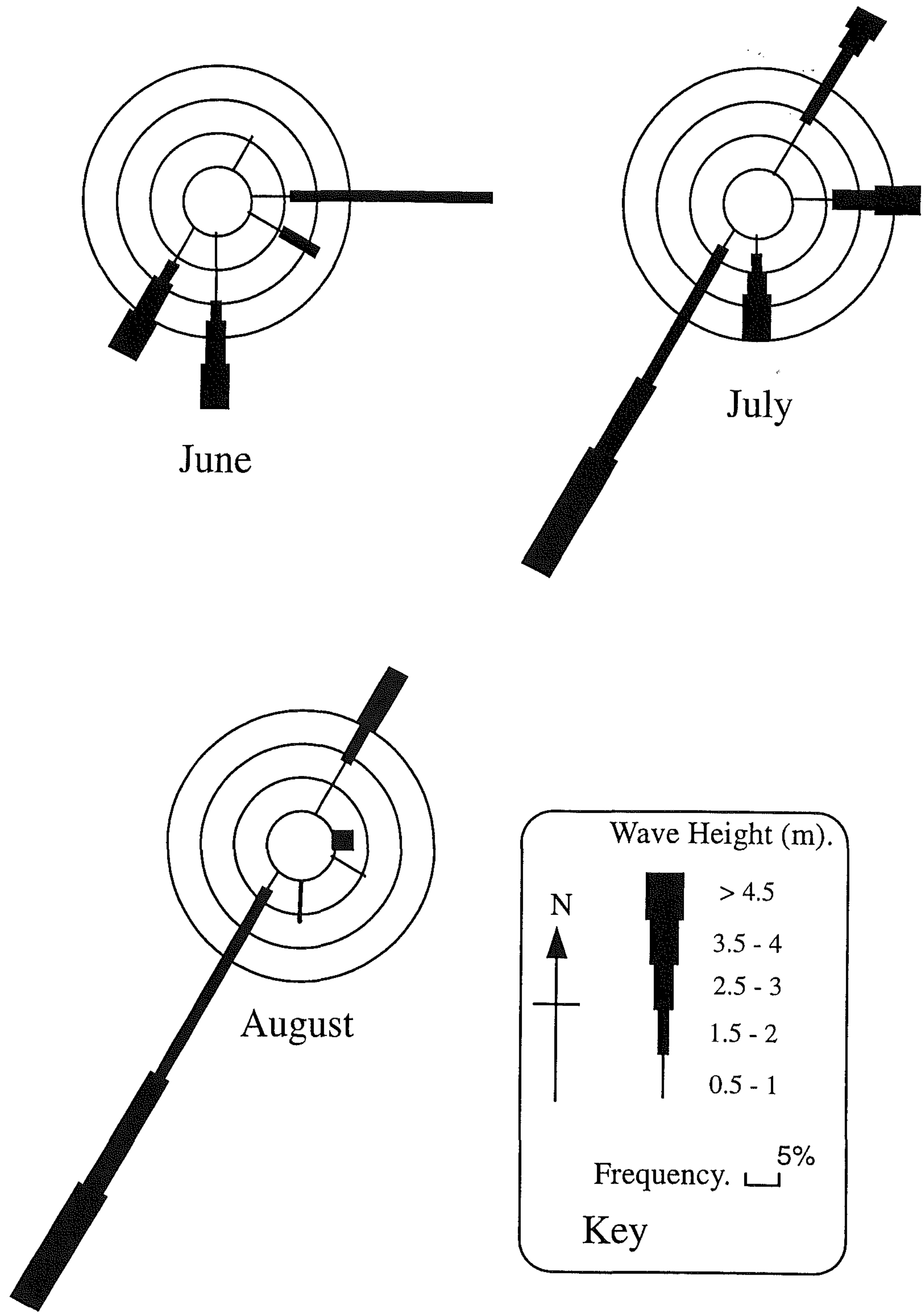


Fig. 4.10: Waveroses for N.Z. Met. Service Chalmers coastal forecast area for June, July and August 1994.

April had two swells on 2 days, and 1 day of no reported swell. Southwest swell, (73.3%), dominated, peaking at 5m, but with wave heights predominantly within the 1.5 - 2m, (33.3%), 3m, (13.3%), and 4m, (20%), ranges. Northeast, (20%), and south, (6.7%), swells were of only 1m.

May had two swells on 6 days and 2 days of no reported swell. Southwest swells, (71%), dominated, peaking at 5m, but with reported wave heights predominantly of 2m, (38.7%), and 3m, (12.9%). Northeast swells (25.8%), were of only 1m.

Wave roses for the individual months of winter can be seen in Fig. 4.10. June had two swells on 2 days and zero days of no reported swell. East swells, (36.7%; 2m, 30%), were dominant over south, (26.7%), southwest, (23.3%).

July had two swells on 7 days, with zero days of no reported swell. Southwest swell, (58.1%), was dominant over northeast, (29%), east, (19.4%), and south, (16.1%), swells. Southwest swells tended to be predominantly 2m, (22.6%), 3m, (12.9%), and 4m, (19.4%). Northeast swells attained heights of 4m but reported heights of 1m, (19.4%), and 2m, (12.9%), were the most common.

August had two swells on 5 days and zero days of no reported swell. Southwest swells, (74.2%), dominated followed by northeast, (25.8%). The southwest swell heights were predominantly 2m, (32.3%), 3m, (19.4%), and 4m, (19.4%). Northeast swells ranged from 1 - 3m, east swells were 2m, while south and southeast swells were only of 1m.

4.4.1.4 Wave Heights

The mean reported wave height for the total nine month study period was 2.1m. Seasonally this increased from summer, (1.7m), through autumn, (2.2m), peaking in winter at 2.4m, Fig. 4.11. A similar seasonal pattern also is evident for the individual swell directions of southwest, south, and northeast. The mean wave heights for the southeast and east swells peaked in autumn at 3m and 2.4m respectively. The monthly mean wave heights, Fig. 4.12, showed no real patterns. For all swells the monthly mean wave height varied from 1.6 -2.6m. For southwest swells the monthly mean wave height varied from 2 -3.2m. For

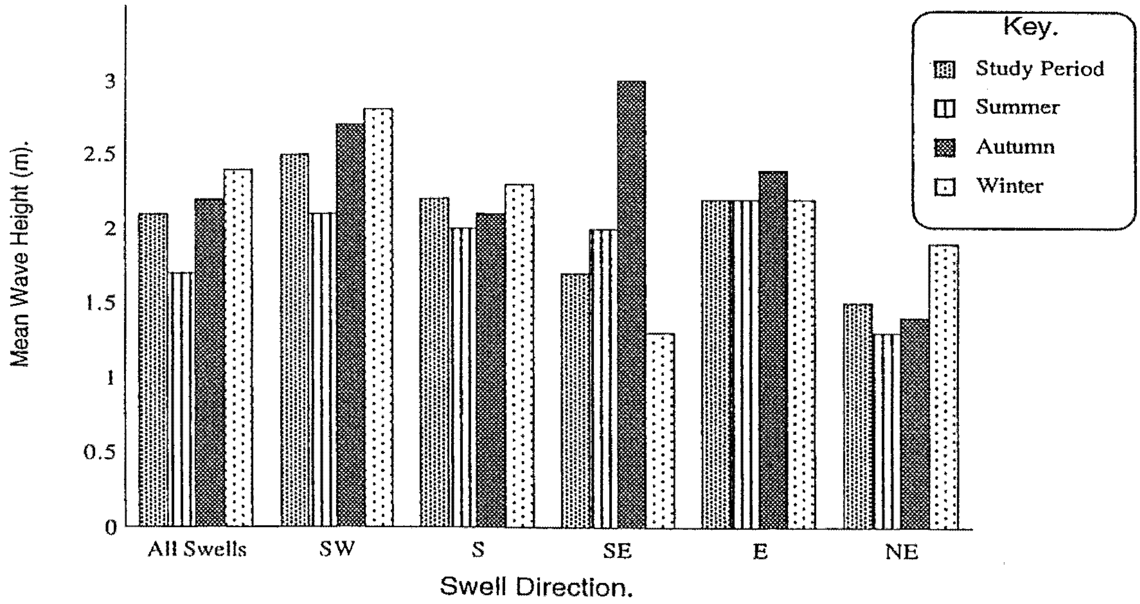


Fig. 4.11: N.Z. Met. Service Chalmers coastal forecast area seasonal mean swell heights. December 1993 - August 1994.

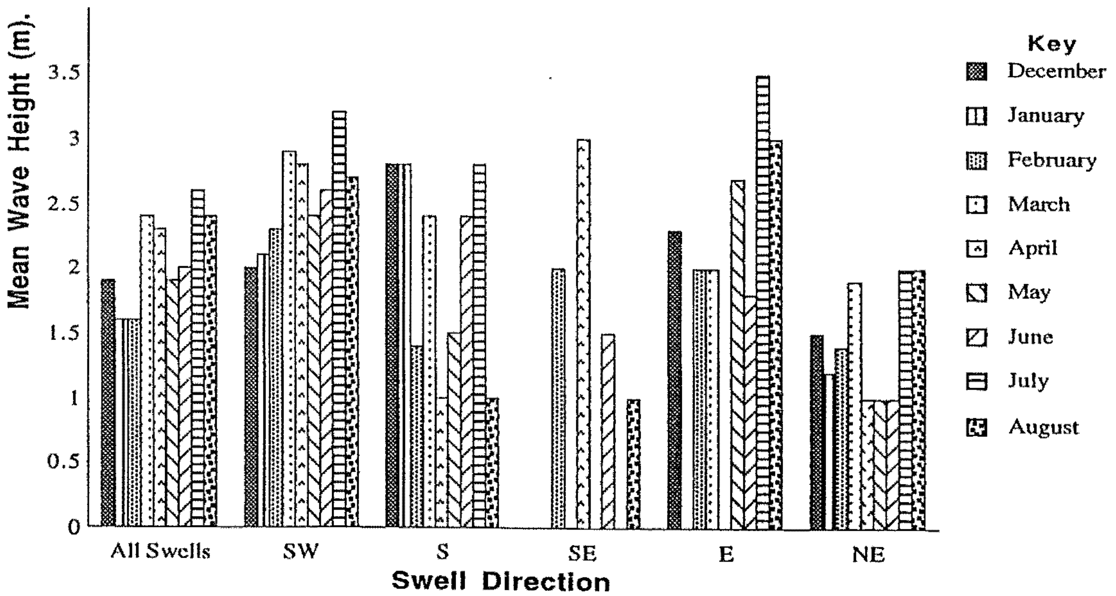


Fig. 4.12: N.Z. Met. Service Chalmers coastal forecast area monthly mean swell heights. December 1993 - August 1994.

south swells the monthly mean wave height varied from 1 - 2.8m. For southeast swells the monthly mean wave height varied from 0 - 3m. For east swells the monthly mean wave height varied from 0 - 3m. For northeast swells the monthly mean wave height varied from 1 - 2m.

4.4.1.5 Sea States

Reported sea states, Fig. 4.13 were dominated by rough seas, (47%), followed by slight, (22%), moderate, (17%), very rough, (17%), and high, (2%).

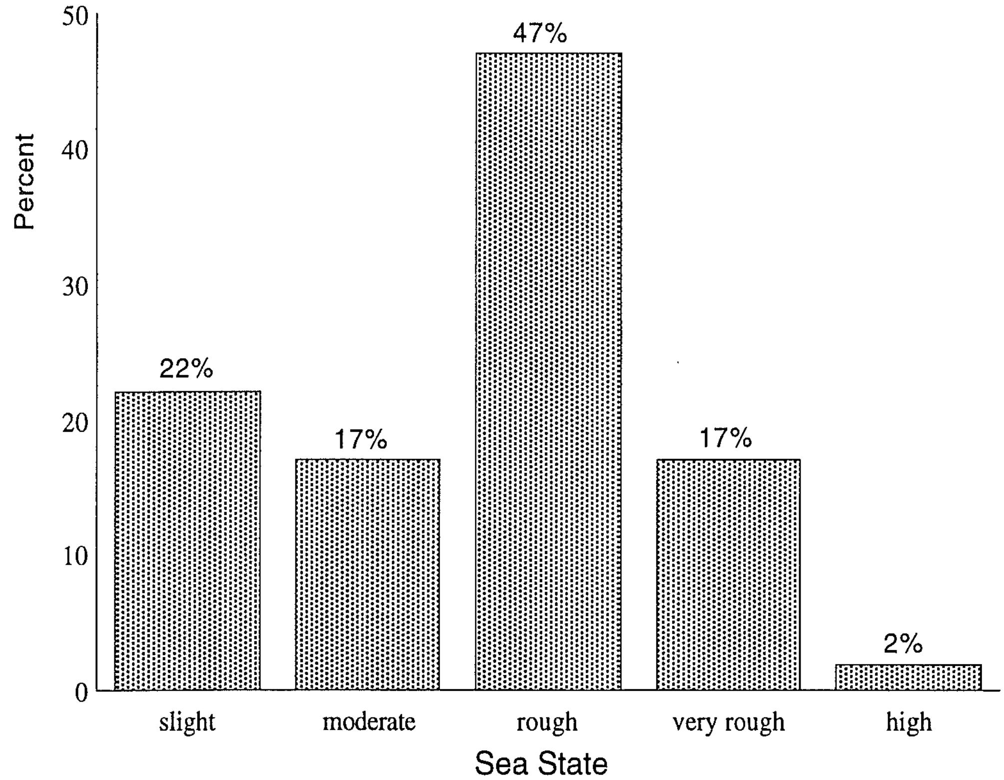


Fig. 4.13: N.Z. Met. Service Chalmers coastal forecast area sea state distribution.

4.4.2 SHORE BASED OBSERVATIONS

4.4.2.1 Total Study Period

The wave roses for the total, 6 month study period, and for the two seasons, summer and autumn, can be seen in Fig. 4.14. For the total, six month study period two swell directions were observed on 38 days. South swells, (90.1%),

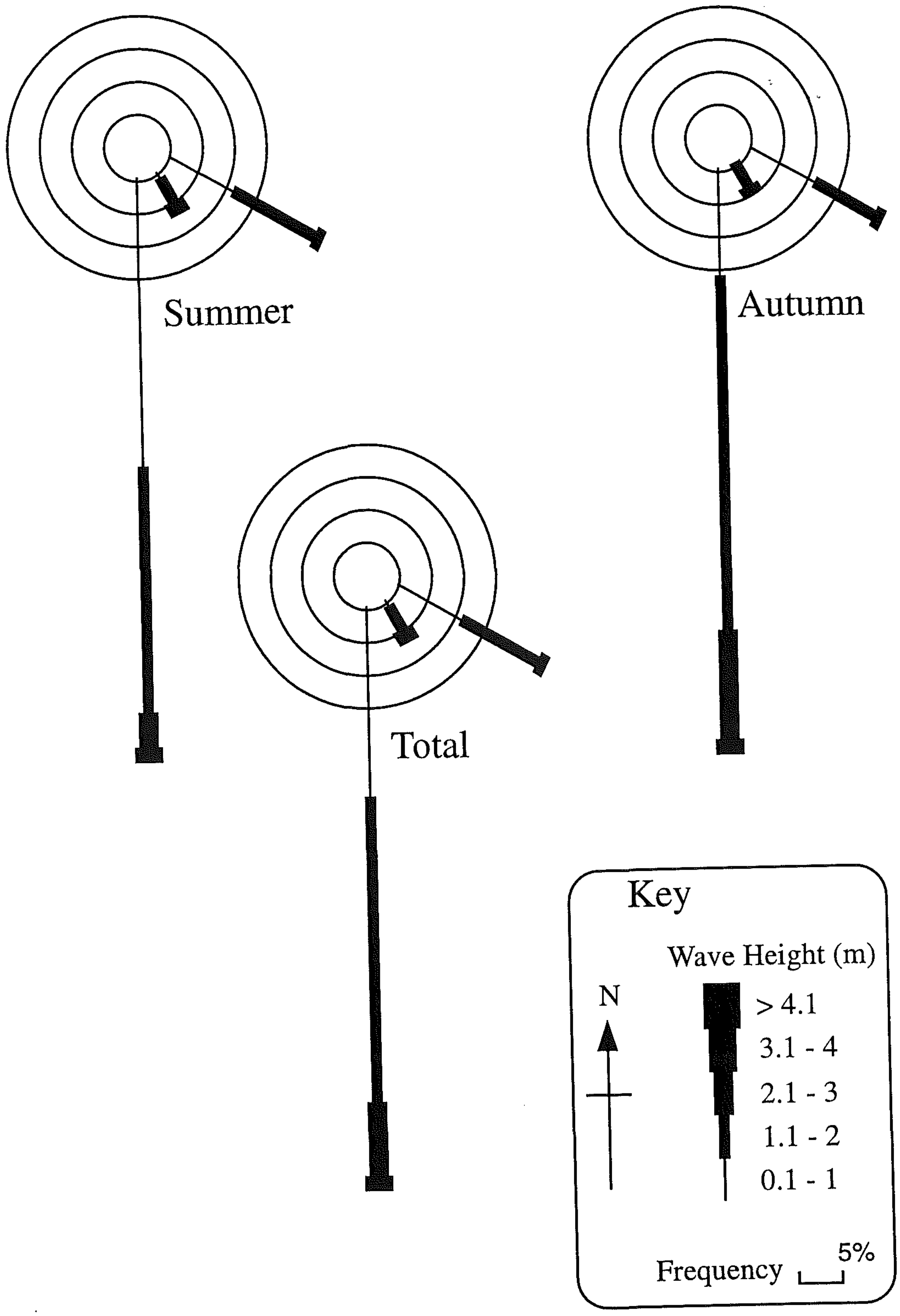


Fig. 4.14: Observation waveroses for summer, autumn and the total study period, (December 1993 - May 1994).

dominated followed by east-southeast, (26.2%), and south-southeast, (5.8%), swells.

4.4.2.2 Seasonal Analysis

The summer period had two swells directions observed on 21 days. South swells, (91.3%), dominated followed by east-southeast, (27.5%), and south-southeast, (7.5%), Fig. 4.14.

Autumn had two swell directions observed on 17 days. It was domianted by south swells, (89.1%), followed by east-southeast, (25%), and south-southeast, (4.3%) swells, Fig. 4.14.

4.4.2.3 Monthly Waveroses

The wave roses for the individual months of summer can be seen in Fig. 4.15. The month of December had two swell directions observed on 6 days. South swells, (81%), dominated followed by east-southeast, (38.1%), and south-southeast, (9.5%), swells.

January had two swell directions observed on 10 days, South swells, (100%) were observed every day, with wave heights predominantly in the 0.1 - 1m, (54.8%), and 1.1-2m, (38.7%), ranges, and peaking at 3m. East-southeast swells, (32.3%), were typically small, (0.1 - 1m, 22.6%), peaking at only 1.5m.

February had two swell directions observed on 5 days. South swells, (89.3%), dominated, with wave heights predominatly in the 1.1 - 2m, (46.4%), and 0.1 - 1m, (35.7%), ranges, peaking at 2.5m. East-southeast swells, (14.3%), ranged from 1.1 - 2m.

The wave roses for the individual months of autumn can be seen in Fig. 4.16. The month of March had two swell directions observed on 10 days. South swells, (87.1%), dominated, peaking at 4m but predominantly between 1.1 - 2m, (48.4%), 2.1 - 3m, (16.1%), and 0.1- 1m, (16.1%). The east-southeast swells, (38.7%), peaked at 2.5m, but were predominantly between, 0.1 - 1m, (19.4%), and 1.1 - 2m, (16.1%).

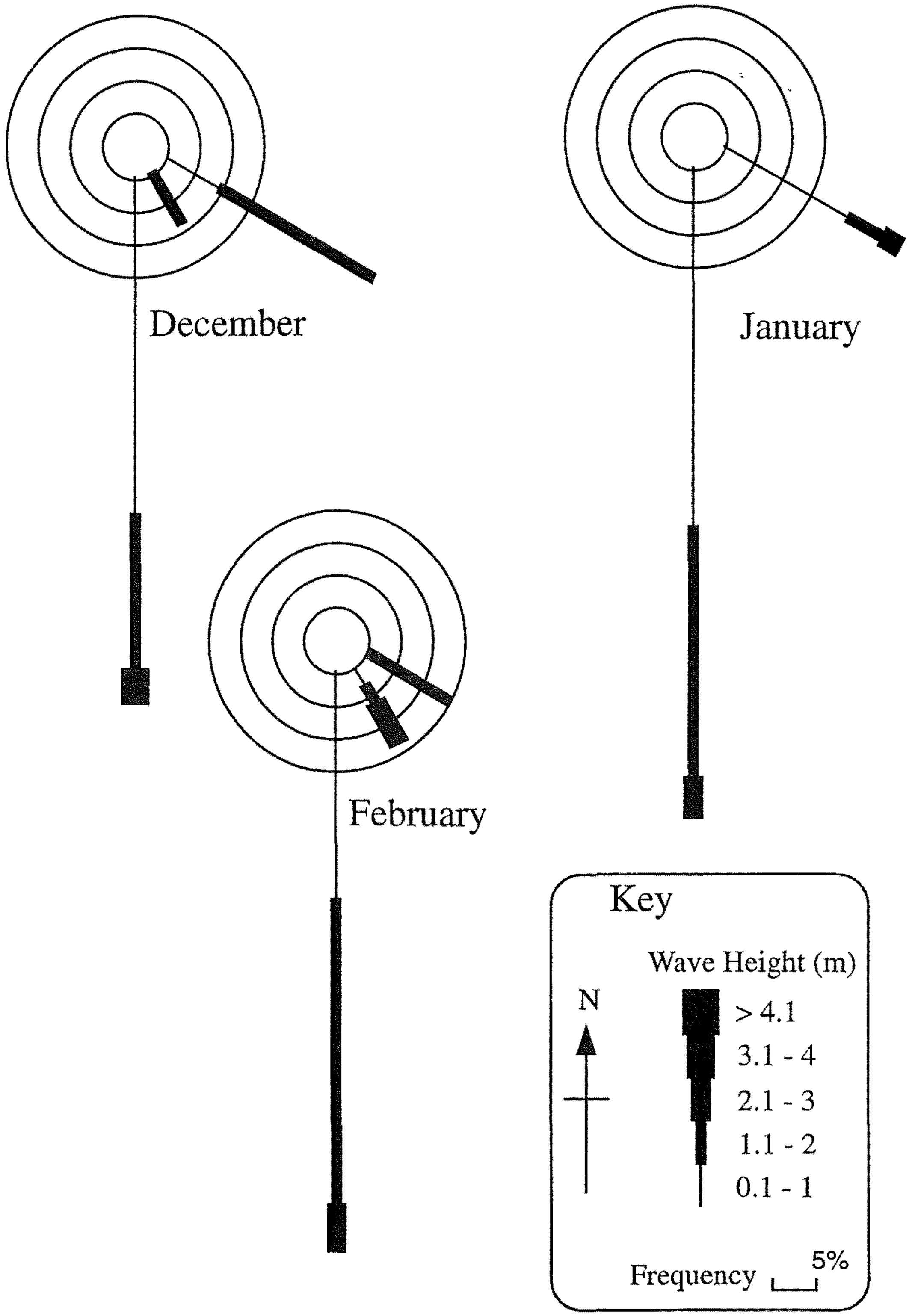


Fig. 4.15: Observation waveroses for December 1993 and January and February 1994.

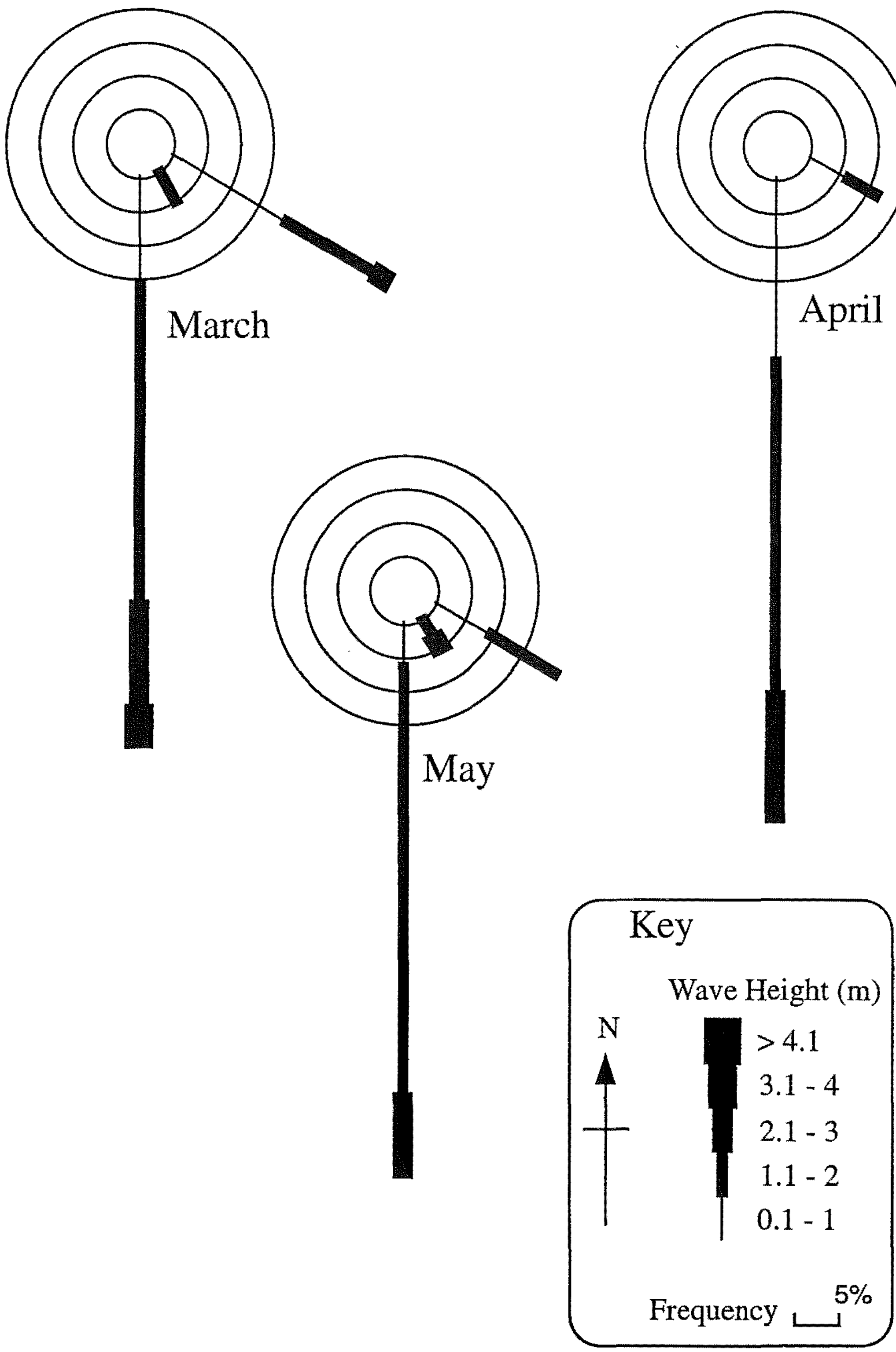


Fig. 4.16: Observation waveroses for March, April and May 1994.

April had two swell directions observed on 3 days. South swells, (96.7%), dominated, peaking at 3m, but predominantly in the 1.1 - 2m, (50%), range, (2.1 - 3m, 30%; 0.1 - 1m, 26.7%). East-southeast swells, (13.3%) ranged from 1 - 2m.

May had two swell directions observed on 4 days. South swells, (83.9%), were the most dominant, peaking at 3m, but with wave heights of 1.1 - 2m, (64.5%), being the most common. The east-southeast swells, (22.6%), ranged from 1 - 2m, while the south-southeast swells, (6.5%), ranged from 2 - 2.5m.

4..4.2.4 Wave Heights

The mean of all observed wave heights was 1.6m. Seasonally the mean wave height of all observed wave directions, (Fig. 4.17), increased from 1.3m for the summer to 1.8m for autumn. A similar pattern was also observed, (Fig, 4.17), for the three different inividual swell directions as well. The monthly mean wave heights showed no real patterns, (Fig. 4.18), except that the autumn months tended to have higher mean heights. Monthly mean wave heights for all observed swells ranged from 1.2 - 1.8m. Monthly mean wave heights for south swells ranged from 1.2 - 1.9m. Monthly mean wave heights for south-southeast swells ranged from 0 - 2.3m. Monthly mean wave heights for east-southeast swells ranged from 1.1 - 1.8m. When compared to the wind direction at the time of observation, the mean wave height was larger under onshore southerly orientated winds (south, southwest, and southeast) (1.8m), than that observed under offshore northerly orientated winds, (north, northwest, and northeast) (1.3m).

4.4.2.5 Wave Periods

Wave periods were recorded on 129 days over the six month observation period. The wave periods ranged from 5.4 - 16.8 seconds, with a mean period of 9.6 seconds. Seasonally the mean wave period increased from 9 seconds in summer to 10.2 seconds in autumn. South swell wave periods ranged from 5.4 - 16.8 seconds with a mean of 9.6 seconds. The east-southeast swells wave periods ranged from 6.8 - 14.1 seconds with a mean of 9.8 seconds. The south-southeast swells wave periods ranged from 6.4 - 10 seconds with a mean of 8.5 seconds. Under onshore southerly orientated winds, (south, southwest, and southeast), the wave periods ranged from 5.4 - 14.3 seconds with a mean of 8.9 seconds. This was lower than that obsreved under offhore northerly orientated, (north, northwest, and northeast) winds, (9.9 seconds), which ranged from 6 - 16.8 seconds.

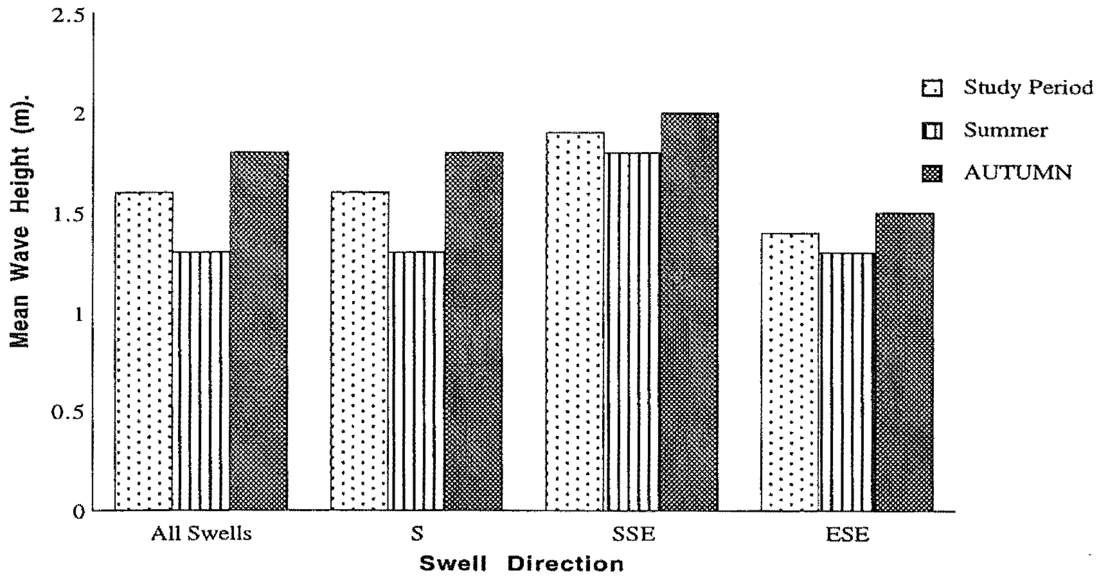


Fig. 4.17: Observation mean seasonal wave heights. December 1993 - May 1994.

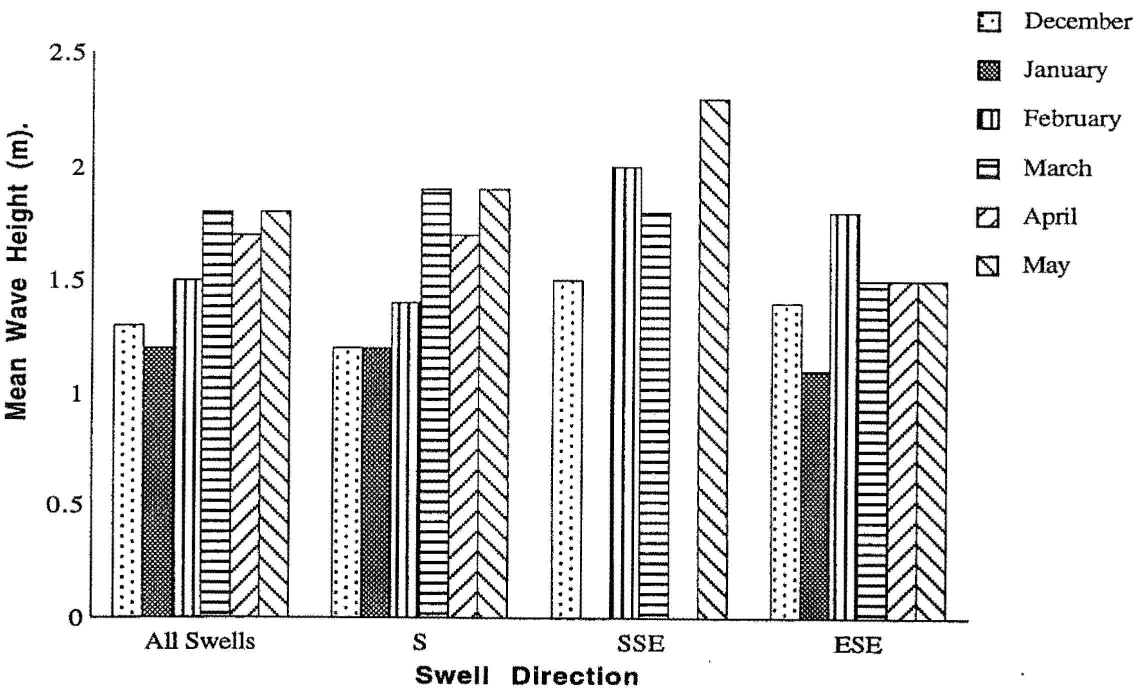


Fig. 4.18: Observation mean monthly wave heights.

4.4.2.6 Inshore Sea States

The observed inshore sea states, (Fig. 4.19), were dominated by smooth, (34.8%), and slight, (33.5%), seas, followed by moderate, (14%), rippled, (9.1%), glassy, (5.5%), and rough, (3%), seas. With respect to the wind direction at the time of observation, glassy, rippled and smooth seas were usually observed under offshore northerly orientated winds (north, northwest, and northeast), while the slight, moderate and rough seas, were dominantly observed under onshore southerly orientated winds, (south, southwest, and southeast).

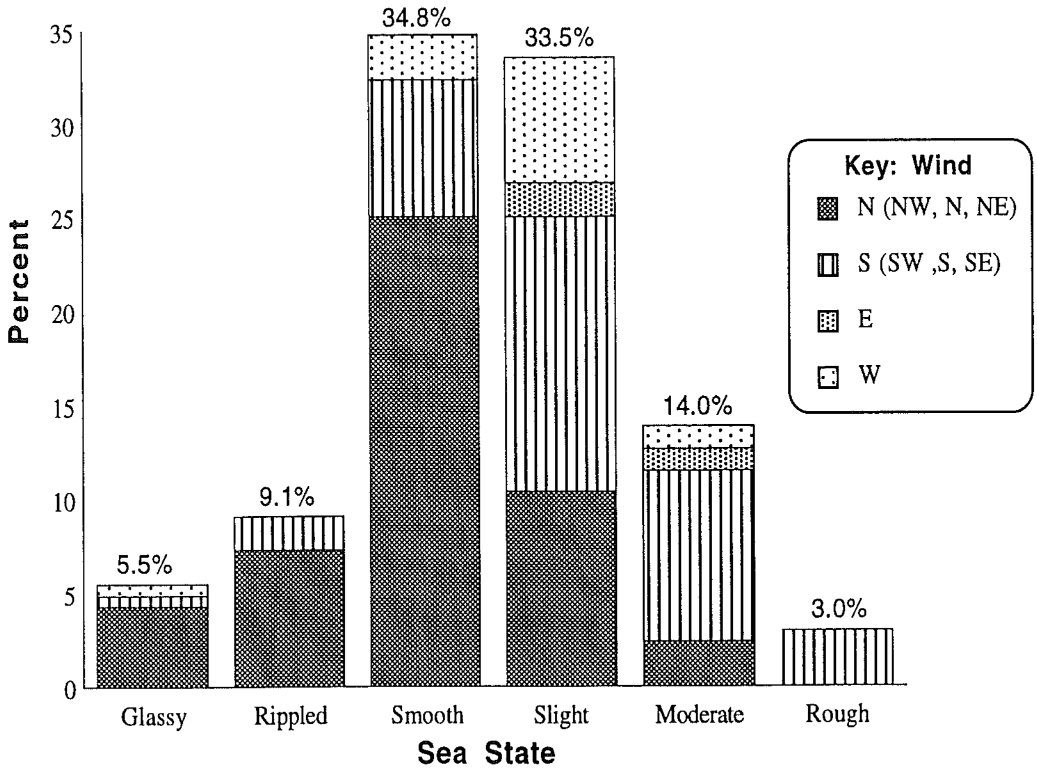


Fig. 4.19: Observation inshore sea state distribution with respect to wind direction at the time of observation.

4.4.2.7 Breaker Type

The type of breaker observed at the coast was recorded on 164 days over the six month period. The distribution of breaker types with respect to the wind direction at the time of observation can be seen in Fig. 4.20. On 90 (54.9%) of these days the breaker type was observed as the spill-plunge variety. Purely spilling breakers were observed on 70 days, (42.7%), while purely plunging waves were observed on only 4 days, (2.4%). With respect to the wind direction at the time of observation it can be seen from Fig. 4.20 that spilling waves were predominantly observed under onshore southerly orientated winds, (south, southwest, and southeast), while spill-plunge breakers were predominantly observed under offshore northerly orientated winds, (north, northwest, and northeast). Plunging breakers were only observed under offshore northerly orientated winds. Westerly winds tended to favour spill-plunge breakers, while under easterly winds the breakers were always of the spilling variety.

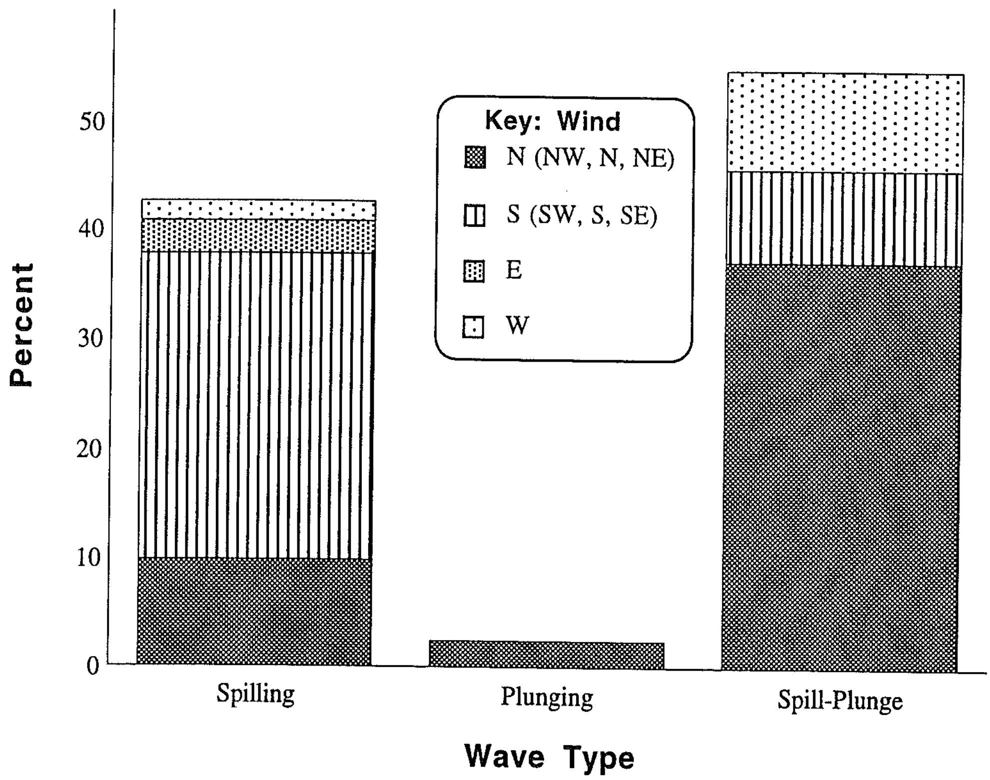


Fig. 4.20: Observation breaker type distribution with respect to wind direction at the time of observation.

4.5 DISCUSSION

4.5.1 SWELL DIRECTION

In the New Zealand Meteorological Service Ship Report Data swell directions of west, northwest, and north were observed, (Fig. 4.4). These were not present in any of the other data sets. The reason for this is that the area covered by Grid Square 44 extends well to the south of New Zealand, (45.0° - 49.9° S), and is therefore open to westerly swells passing to the south of the country. It also extends quite far to the east, (170.0° - 179.9°E), therefore being open to north and northwest swells. In the more localised Otago coastal area it is apparent from the data sets of Hodgson (1966), (Fig. 4.2), and that gathered within this study from the N. Z. Met. Service 'Chalmers' swell reports, (Fig. 4.4), that the swell direction is restricted to southwest, south, southeast, east, or northeast.

The Grid Square 44 swell data are dominated by an almost even distribution of south, (22.7%), and southwest swells, (22.6%). The Chalmers swell report data however is dominated by southwest swells running some 54.5% of the time for the nine months for which data was collected, (Fig. 4.6). Southwest swell also appeared to dominate on both a seasonal, (Fig. 4.7), and monthly basis, (Figs. 4.8, 4.9, & 4.10). January and June are the only months where the southwest swell did not dominate. These months were dominated by northeast, and east swells, respectively. Thus the south swells do not appear to be as dominant as Grid Square 44 data would indicate. It is only for the individual months of June and March that south swells appear to be of major importance predominating over southwest swells and being of about equal frequency with southwest swell respectively.

In the Chalmers swell report data set it is the northeast swell that has the second highest frequency of occurence, after the dominant southwest swell, (Fig 4.6). Seasonally the frequency of occurence of northeast swells decreases from a summer peak to a winter low. (Fig. 4.7). This seasonal pattern is consistent with previous findings for the east coast of the South Island (Brown, 1976; Pickrill &

Mitchell, 1979) who concluded that there was an increase in the frequency of northeast swells within the summer months. Within the present Chalmers data set the northeast swell was also the second most frequently reported swell direction for 6 of the 9 months. In January it was the most frequently reported swell direction and in June it was the least frequent.

East swells had a similar frequency of occurrence for both the present Chalmers data set, (11.4%; Fig. 4.6), and for the Grid Square 44 data set, (10.4%; Fig. 4.4). There was no apparent seasonal trend, but east swells did have their highest frequency in winter due to a high frequency of occurence in July and their dominance of the month of June.

South-southeast swells were the most infrequently reported swell direction, being completely absent from five of the nine months.

The Chalmers coastal forecast area extends offshore for 100km, and waves in it could thus be considered to be an offshore forecast. Due to the discrepancies of the Grid Square 44 data it can probably be discounted as a measure of the coastal Otago wave climate. It can thus be concluded that the offshore coastal Otago wave climate is typically bimodal in nature, being dominated by a predominance of southwest swells throughout the year, and less frequent northeast swells, the frequency of which peaks in the summer months. South, east, and southeast swells are typically a lot less frequent, but may occasionally predominate on a monthly basis. It also should be pointed out that the Chalmers data set is only for a nine month period. Ideally a whole year, or even better several years of data should be used to gain more accurate indication of the monthly, seasonal, and overall swell directions in the Chalmers coastal forecast area.

From the shore based observations it can be seen that for Tomahawk and St. Clair - Ocean beaches that the direction of swell approach has been restricted by wave refraction to either south, south-southeast, or east-southeast. From the observation wave roses it is clearly seen that south swells were overwhelmingly the most frequently observed swell direction for the total six month period of data collection (Fig 4.14; 90.1%). This is also true on both a seasonal, (Fig.

4.14), and a monthly basis. The south swell frequency for the individual months varied from 81% - 100%. East-southeast swells were observed much less frequently and south-southeast swells even less frequently.

The observed south swells were a combination of offshore south and refracted offshore southwest swells. During the data collection it became apparent that the refracted southwest swell approached the beaches at bearings of about 185° - 190°, ie; just to the west of south. From a comparison with the Chalmers swell data it is obvious that the south-southeast and east-southeast swells of the shore based observations are the refracted remains of offshore southeast, east, and northeast swells.

The Cape Saunders data set of Hodgson (1966) is also shore based observations for the south coast of the Otago Peninsula but it displays southwest, east, and northeast swell directions, not observed at the Tomahawk site. However this can be explained through locational differences, (Fig. 4.1). Being situated almost on the eastern tip of the south coast of the Otago Peninsula Cape Saunders is more open to the east therefore allowing for the observation of east swells. Also as Cape Saunders is not actually open to the northeast it is the present authors opinion that some longer period northeast swell would have been refracted around to the east before being recorded as east swell, at the Cape Saunders location. The recorded northeast swell would possibly have been observed under conditions of short period northeast swell pushing past Cape Saunders, just offshore to the east. Given the small occurence of southeast swells in the Chalmers data record it is also possible that some long period east swells refracting around to the southeast, (on approach to the south coast of the Otago Peninsula), may have been recorded as southeast swells at Cape Saunders. There is also the possibilty that 1964 had a higher frequency of occurrence of southeast swells. Having observed numerous long period, (greater than 10 seconds), southwest swells approaching the south coast of the Otago Penisula at about 185° - 190°, and the approach of southeast swells, the author would question the comment of Hodgson (1966) that the southeast swells in his record are refracted long period, (> 10s), southerly swells. The observed southwest swell at Cape Saunders may possibly have been locally generated southwest wind swell, refracted to a lesser extent of the deeper waters off Cape Saunders.

A comment of Hodgson (1966) was that swell directions at Cape Saunders were considered to be more valid with respect to open sea conditions rather than those observed at Taiaroa Head because "*the direction of swell approach at Taiaroa Head is persistently affected by refraction around the Otago Peninsula.*" (Hodgson, 1966, p80). He also states that waves breaking at St. Clair and St. Kilda were considered to be "*less effected by wave refraction than those further north.*" (Hodgson,1966, p80). These comments would be correct if considering the dominant offshore southwest and also south swells alone as these swells do undergo greater refraction while they move to the north around the Otago Peninsula. Northeast swells however, (present at 31.1%), in the Chalmers data set, would be less effected by refraction at Taiaroa Head than at Cape Saunders. Also northeast and east swells having been refracted around to the southeast before breaking on the shores of St. Clair and St. Kilda, have been extremely modified by refraction. Hodgson (1966) also noted a higher occurrence of northeast swells observed at Taiaroa Head.

The frequency of south swells in the Tomahawk shore based observations is much greater than the combination of southwest and south swells for the offshore Chalmers data set. The reason for this is that there is an almost continual southwest groundswell propagating up from the Southern Ocean into the south coast of the Otago Peninsula. On days of no reported swell small southwest groundswells are usually still to be found reaching the south coast of the Otago Peninsula. Also by the time northeast swells have been completely refracted the Otago Peninsula, they can often be too small to be detected on the south coast. This is especially so for small northeast swells which dominate the northeast swell record, (1 - 1.5m, 22.3%; or 72% of all reported northeast swell). Often southwest groundswell was observed on the south coast of the Otago Peninsula when offshore small northeast swells had been reported by the N.Z. Met. Service.

Refracted southwest swells arriving at the two study beaches arrive at an angle so as to create a slight longshore drift from west to east, along the beaches. This easterly longshore drift has been observed to increase in magnitude with extended periods of southwest winds. The dominance of both southwest swells and southwest winds within the respective data sets is thus taken to indicate that the net longshore drift along the south coast of the Otago Peninsula is also from west to east. It should also be pointed out that this in accordance with, and possibly a continuation of, the dominant northerly drift of the south Otago continental shelf hydraulic regime (Carter, *et al*, 1985). Swells also arrive on the south coast of the Otago Peninsula from the east to southeast. This would result in the longshore currents being reversed to move to the west, but a lot less frequently.

4.5.2 WAVE HEIGHTS

Southwest swells tended to be the largest with both the largest overall mean, (2.5m); and the largest reported swell heights of 5m. The lower mean wave heights of the northeast swell, (Fig. 4.11), is in agreement with previous findings for the east coast of the South Island (Brown, 1976; Pickrill & Mitchell, 1979). The increase of the mean reported wave heights, (Fig. 4.11), from summer, through autumn to winter for all reported swell heights is also in agreement with both the previous local work (Hodgson, 1966) and that of the eastern New Zealand wave climate presented by Pickrill and Mitchell (1979). Fig. 4.17 shows that the shore based observations also show a seasonal increase in mean observed wave heights from summer to autumn, but these means tended to be lower than those of the Chalmers swell reports. However Fig. 4.12 shows that the monthly means are quite variable for the Chalmers data set, as does Fig. 4.18 for the shore based observations.

During the collection of the field data it was apparent that extended periods of southwest winds were associated with increasing wave heights, while extended periods of northerly winds were associated with a lowering of the southerly swell heights. These observations are apperent when mean wave heights are calculated with respect to the wind direction at the time of observation. The mean swell height was larger under under onshore southerly orientated winds, (southwest, south, & southeast), (1.8m), than under offshore northerly orientated winds, (northwest, north, & northeast), (1.3m). This finding is in agreement with the observations of Elliot (1958). The reason for this is that the southwest winds experienced on the Otago Coast are associated with deep depressions passing to the south the region which are also responsible for bringing increased amounts of southwest swell to the the region as well. As the swell generating depressions pass away to the east the southwest winds die out to be replaced by northerlies which help blow down the now decaying southwest swell.

4.5.3 WAVE PERIODS

The observed wave periods varied from 5.4 - 16.8 seconds, thus being similar to that for Grid Square 44, (4 - 15s), and slightly less varied than in the data of Hodgson (1966) who recorded wave periods up to 25 seconds. The mean period of the Tomahawk shore based observations was 9.6 seconds. Under offshore northerly orientated winds, (northwest, north, & northeast), the mean period increased to 9.9 seconds, but under onshore southerly orientated winds, (southwest, south, & southeast), the mean period dropped to 8.9 seconds.

Thus in agreement with the observations of Elliot (1958) the Tomahawk observations would tend to indicate that southerly orientated winds (southwest, south, &southeast), favour higher energy shorter steeper waves, having increased heights and lower periods. The northerly orientated winds, (northwest, north, & northeast), tended to favour lower energy flatter waves, having decreased heights and increased periods. These combinations also tend to suggest that the onshore southerly orientated winds, (southwest, south, & southeast), should be associated with erosion on the two study beaches, while the offshore northerly orientated winds, (northwest, north, & northeast), should be associated with accretion, as was proposed by Elliot (1958). These ideas will be further discussed later when examining the beach profile changes within Chapter 5. Beach Profile Change.

4.5.4 BREAKER TYPE

The distribution of the observed breaker types with respect to the wind direction at the time of observation, (Fig. 4.20) shows similar patterns to those observed by other workers (Galloway, *et al*, 1989; Cope, 1993). Thus purely plunging breakers were only observed under offshore northerly orientated winds, (northwest, north, & northeast). More typically these winds tended to be associated with spill-plunge breakers. Onshore southerly orientated winds tended to favour spilling breakers. Obviously the combination of the nearshore slope and the heights and periods of the breakers tended to favour spill-plunge breakers under the offshore wind conditions rather than the purely plunging breakers as observed in the other studies. It should be pointed out that while the local winds do influence the breaker type, that the other factors of the nearshore slope and the heights and periods of the incoming swell also influence the type of breaker experienced on the beach (Pethick, 1984). This helps to explains the variability of the data.

Plate 4.1: Plunging breaker on St. Kilda beach.
2 meter wave with smooth seas.

4.5.5 SEA STATE

The sea state, (Table 4.1), is a descriptive term applied to the sea surface which refers to the average height of the larger well formed waves, that is to the average of about the highest one-third of the waves present (Hydrographic Office, 1993). From this one might expect a similar frequency of sea state heights to the reported swell heights, but this is not so. Chalmers sea states were domimantly rough, (47%), but days with reported swells over 2.5m and up to 4m were only present for 28.7% of the time. Very rough seas were reported at 17% but swells over 4m and up to 6m were reported at only 0.8%. Slight and moderate seas were reported at 22% and 17% respectively but the distribution of reported swell heights, over 0.5m and up to 1.25m, and over 1.25m and up to 2.5m were reported at 26.4% and 44.3% respectively. This would suggest that a lot of the rough and very rough reported sea states were associated with waves in the slight and moderate swell height groupings. Thus the reported sea states appear to have over estimated the state of the sea surface in comparison to the reported swell heights. This appears to be in contradiction to the definition of the sea state as stated by the Hydrographic Office (1993). However it is also stated "*there is a direct relationship between the local wind speeds and the heights of the locally generated waves.*" (Hydrographic Office, 1993, p182). It was found that this may the reason behind the apparent discrepancies. Having listened to the N.Z. Met. Service coastal area forecasts for New Zealand waters almost every day for the past nine months it was picked up that the reported sea state was directly related to the highest forecast wind speed, (excluding the outlook wind speeds), for the coastal forecast area concerned, (Table 4.2). For example the forecast of '*southwest 20 knots, rising to 40 knots*' would be associated with a sea state forecast of '*seas becoming Very Rough*'; '*southwest 30 knots, easing to 20 knots*' with, '*Rough seas easing*'; and '*southwest 30 knots rising to 45 knots, southwest winds later easing to 20 knots*' with, '*seas becoming Very Rough for a time*'.

The most unusual report observed for all New Zealand coastal forecast areas was that for 50kt. winds, High seas, (over 6m up to 9m), but with no reported swell. For the Chalmers coastal forecast area the most unusual report was that for, Very Rough seas, (over 4m up to 6m), with a 1m swell. Obviously reports such as these do not make sense. From these observations it is considered here that wind duration and fetch length, the two variables that along with windspeed are the main factors that determine the heights to which waves will grow, may not have been accounted for in the reporting of the sea state which is supposedly an indication of the average height of the highest one-third of all waves. It would appear that wind speed alone is the only factor used in the determination of reported sea state for New Zealand coastal waters. Obviously some clarification is needed here from the New Zealand Meteorological Service as to what the reported sea state indicates

Table 4.2: Relationship of the Reported Sea State to the Highest Forecast Wind Speed in Knots. (N.Z. Met. Service Coastal Area Forecasts).

Sea State	Highest Forecast Wind Speed. (Knots)
Slight.	10 - 15
Moderate.	20
Rough.	25 - 30
Very Rough.	35 - 45
High.	50 - 55
Very High.	55 - 60

Note (1): It should be noted that the author is unsure as to whether the 55kt. wind speed, is associated with High, of Very High seas, and also as to the sea state reported for winds less than 10 knots.

Note (2): The highest forecast wind speed does not take into account those speeds reported under the Outlook.

As the recorded wave heights already gave an indication of the average of the highest one-third waves the inshore sea states as observed from Tomahawk were recorded to give an indication of the state of the sea surface between the dominant swells. Thus the maximum roughness of the sea state was seen as being limited by the recorded wave height. For example with an estimated breaker height of 2.5m, no matter how rough the sea was it could only be reported as Moderate, (over 1.25m up to 2.5m), because a sea state of Rough, (over 2.5m up to 4m), would thus indicate that the estimated breaker height should be over 2.5m. Also under strong groundswell conditions a clean lined up 2m groundswell, with light offshore winds may occur with only Smooth seas, ie; wavelets of only 0.1m - 0.5m, see Plate 5.1. It would seem to the author that this method for the reporting of sea states, (the state of the sea surface between the predominant swells), is more appropriate, than that which has been observed to be reported for the New Zealand coastal waters, as it attempts to give an indication of the state of the sea surface as a separate entity to the estimated wave height.

From Fig. 4.19 it can be seen that the inshore sea state as observed from the Tomahawk location was influenced by the wind direction at the time of observation. Thus offshore northerly orientated winds, (northwest, north, & northeast), tended to favour the lower sea states of Glassy, Rippled and Smooth, with long clean lines of swell. Onshore southerly orientated winds, (southwest, south, &southeast), on the other hand tended to bring about increased sea states of Slight, Moderate and Rough, representing, messy, and more confused seas.

4.6. CONCLUSIONS

The offshore Otago wave climate is dominated by a bimodal distribution with a year round predominant southwest swell and a secondary northeast swell whose frequency of occurrence peaks in the summer months. South, east and southeast swells are typically a lot less frequent but may occasionally be of greater frequency within an individual month.

Inshore, on the two study beaches refraction restricts the swell approach to south, south-southeast, and east-southeast. Refracted offshore southwest swells approach the study beaches from just west of south, (185° - 190°), and are thus not completely refracted. They therefore produce easterly longshore currents which have been observed to be enhanced by extended periods of strong southwest winds. The predominance of both the southwest swell in the offshore wave record and the strong influence of southwest winds has thus been taken to imply that the net longshore drift along the two study beaches is to the east. A less frequent long shore drift to the west occurs when offshore northeast, east and southeast swells are refracted around to approach the beaches from a southeasterly direction.

A continual pulse of southwest groundswell from the Southern Ocean reaches the south coast of the Otago Peninsula during times of both reported small northeast swells, and no reported swells. This results in the south swell observed on the south coast of the Otago Peninsula having a higher frequency than the combined frequencies of the reported offshore southwest and south swells.

The mean heights of the waves observed from Tomahawk, (1.6m), were lower than the mean of the forecasted offshore swell heights for the Chalmers area, (2.1). Both sets of data however showed that the summer period had the lowest mean wave height. The wave periods ranged from 5.4 - 16.8 seconds with a mean of 9.6 seconds.

The wind direction appeared to have an influence on the wave characteristics. Thus southerly orientated winds, (southwest, south, & southeast), tended to favour higher energy shorter steeper waves, having increased heights, and lower periods. The northerly orientated winds, (northwest, north, & northeast), tended to favour lower energy flatter waves, having decreased heights and increased periods. These combinations would also tend to suggest that the onshore southerly orientated winds, (southwest, south, & southeast), should be associated with erosion on the two study beaches, while the offshore northerly orientated winds, (northwest, north, & northeast), should be associated with accretion, as was proposed by Elliot (1958). This of course will be further discussed and analysed within Chapter Five, Beach Profile Change.

Breaker types were predominantly either spilling, under onshore southerly orientated winds, (southwest, south, & southeast), and spill-plunge under offshore northerly orientated winds, (northwest, north, & northeast

The sea states reported for the Chalmers forecast area were shown to overestimate the size of the sea in comparison to the predicted swell heights. The reason for this was found to be related to the fact that the reported sea state was directly related to the highest forecast windspeed for the forecast area concerned, and that the other two important factors of fetch length and wind duration appear to have not been considerded. Is it a forecast of the highest windspeed, or the state of the sea surface with respect to the average of the one-third highest waves? Some clarification is thus needed as to what the reported sea state is

Estimations of the inshore sea state as observed from Tomahawk were based on what is seen as a more sound method of the describing the state of the sea surface. That is an indication of the state of the sea surface, between the predominant swells. This gives the sea state as a separate entity to that of the wave heights, not just a reiteration of the significant height of the waves. The observations showed that onshore southerly orientated winds, (southwest, south, & southeast) resulted in messy confused seas and therefore higher sea states than offshore northerly orientated winds, (northwest, north, & northeast) which created smoother seas and reduced sea states.

CHAPTER FIVE

BEACH PROFILE CHANGES

5.1 INTRODUCTION

This chapter looks at the variations that were observed in the beach profiles, and works towards establishing links between these changes and changes within the wind and wave environments. First however, the findings of previous profile change investigations within the local area are discussed in Part 2. The methods are then set out in Part 3, followed by the results in Part 4. The results are discussed in Part 5 discussing the links between the wave and wind environment variations in relation to the accretional and erosional cycles experienced at St. Clair and the two other profile sites.

5.2 PREVIOUS LOCAL WORK

With coastal geomorphic research being rare in the Otago region it is not surprising that research into beach profile changes is even rarer. Brockie (1976) noted that studies of the differences in the state of Otago beaches between summer and winter had been largely ignored and also added "*Detailed investigations of coastal change along the southeastern coast of the South Island have not been carried out*" (Brockie, 1976, p73).

Despite not actually profiling any beaches or collecting any wave data record Elliot (1958) tentatively concluded from observations on the Otago Coast that erosion was associated with southwesterly winds and accretion with northeasterly weather. The reason for this was that southwest winds were seen to build up and steepen the dominant southerly swell, while northeast winds flattened the southerly swell out, thus resulting in erosional and accretional conditions respectively.

Nicholson (1979) made monthly surveys of the Otago Peninsulas north coast beaches of KaiKai, Murdering, Long, and Purakanui. Profile change varied greatly between the beaches with respect to magnitude and trend, but no distinct seasonal patterns were observed. Here no attempt to link the profile changes to the wave and wind environments was attempted. It should also be noted that these beaches are distinctly geographically removed from the south coast sites researched in this study, the two areas being subject to very different inshore wave climates.

More recently the Otago Regional Council has established several beach profile baselines for assessing coastal change but as yet little further progress has been accomplished (Kirk, 1991).

It can thus be seen that for the present study site and also for most of the Otago coast in the greater Dunedin area, that there is little established knowledge on the nature of coastal profile changes and even less detail of the relationships of these changes to the local wave and wind climates.

5.3 METHODS

An examination of the changes in the beach profiles at St. Clair is the main thrust of this study. At St. Clair the seawall provides an easily relocatable bench mark from which beach profiles can be easily resurveyed. Initially two profiles were set up at the western, Profile 1, and eastern, Profile 3, ends of the seawall. However along Profile 1 the sand had been completely eroded out by January 26, leaving a stable rocky profile. Thus Profile 2 was set up in the center of the seawall to pick up the sand level fluctuations, occuring along the beach to the east of Profile 1, but west of Profile 3. Two other profiles were also set up at St. Kilda, Profile 4, and Tomahawk, Profile 5, beaches respectively. Both of these sites had relocatable bench marks in the way of wooden posts on the backshore driven well into the sand, allowing accurate resurveying of the profiles. The wooden posts were already present on the beach, being the remains of some previous sand management scheme, such as sand fencing, etc. The general locations of the five profile sites can be seen in Fig. 5.1.

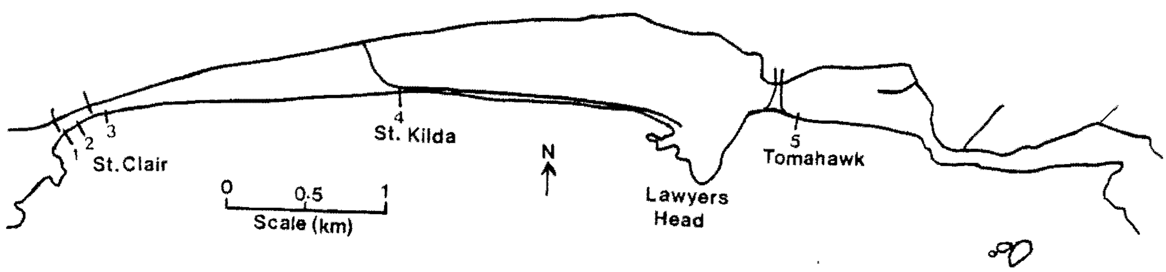


Fig. 5.1: General Profile Locations.

The profiles were surveyed within 1.5 hours of low tide, so as to survey as much of the beach as possible. Unfortunately the profile surveys did not extend very far out into the swash zone due to the usually rough nature of the wave environment. The low water mark for each respective daily profile was calculated using the tidal harmonic tables and equations of the Hydrographic Office (1993). For each profile site the mean low water mark was then calculated and profile closure depths established approximately 0.2m, below this, for volume calculations.

For each individual profile site all the surveys were collectively graphed to give an indication of the total changes in the sand envelope over the study period.

Excursion Distance Analysis, EDA, was carried out to show the patterns of erosional and accretionary phases as they occurred through the study period and also to also identify where on the beach profile these changes were taking place.

EDA does this by comparing the spatial movement of the beach contours through time by plotting the horizontal position of the beach contour from the bench mark, such as the seawall at St. Clair. Thus on an EDA plot erosion shows up as negatively sloping lines indicating a retreat of the contour, while positively sloping lines indicate an advance of the contour under accretionary conditions. Also where the contours converge on an EDA plot this indicates a steepening of the beach, while diverging contours indicates a reduction in beach gradients.

The systematic changes of the profiles between individual surveys were assessed visually by way of graphing the two consecutive profiles. Numerically changes between surveys were assessed by calculating the volume of the profile algebraically assuming a one meter wide profile, above the closure depth seaward of the benchmark. Volume changes of greater than plus or minus three cubic meters were considered to be strong events of accretion or erosion.

For each profile a summary of the wave conditions during each of the strong individual erosion and accretion events was calculated to give an indication of the predominant wave conditions which were responsible for the resulting erosion or accretion of the respective profiles. To see if there was any difference in the mean wave steepness, mean wave height and maximum wave height between erosional and accretional conditions, the average mean wave steepness, mean wave height, and maximum wave height for all strong events of all profiles was calculated.

Wind roses were drawn up for the main erosion and accretion events after they were identified to see if there was any distinct link between wind variation and profile change, such as that proposed by Elliot (1956).

To assess the usefulness of the Dean (1973) equation of critical wave steepness to the beaches in the present study the values for critical wave steepness obtained from the Dean (1973,*in* Allen, 1985) equation were compared to the wave steepness values obtained by from the shore based obsevations. Rapid sediment analysis of sediments collected on May 1 gave a mean sediment size of 1.75 phi, which corresponded to a mean fall velocity of $0.04ms^{-1}$.

5.4 RESULTS

5.4.1 PROFILE 1

Profile 1 was situated just 2 meters east of the western end of the main St. Clair seawall. The profile has a rock base, over which the sand is deposited or eroded. From the sweep zone plot, Fig. 5.2, it can be seen that variation occurred along the entire profile length, with the sand envelope, sitting against the seawall. Minimum vertical change, (0.25m) occurred at the base of the seawall, while the maximum verticall change, (1.6m) occurred at the position of the berm, present on January 9, about 20 meters out from the seawall. The width of the beach varied from 30 to 70 meters The sand envelope had a maximum volume change of 26.98m³ for the survey period.

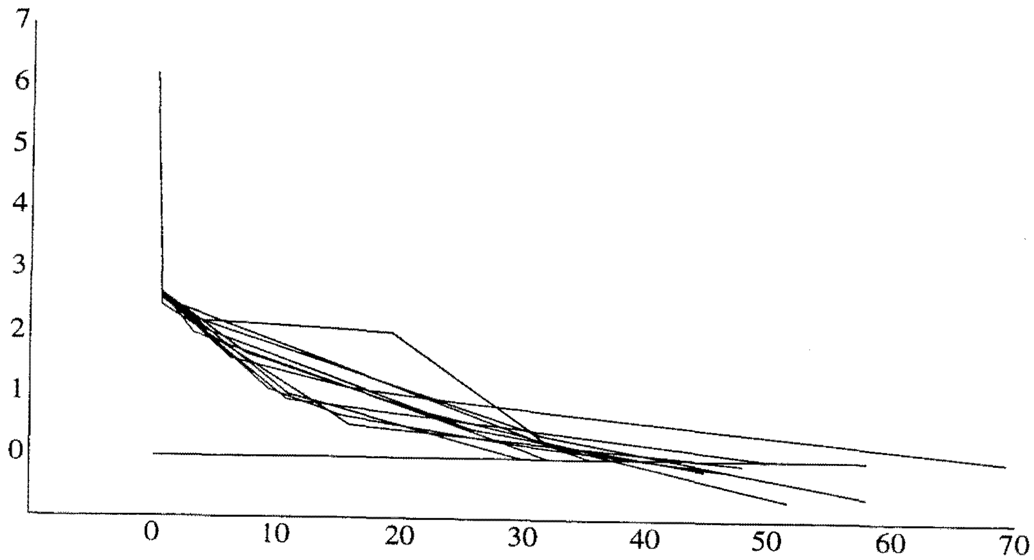


Fig. 5.2: Profile 1 Sand Envelope. (January 9 - June 20 1994).

From the EDA, Fig. 5.3, it can be seen that the 3 meter contour was stationary throughout the study period not leaving the seawall. Thus discounting the 3 meter contour, the profile was steepest on January 4 and flattest on June 20. The 2 meter contour initially retreated, indicating erosion of the prominant berm of January 4, Fig. 5.5, but then remained fairly stable. The intial erosion of the upper foreshore, indicated by retreat of the 1 and 2 meter contours, was associated with accretion on the lower foreshore, with the 0 meter contour advancing. The 0 meter contour showed the most variation indicating that the most change occurred on the lower foreshore. The last survey period showed marked accretion. This also shows up, (+20.21m³) on the volume plot, Fig. 5.4, which also shows the intial erosional phase. The maximum volume change for an accretion event was +20.21m³, (May 15 - June 20). The maximum volume change for an erosion event was -10.49m³, (January 19 - 26)

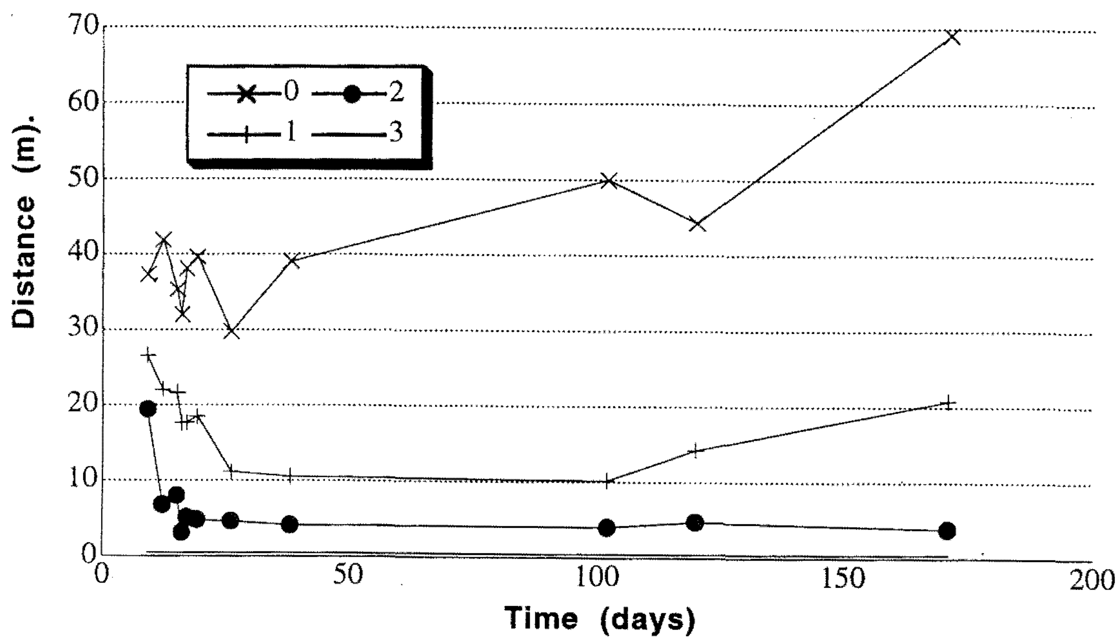


Fig. 5.3: Profile 1 Excursion Distance Analysis.

The prominant berm present on January 4 was eroded by January 12,(-9.91m³), with the profile then remaining stable to January 15, Fig. 5.5. Sand had eroded out by January 16, (-9.35m³), Fig. 5.5. The profile then remained stable until January 19, but by January 26 more sand had again been eroded out, (-10.49m³), Fig. 5.6. By February 7 there was no sand left leaving only the rocky base of the profile, Fig. 5.7. With the rocky profile base being quite stable surveying of this profile ceased after this point until April 12, Fig 5.7, by when some sand had accreted back over the rocky base, (+6.86m³). By April 30 the sand had again eroded off the profile, Fig. 5.7, but by June 20, Fig. 5.8, a substantial amount of sand, (+20.21m³), had been redeposited over the rocky base.

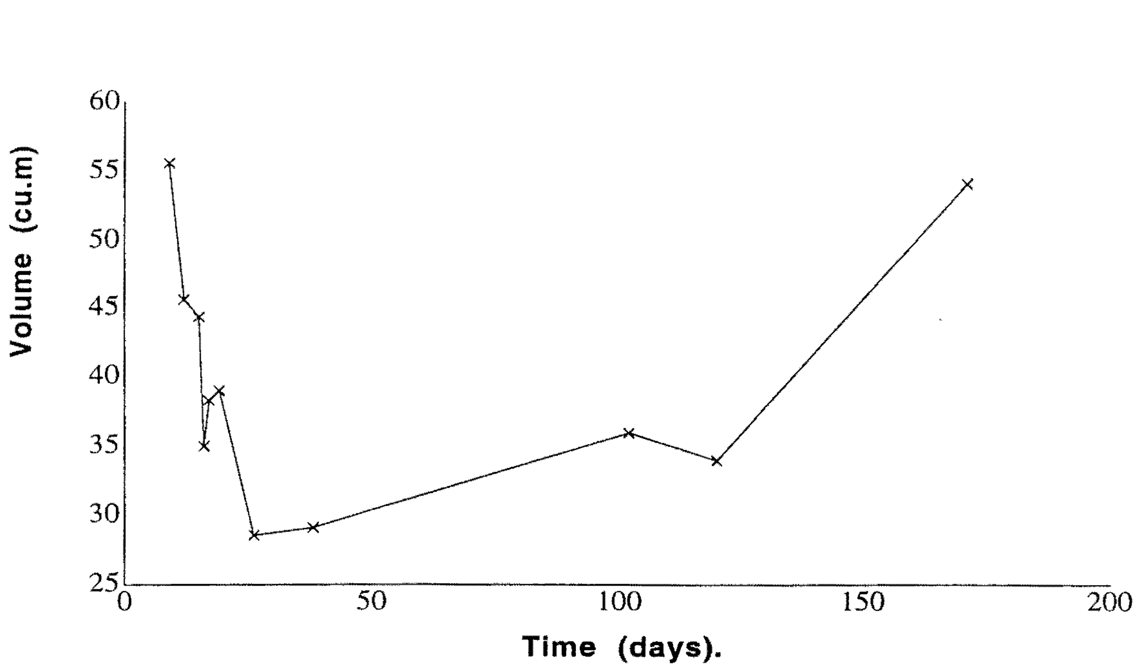
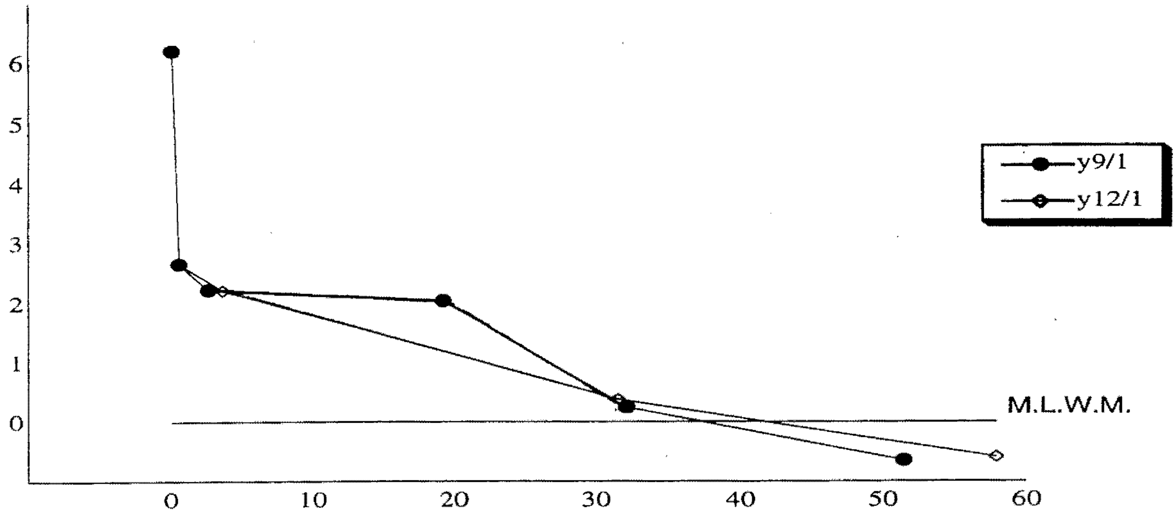


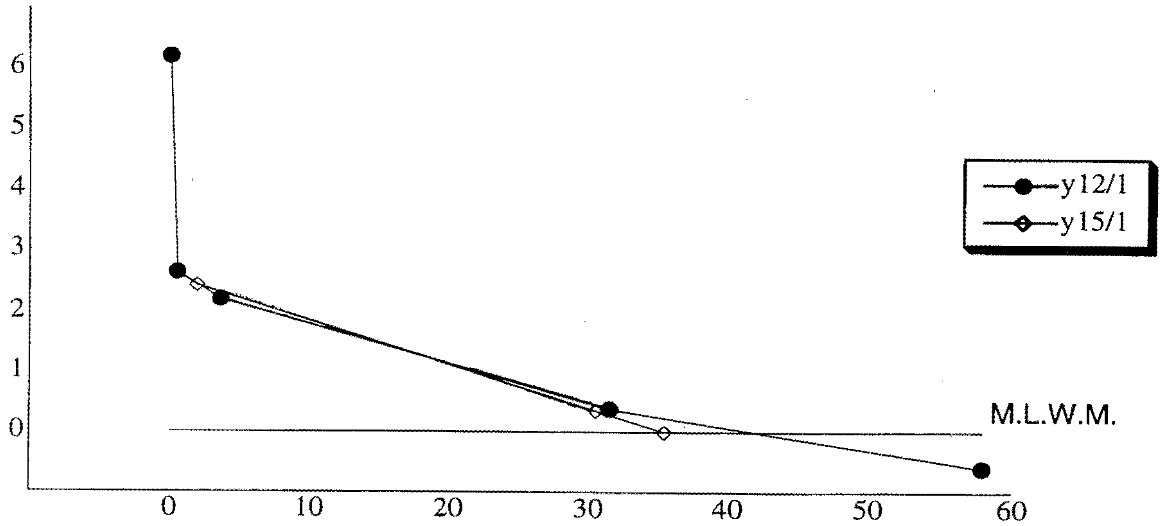
Fig. 5.4: Profile 1 Volume Changes.

The irregular nature of the rocky base of the profile led to some problems in the calculation of the profile volumes. From observation the rocky base of the profile appeared to be relatively stable. However depending on where the survey staff was placed the rocky base height could show considerable variation due to the irregular nature of the rocks. This variation thus led to some inaccuracies in the volume calculations. The classic example of this is from January 16 to 17, Fig. 5.6, where the amount of sand on the profile decreased but the volume calculations indicated an increase.

Table 5.1 shows a summary of the wave conditions for the significant erosion events of Profile 1. Also included is the erosion event of April 12 to 30 which after adjusting for rock inaccuracies actually eroded ($-6.17m^3$), as opposed to ($-2.02m^3$). From Table 5.1 it can be seen that the erosion events of Profile 1 were dominated by south swells, with mean wave steepness typically greater than 0.011, and peak wave heights of 1 to 3 meters.

The two significant accretionary events wave conditions were not summarised due to the extra long time between surveys.





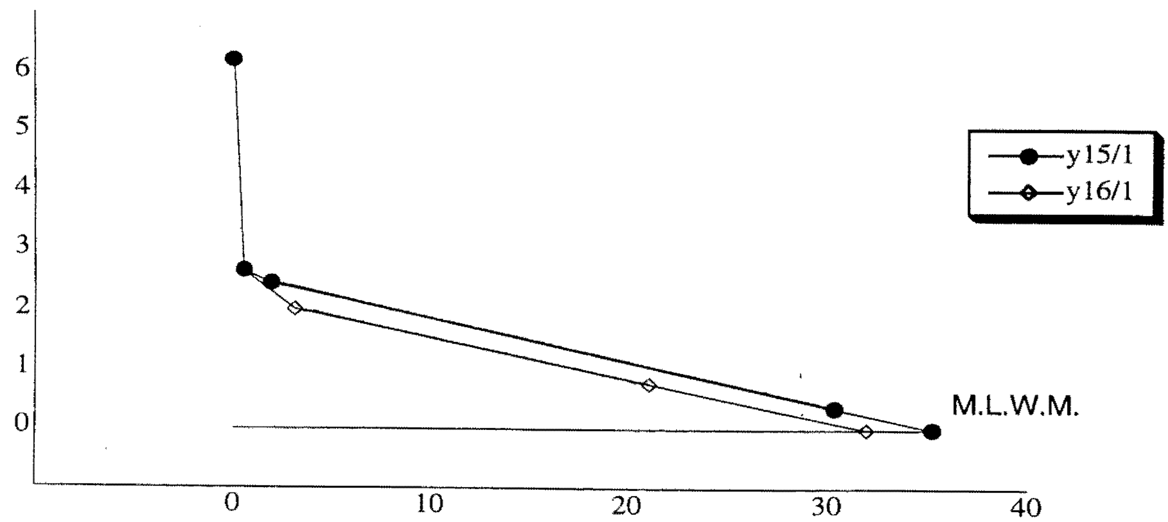
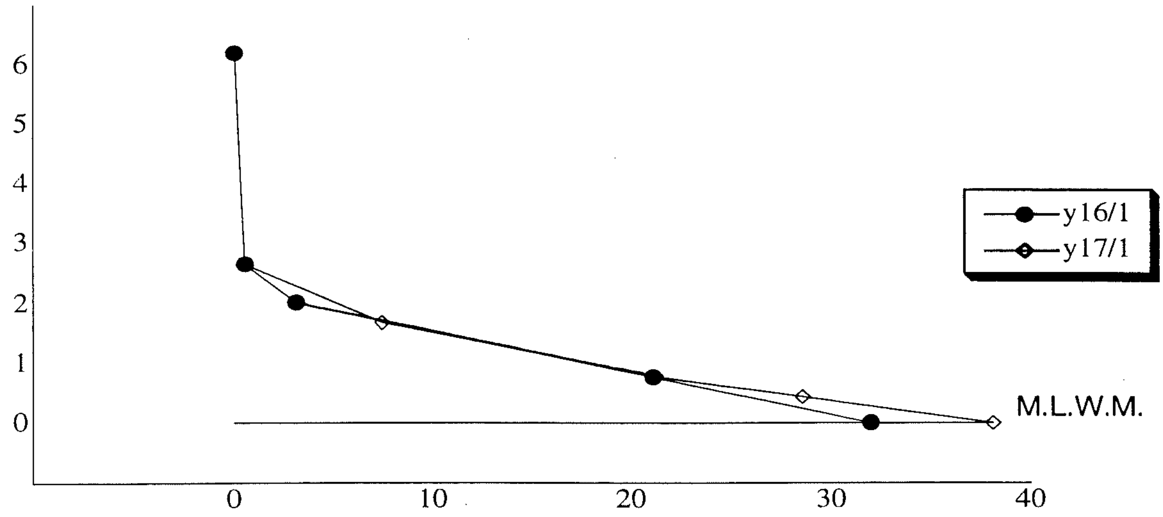
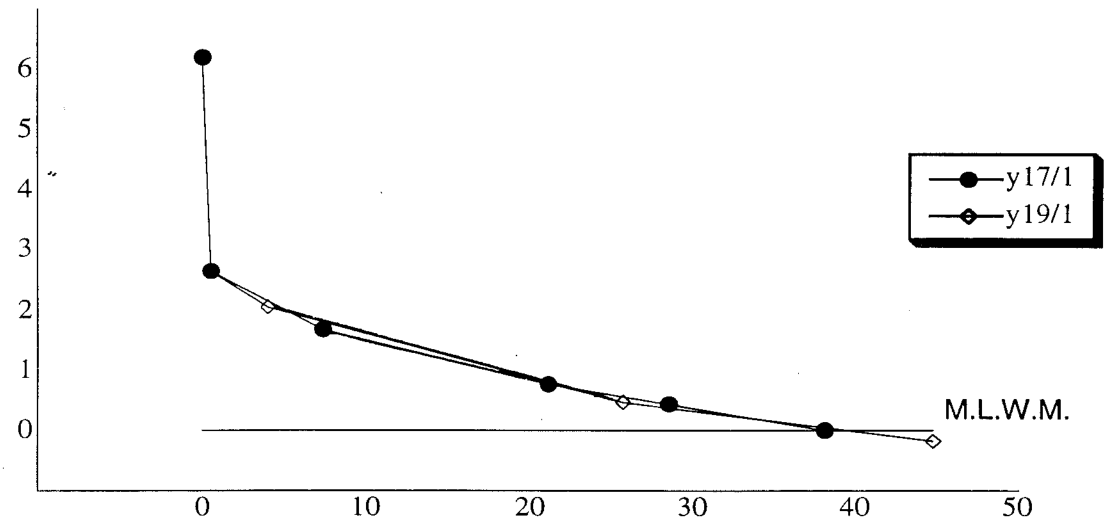


Fig. 5.5: Profile 1 Variation. January 9 to January 16.
Note: indicates sand.





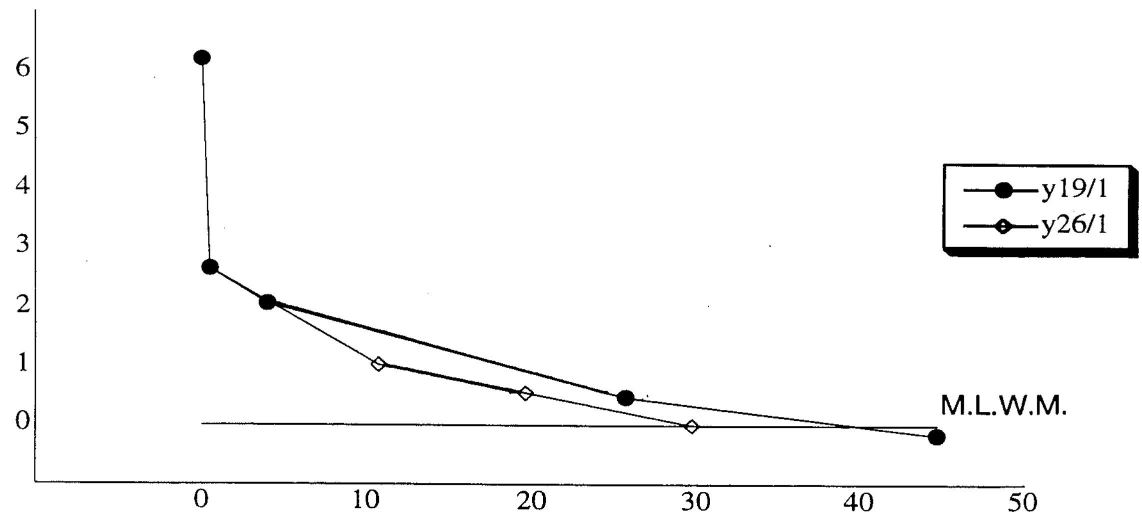


Fig. 5.6: Profile 1 Variation. January 16 to January 26.
Note: indicates sand.

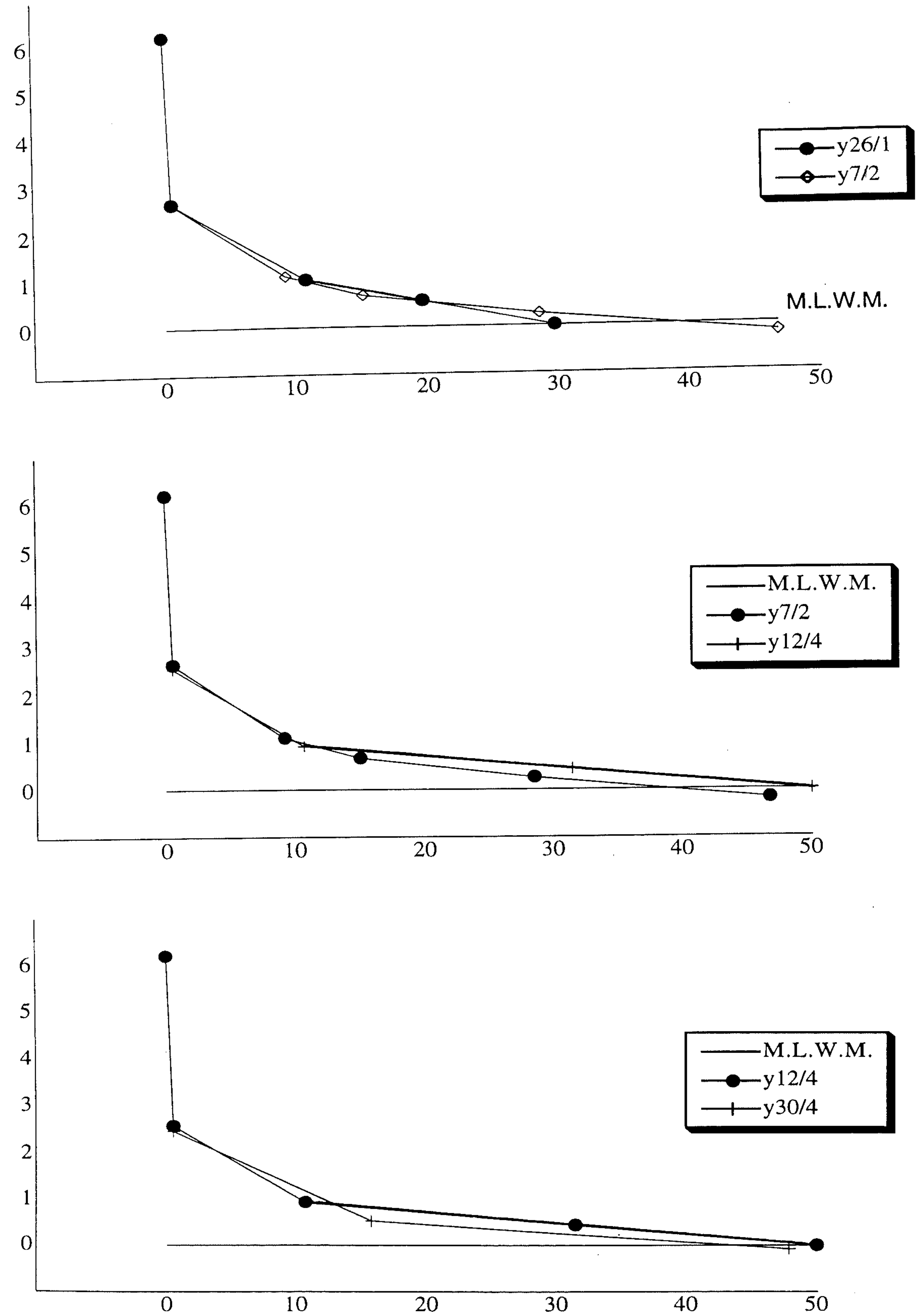


Fig. 5.7: Profile 1 Variation. January 26 to April 30.
Note: indicates sand.

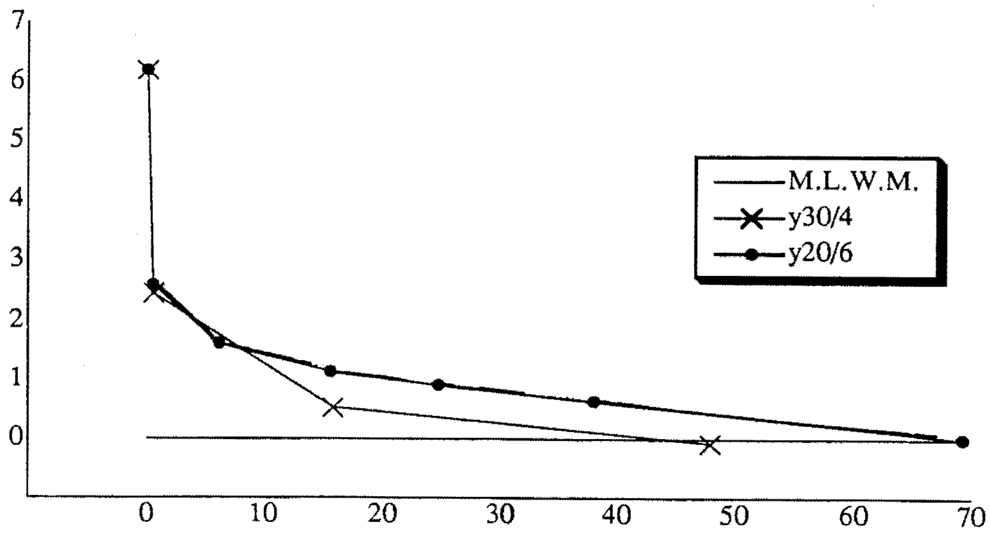


Fig. 5.8: Profile 1 Variation. April 30 to June 20.
Note: indicates sand.

Table 5.1: Summary of Wave Conditions during Profile 1 Erosion Events.

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Jan. 9 - 12 (-9.91m³)				
S	0.1 - 1.5m	0.7m	0.00058 - 0.01242	0.00524
Jan. 15 - 16 (-9.36m³)				
S	---	1m	0.01272 - 0.01428	0.0135
Jan. 19 - 26 (-10.49m³)				
S	1 - 2.5m	1.6m	0.00512 - 0.02773	0.01158
ESE(1)	---	1m	---	0.01387
Apr. 12 - 30 (-6.17m³)				
S(18)	0.5 - 3m	1.9m	0.00379 - 0.02327(15)	0.01218
ESE(3)	1 - 2m	1.7m	0.00887 - 0.01515(2)	0.01234

5.4.2 PROFILE 2

Profile 2 was situated in the middle of the main St. Clair seawall just east of the western seawall stairs. The profile is primarily sandy, but has rock rip rap placed at the base of the seawall, which is visible when the sand is eroded out. As with Profile 1 the sweep zone plot, Fig. 5.9, shows that variations occurred across the entire profile, with the sand envelope sitting against the seawall. Here however sand levels on the seawall varied by up to 2.7m. which was the maximum horixontal change of the profile. The width of the beach varies from about 25 to 75 meters. The sand envelope had a maximum volume change of 95.2m³ for Profile 2.

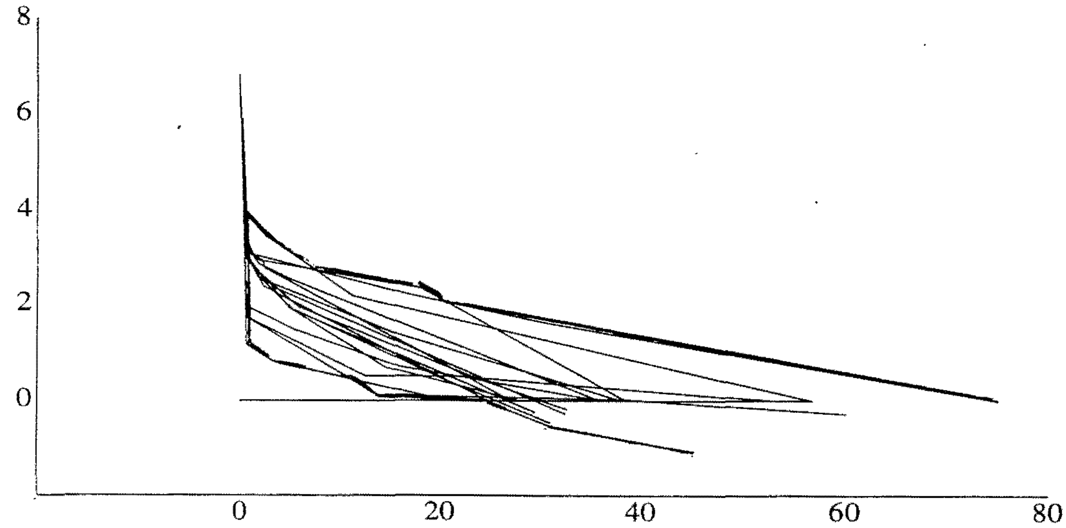


Fig. 5.9: Profile 2 Sand Envelope. (January 26 to June 20).

From the EDA, Fig. 5.10, four prominant accretionary peaks can be seen, along with four erosional valleys. This pattern is repeated on the volume plot, Fig. 5.11. Strong erosion by April 12 pushed the 2 meter contour right back on to the seawall, with the 3 and 4 meter contours. Strong erosion also resulted in the 1 meter contour eroding back to within 1.5m of the seawall on May 15. The 2m meter contour remained on the seawall until May 15, before advancing with the 1 meter contour due to strong accretion between May 15 and June 20.

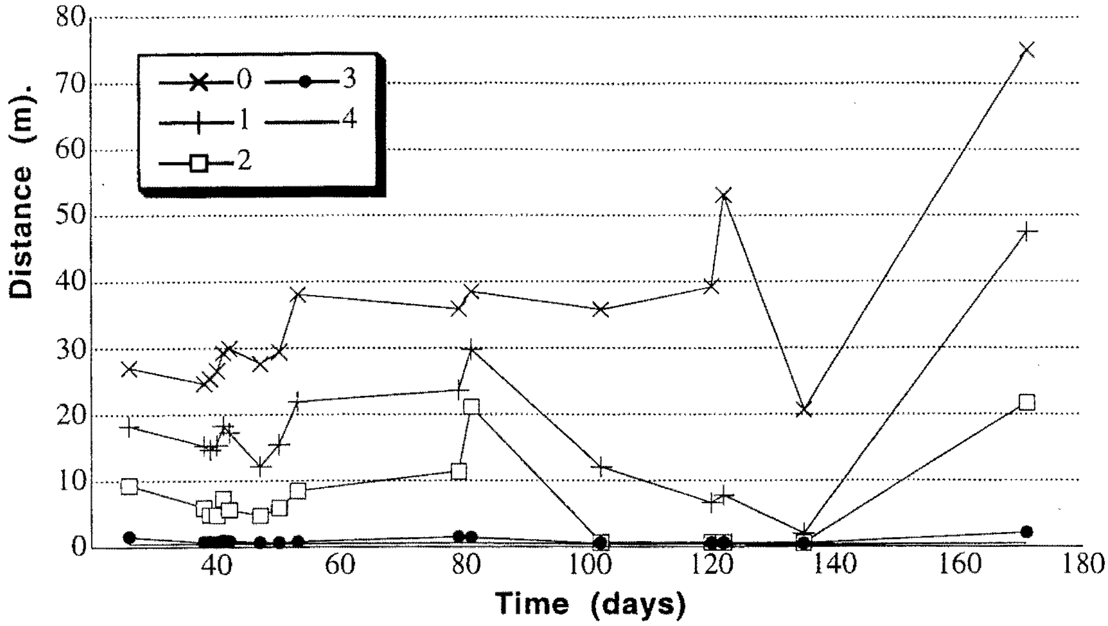


Fig. 5.10: Profile 2 Excursion Distance Analysis.

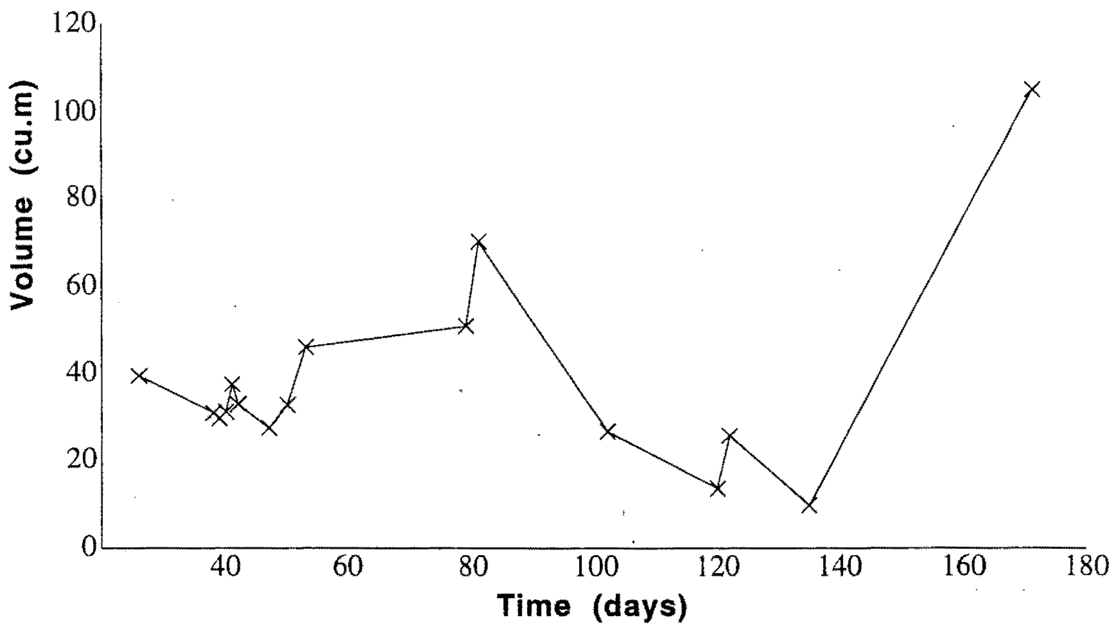


Fig. 5.11: Profile 2 Volume Changes.

Profile 2 eroded from January 26 to February 7, (-8.55m^3), then remained stable through to February 9, Fig. 5.12, before accreting by February 10, (+6.37m^3), and then eroding by February 11, (-4.61m^3), and February 16, (-5.54m^3), Fig. 5.13. The profile then progressively accreted through February 19, (+5.29m^3), 22, (+13.42m^3), March 20, (+4.79m^3), Fig. 5.14, and March 22, (+19.31m^3), before eroding by April 12, (-43.61m^3) and 30, (-13.12m^3), Fig 5.15, with the rock rip rap being exposed on April 30. The profile had accreted slightly by May 2, (+12.20m^3), but had again eroded by May 15, (-16.04m^3), lowering the level of the rock rip rap on the seawall, before strongly accreting by June 20, Fig. 5.16.

Table 5.2 is a summary of the wave conditions present during five of the six significant accretionary events of Profile 2. Again the last accretionary event was not included due to its extra long time period. Thus from Table 5.2 it can be seen that the first two accretion events were dominated by small south swells, with mean wave steepness less than 0.009. The next accretion event was dominated by south-southeast swells. Although having larger, steeper south swells the third and fourth events also had significant occurences of east-southeast and south-southeast swells respectively. The sixth accretion event also had east-southeast swells present for its duration.

Table 5.3 is a summary of the wave conditions present during the six strong erosion events of Profile 2. From this it can be seen that the erosion events were mostly dominated by large steep south swells.

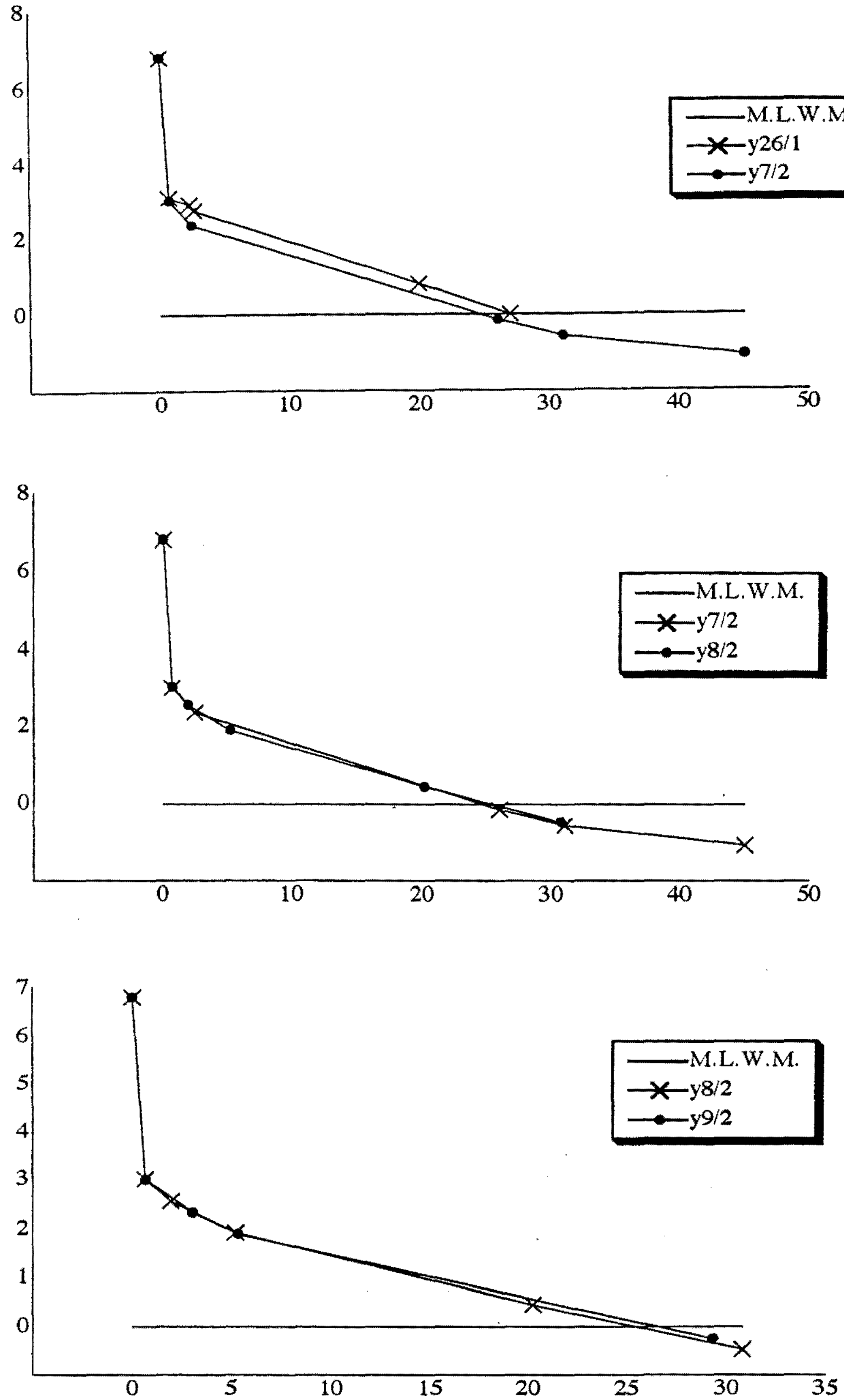


Fig. 5.12: Profile 2 Variations. January 26 to February 9.

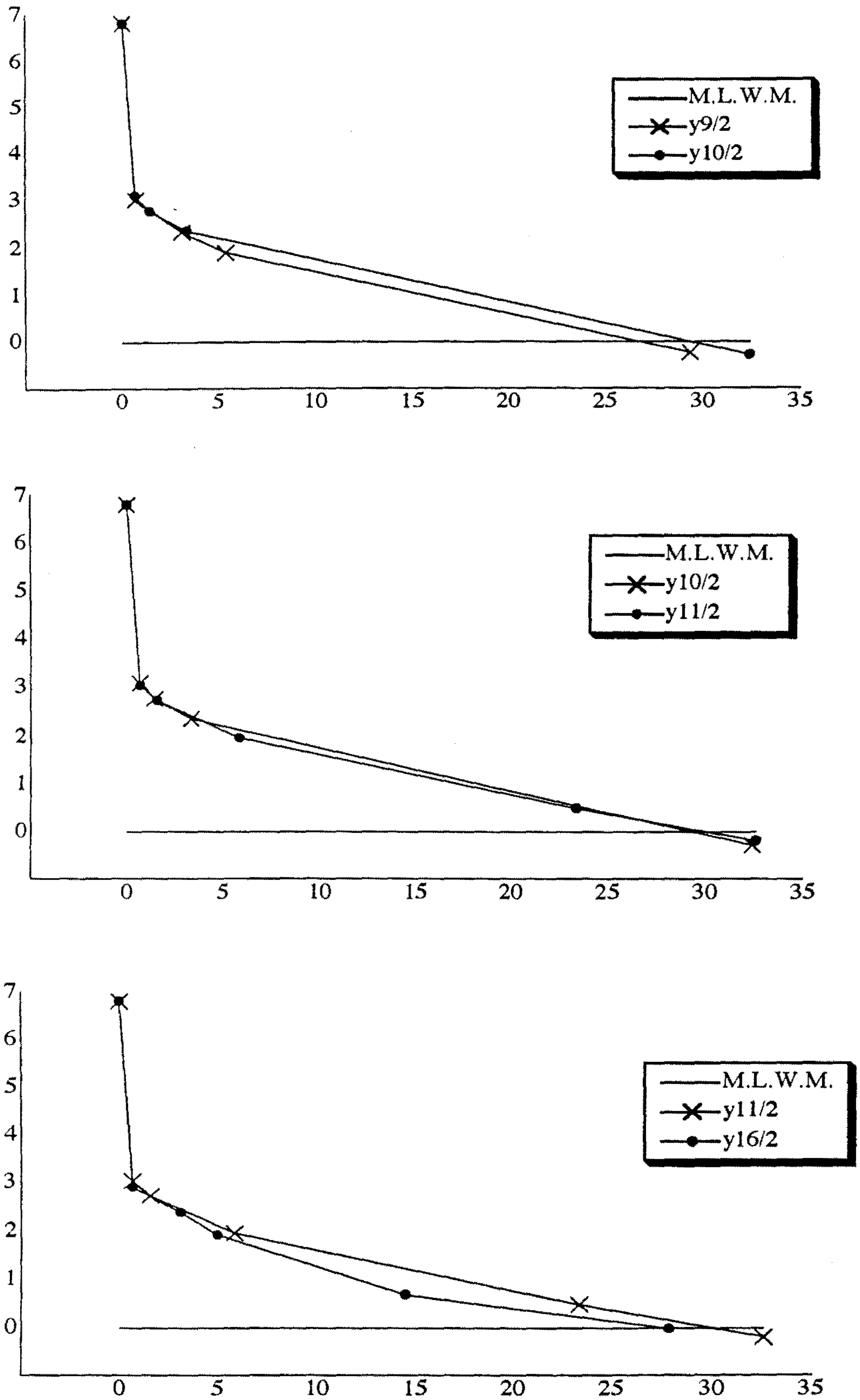


Fig. 5.13: Profile 2 Variations. February 9 to 16.

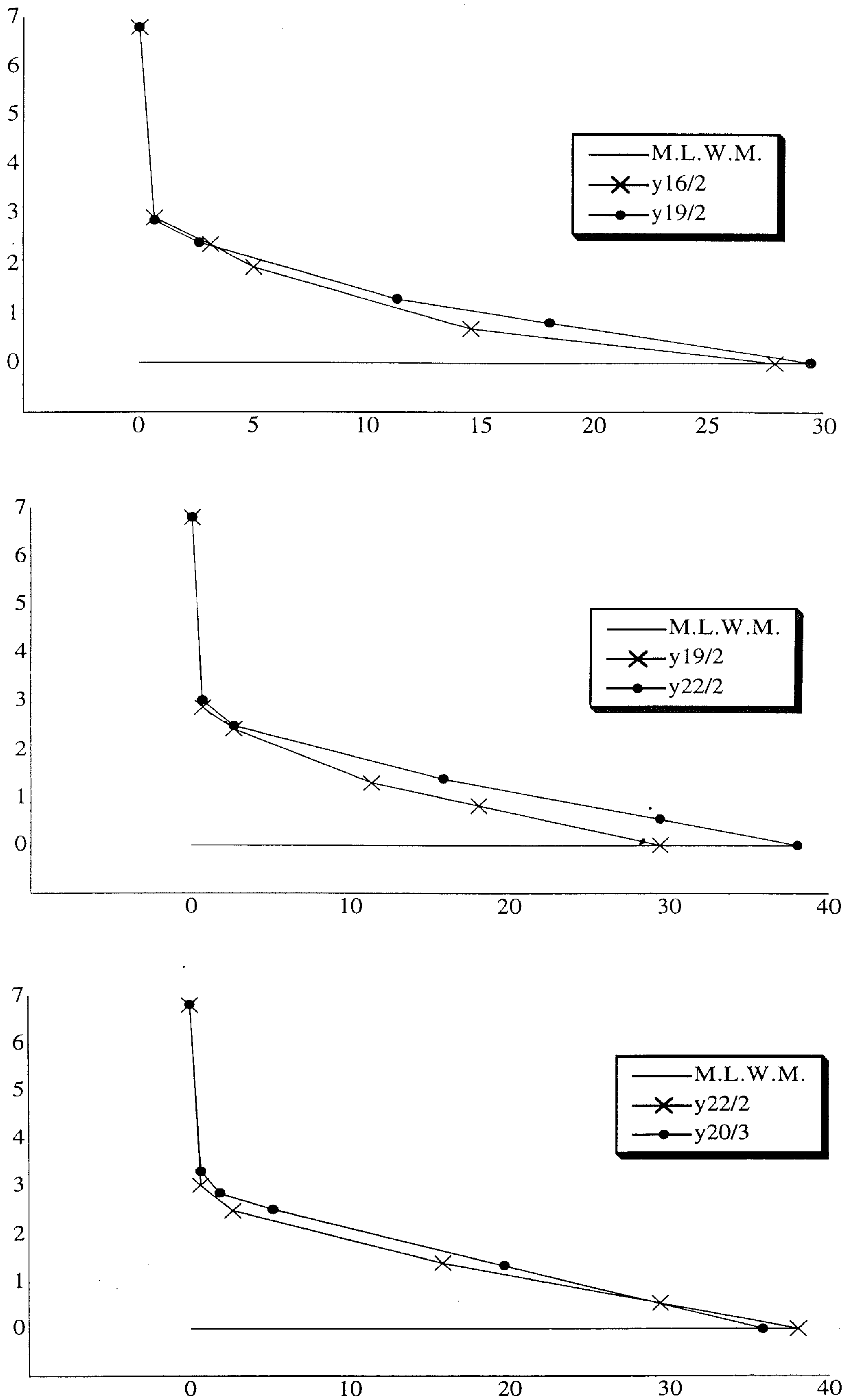


Fig. 5.14: Profile 2 Variations. February 16 to March 20.

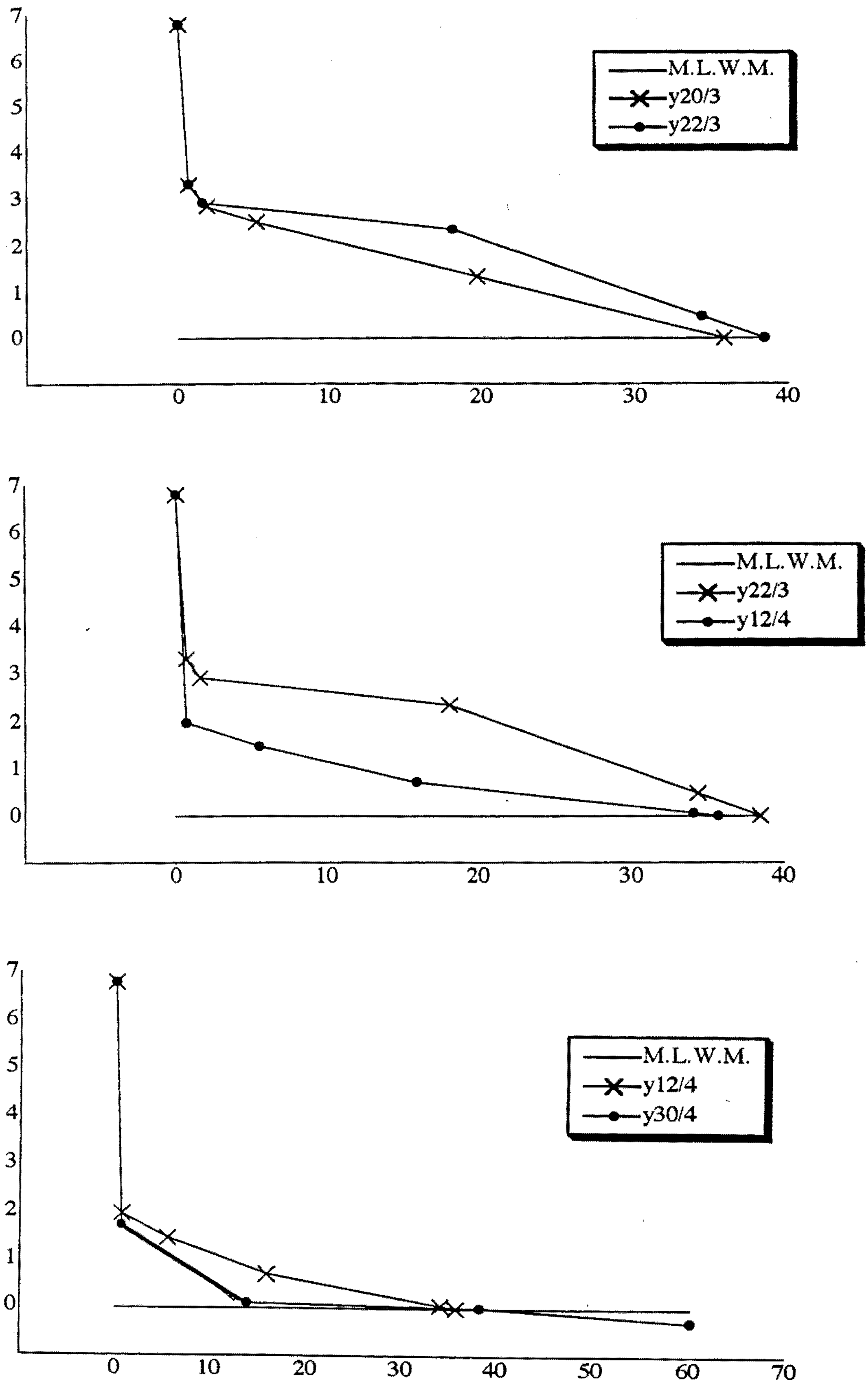


Fig. 5.15: Profile 2 Variations. March 20 to April 30.
Note: indicates rocks.

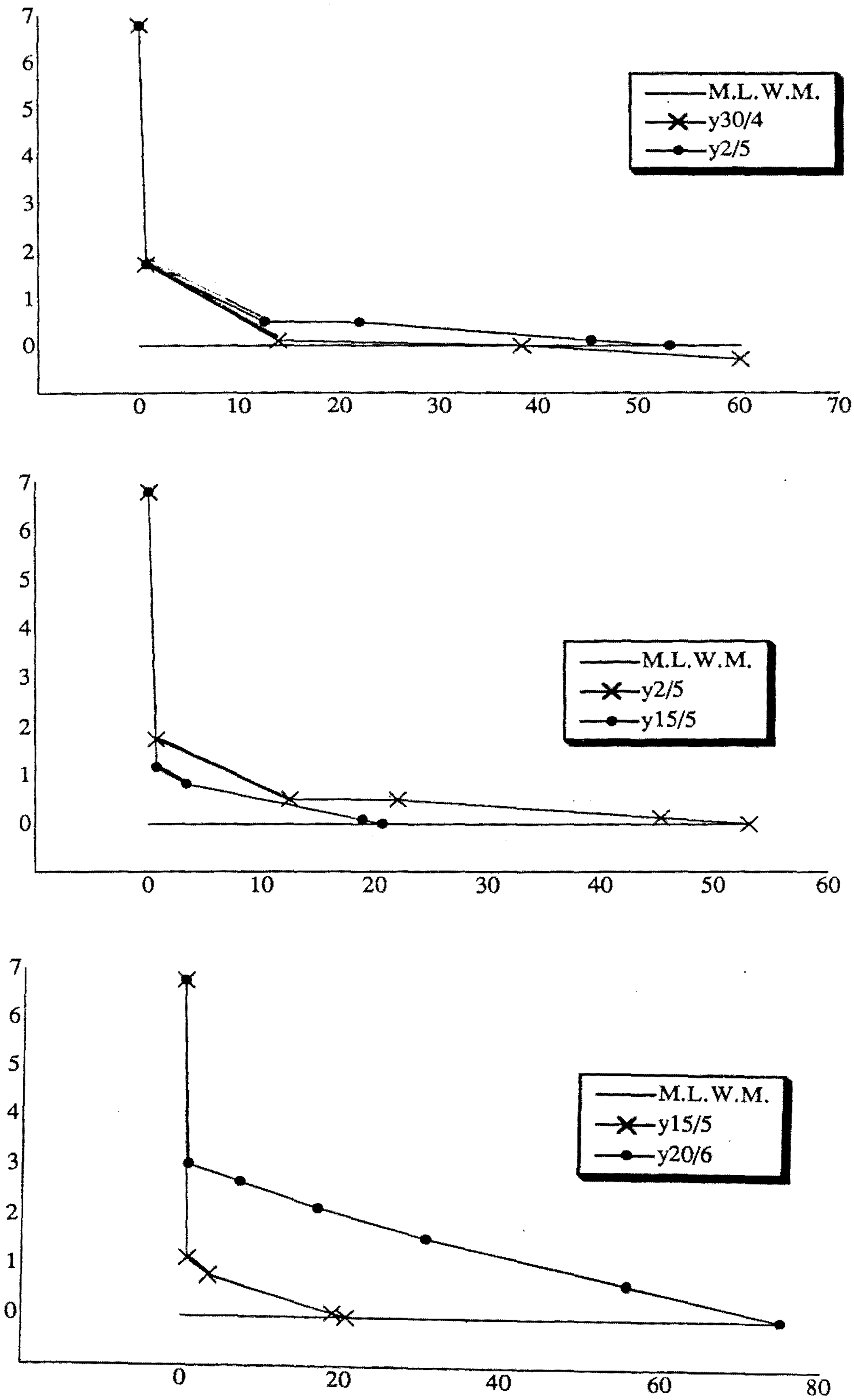


Fig. 5.16: Profile 2 Variations. April 30 to June 20.
Note: indicates rocks.

Table 5.2: Summary of Wave Conditions during Profile 2 Accretion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Feb. 9 - 10 (+6.37m³)				
S	---	0.5m	0.00371 - 0.00414	0.00392
Feb. 16 - 19 (+5.29m³)				
S	1 - 1.5m	1.2m	0.00629 - 0.01214	0.00828
SSE(1)	---	1m	---	0.01565
Feb. 19 - 22 (+13.42m³)				
S(1)	---	2m	---	0.01282
SSE	1 - 3m	2m	0.00962 - 0.02932	0.01859
Feb. 22 - Mar. 20 (+4.79m³)				
S(23)	0.5 - 2.5m	1.7m	0.00431 - 0.01603(16)	0.01082
SSE(2)	1.5 - 2m	1.8m	0.00962 - 0.02474	0.01718
ESE(15)	1 - 2.5m	1.6m	0.00476 - 0.02108(9)	0.01014
Mar. 20 - 22 (+19.31m³)				
S(2)	1.5 - 2m	1.8m	0.01242 - 0.01734	0.01488
SSE(2)	1.5 - 2m	1.8m	0.01300 - 0.02474	0.01887
ESE(1)	---	1m	---	0.00828
Apr. 30 - May 2 (+12.2m³)				
S	0.5 - 2m	1.2m	---	---
ESE	1- 2m	1.3m	---	---

Table 5.3: Summary of Wave Conditions during Profile 2 Erosion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Jan. 26 - Feb. 7 (-8.55m^3)				
S	0.5 - 3m	1.8m	0.00414 - 0.03419	0.01818
ESE(6)	0.5 - 2.5m	1.3m	0.00414 - 0.02850	0.01260
Feb. 10 - 11 (-4.61m^3)				
S	---	0.5m	0.00321 - 0.00371	0.00346
Feb. 11 - 16 (-5.54m^3)				
S	0.5 - 2m	1.3m	0.00321 - 0.01421	0.00923
last 4 days				
S	1 - 2m		0.01088 - 0.01421	0.01208
Mar. 22 - Apr. 12 (-43.61m^3)				
S	0.5 - 4m	1.8m	0.00454 - 0.02375(13)	0.01046
ESE(2)	---	1m	0.00593 - 0.00828	0.00710
Apr. 12 - 30 (-13.12m^3)				
S(18)	0.5 - 3m	1.9m	0.00379 - 0.02327(15)	0.01218
ESE (3)	1 - 2m	1.7m	0.00887 - 0.01515(2)	0.01234
May 2 - 15 (-16.04m^3)				
S(13)	1 - 2.5m	1.8m	---	---
SSE(2)	2 - 2.5m	2.3m	---	---
ESE(2)	---	1m	---	---

5.4.3 PROFILE 3

Profile 3 was situated at the eastern end of the seawall. The profile is primarily sandy, but like Profile 2 has rock rip rap placed at the base of the seawall, which is visible when the sand is eroded out. The sand envelope had a maximum volume change of 70.58m³ for Profile 3. As with Profile 1 and 2 the sweep zone plot, Fig. 5.17, shows that variation occurred across the entire profile, with the sand envelope sitting against the seawall. This also shows up on the EDA, Fig. 5.18, with all contours showing some variation. Here the eratic nature of the 3 meter contour between January 12 and February 22 was the result of berm height fluctuations. Thus when the berm height peaked above 3 meters, even if only by 0.01 meters, the contour advanced some 24 meters off the seawall. When it lowered below 3 meters, even if only by 0.01 meters, the contour retreated back to the seawall. Erosion of the upper foreshore on February 7, (18), April 12, (102), and April 30, (120), was associated with accretion on the lower foreshore as indicated by the diverging nature of the 0 and 1 meter contours. Over the total study period the profile firstly accreted, then stabilised before becoming erosional. The last two surveys showed that marked accretion had taken place. This trend can also be seen in the volume plot, Fig. 5.19.

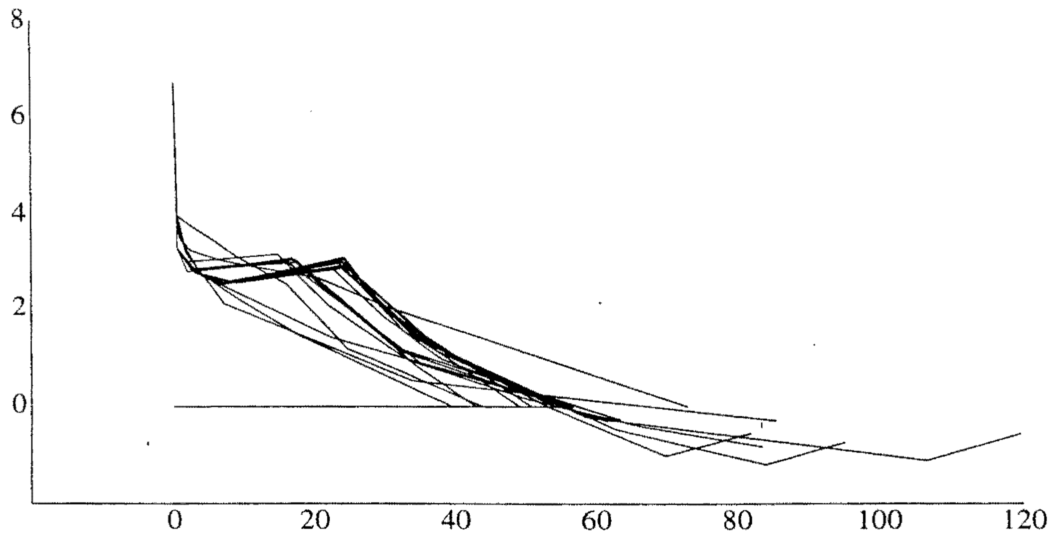


Fig. 5.17: Profile 3 Sand Envelope. December 20 1993 to June 20 1994.

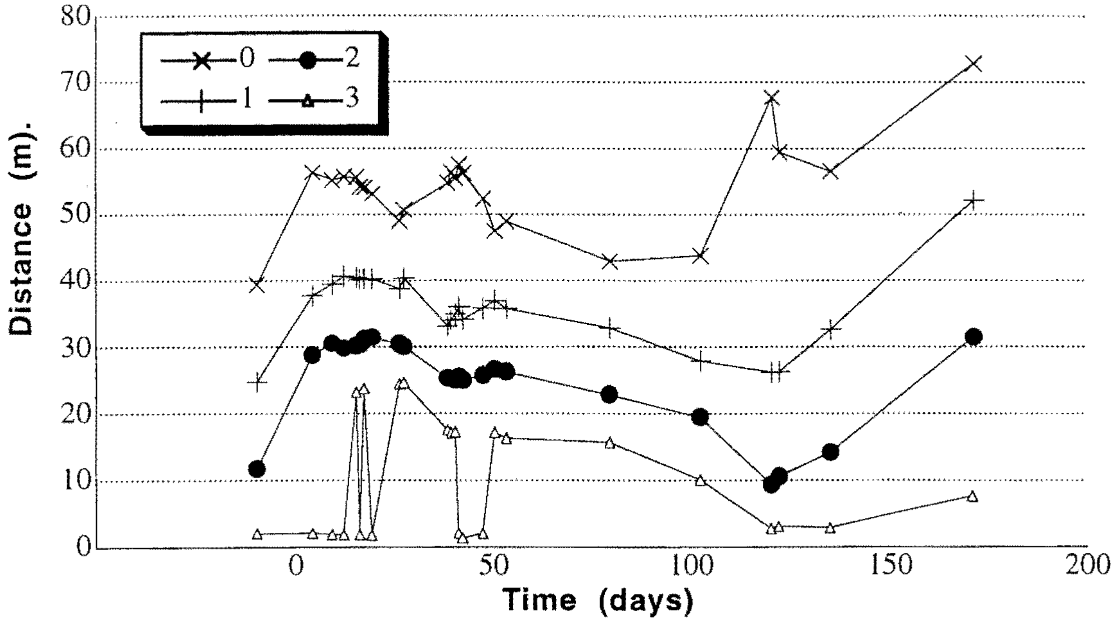


Fig. 5.18: Profile 3 Excursion Distance Analysis.

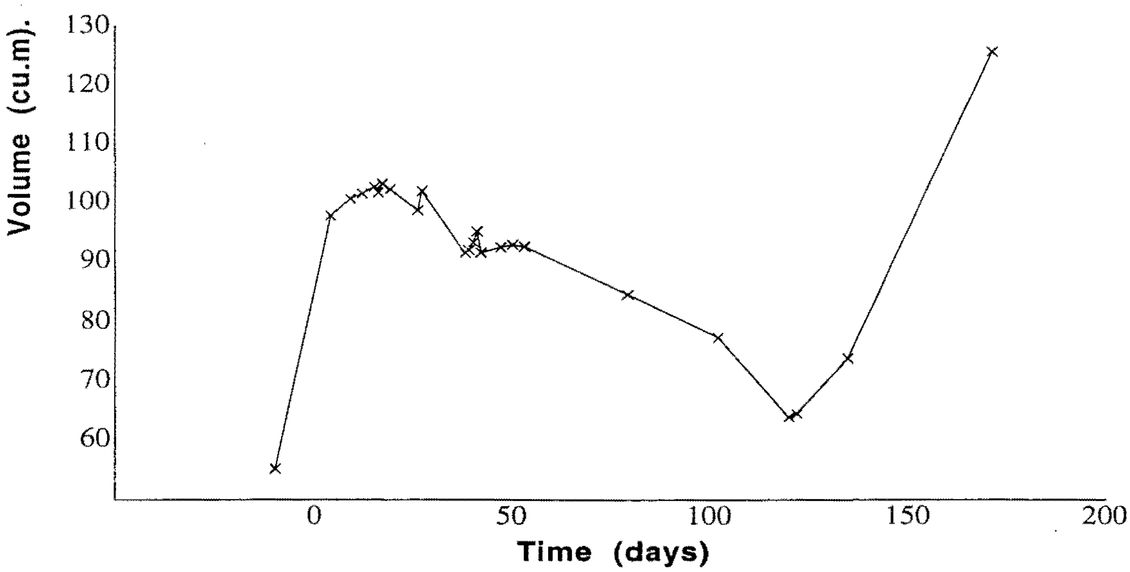


Fig. 5.19: Profile 3 Volume Changes.

From December 20 to January 4 the profile accreted, (+42.65m^3), with the formation of a prominant berm, Fig. 5.20. The foreshore profile then remained stable through to January 19, Figs. 5.20, 5.21, 5.22, while in the nearshore a longshore bar and trough migrated landward, from January 9 to 19. By January 26 the profile eroded slightly, before accreting back on the 27, Fig 5.22. Between January 27 and February 7 erosion, (-10.47m^3), resulted in retreat of the berm ridge, Fig. 5.23. The profile then remained stable through to February 22, Figs, 5.23, 5.24, 5.25, apart from slight erosion, (-3.58m^3), on February 11, Fig. 5.24. The profile then eroded back by March 20, (-8.16m^3), Fig 5.25, and again by April 12, (-7.24m^3), with the berm being pushed back into the seawall, Fig. 5.26. Further erosion, (-13.39m^3), by April 30, revealed the rock rip rap at the base of the seawall, Fig. 5.26. By May 15 there was slight accretion, (+9.34m^3), and by June 20 significant accretion, (+52.03m^3), had occurred, Fig. 5.27.

Table 5.4 shows a summary of the wave conditions for the significant accretion events of Profile 3. Again the last accretionary event was not included due to its extra long time period. The first accretion event had small flat south and east-southeast waves. The second accretion event had steeper south and east-southeast waves. The third event was dominated by south swells but had two days of south-southeast and two days of east -southeast swell as well.

Table 5.5 shows a summary of the wave conditions for the significant erosion events of Profile 3. From this it can be seen that the erosion events were mostly dominated by large steep south swells.

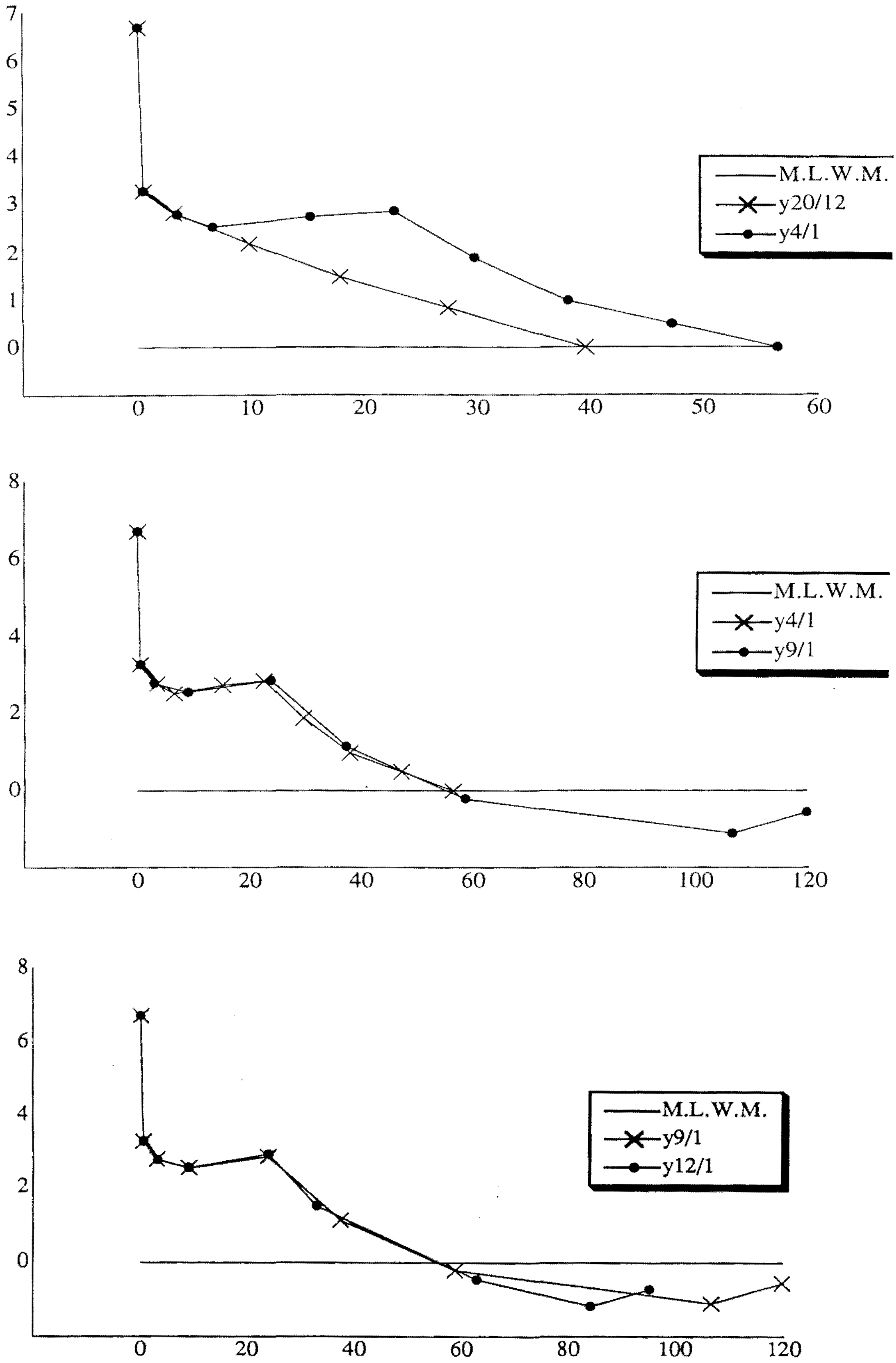


Fig. 5.20: Profile 3 Variations. December 20 1993 to January 12 1994. Note: indicates rocks.

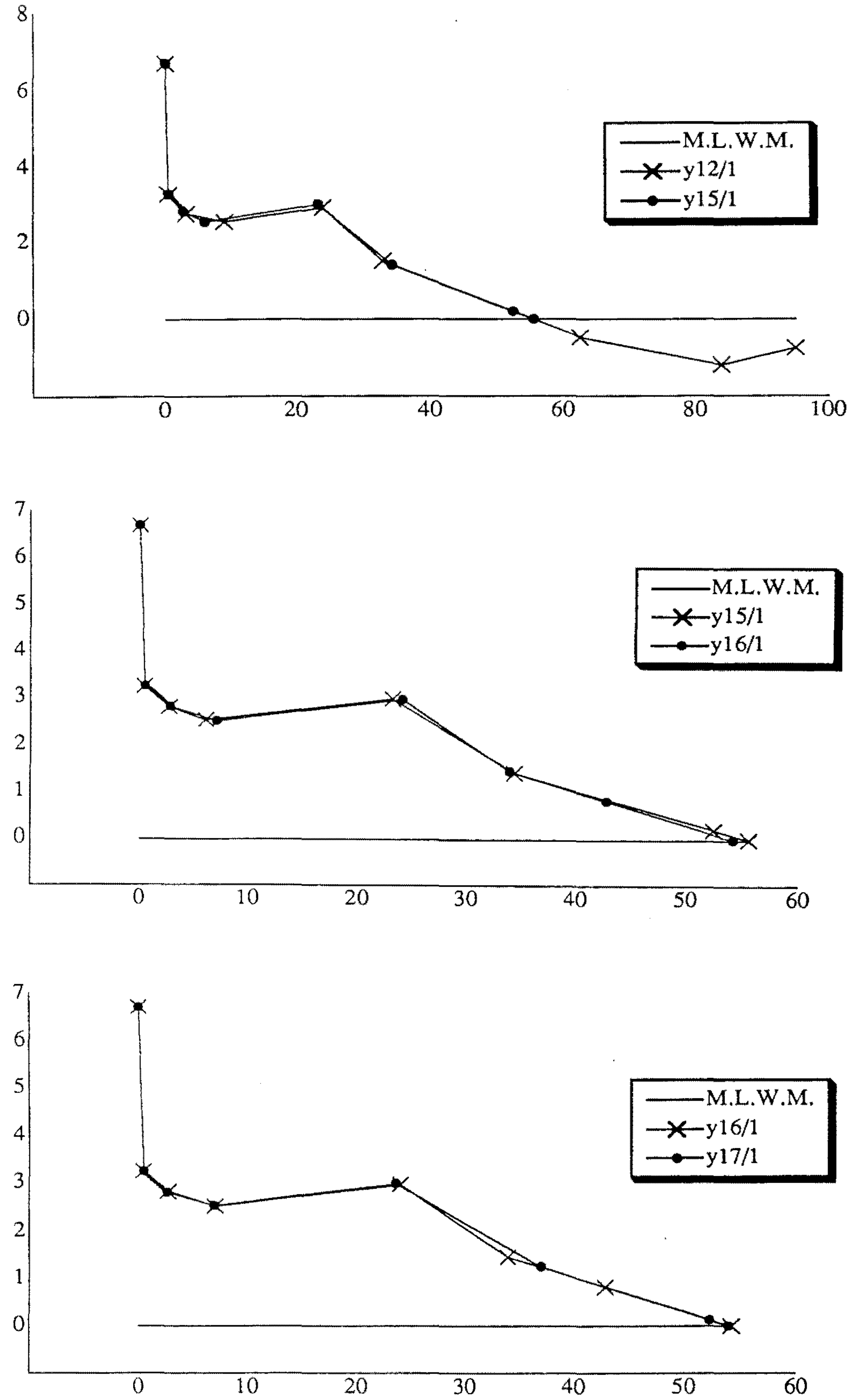
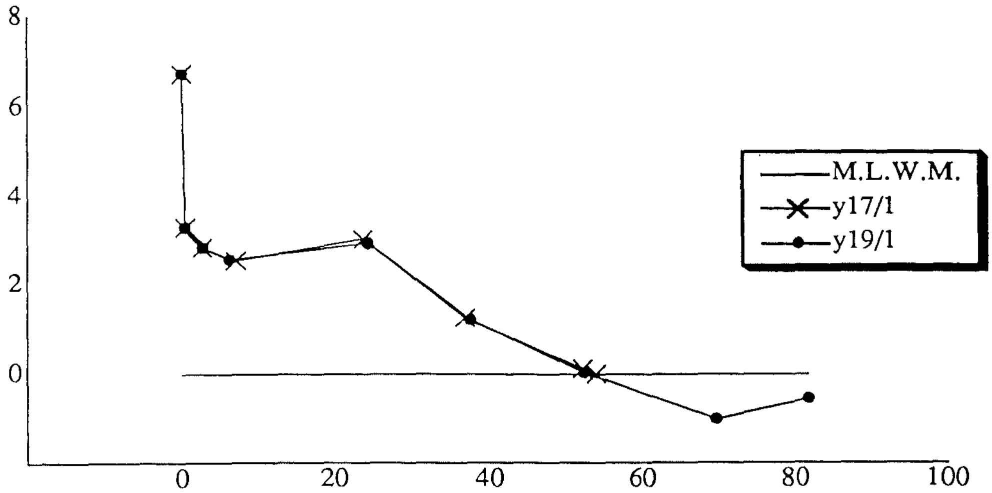
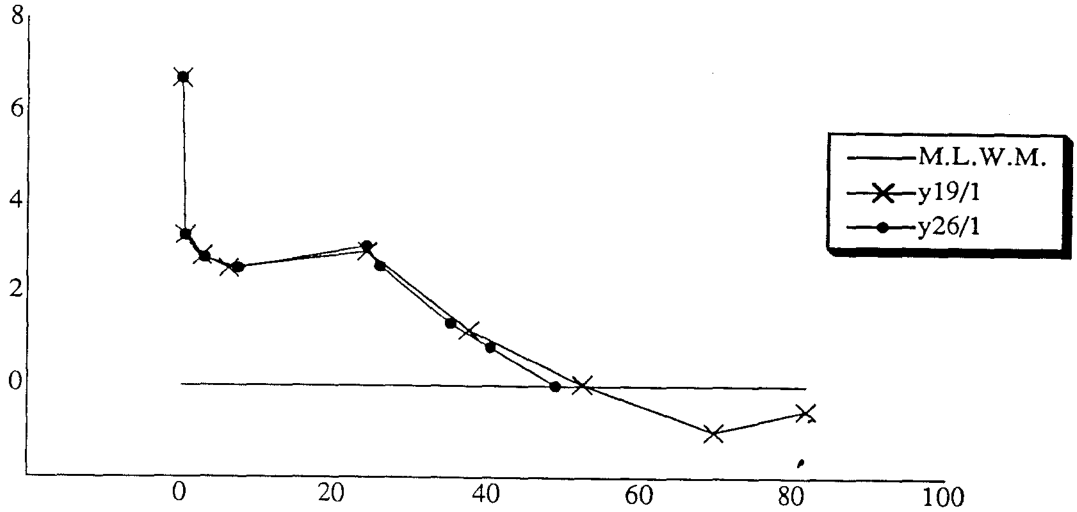


Fig. 5.21: Profile 3 Variations. January 12 to 17.
Note: indicates rocks.





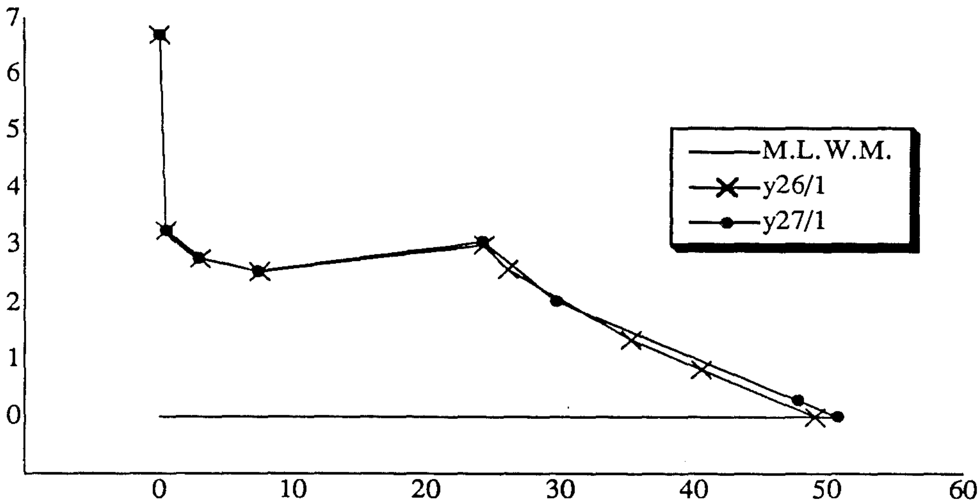


Fig. 5.22: Profile 3 Variations. January 17 to 27.
Note: indicates rocks.

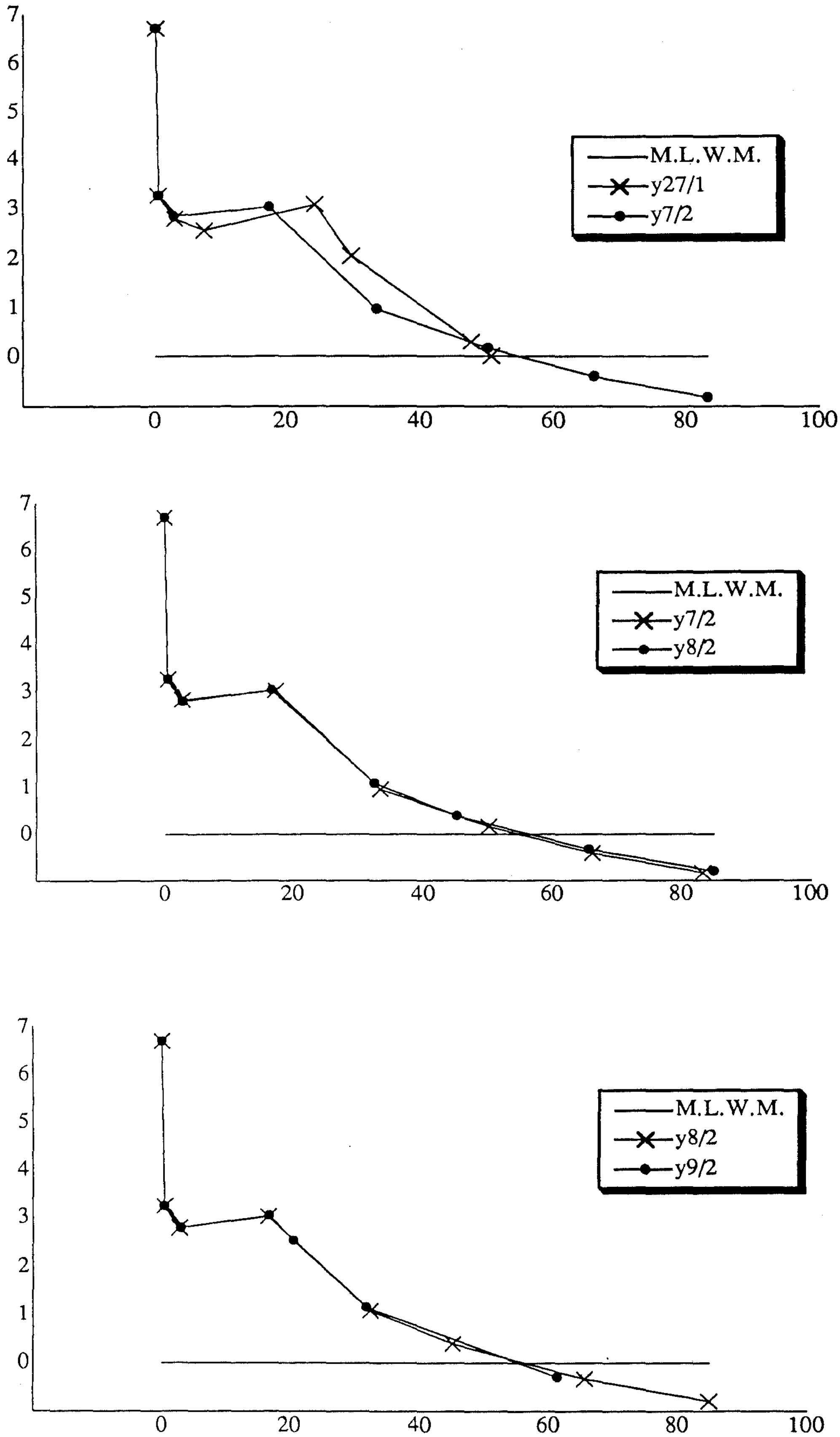


Fig. 5.23: Profile 3 Variations. January 27 to February 9.
Note: indicates rocks.

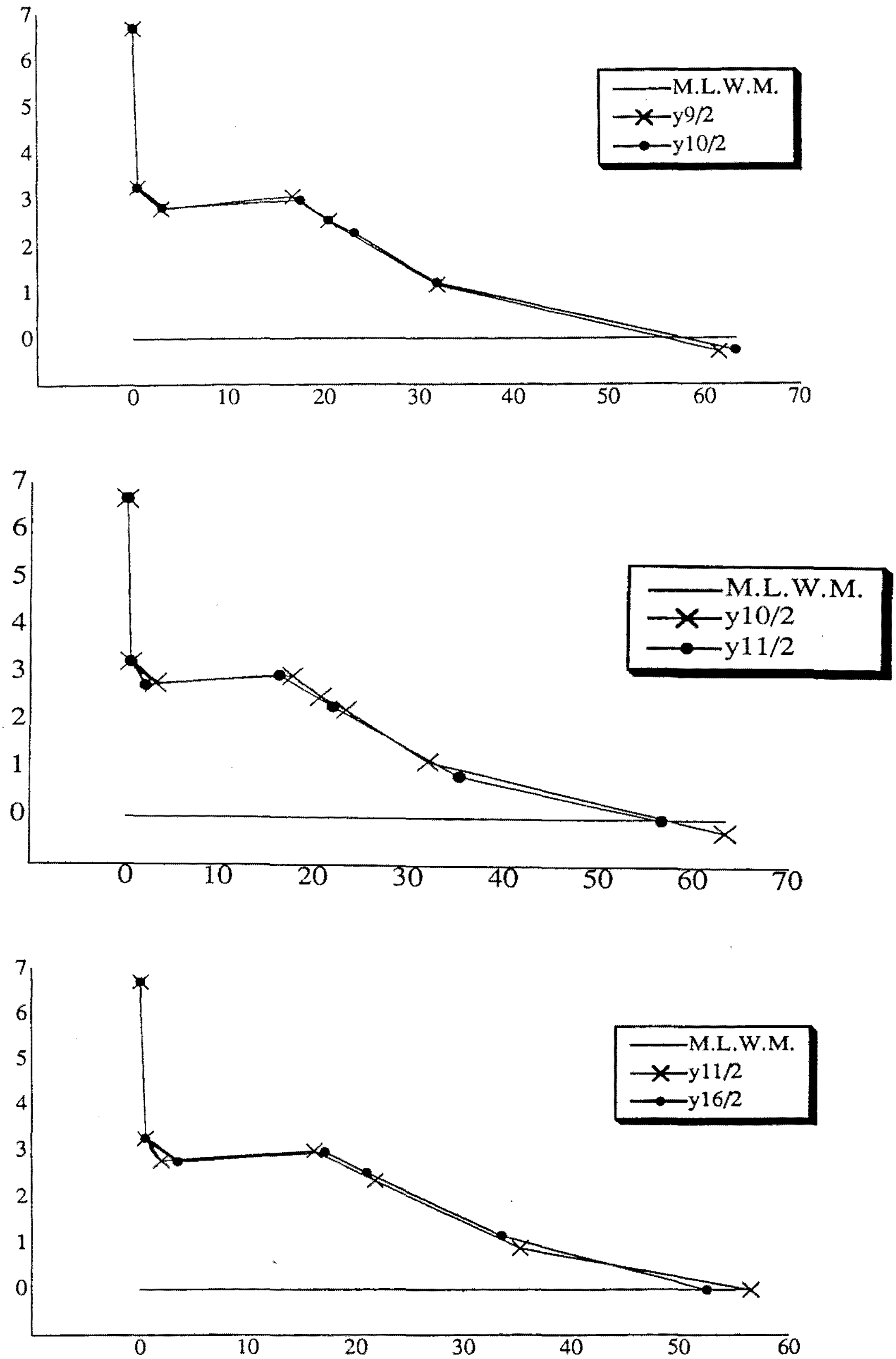


Fig. 5.24: Profile 3 Variations. February 9 to 16.
Note: indicates rocks.

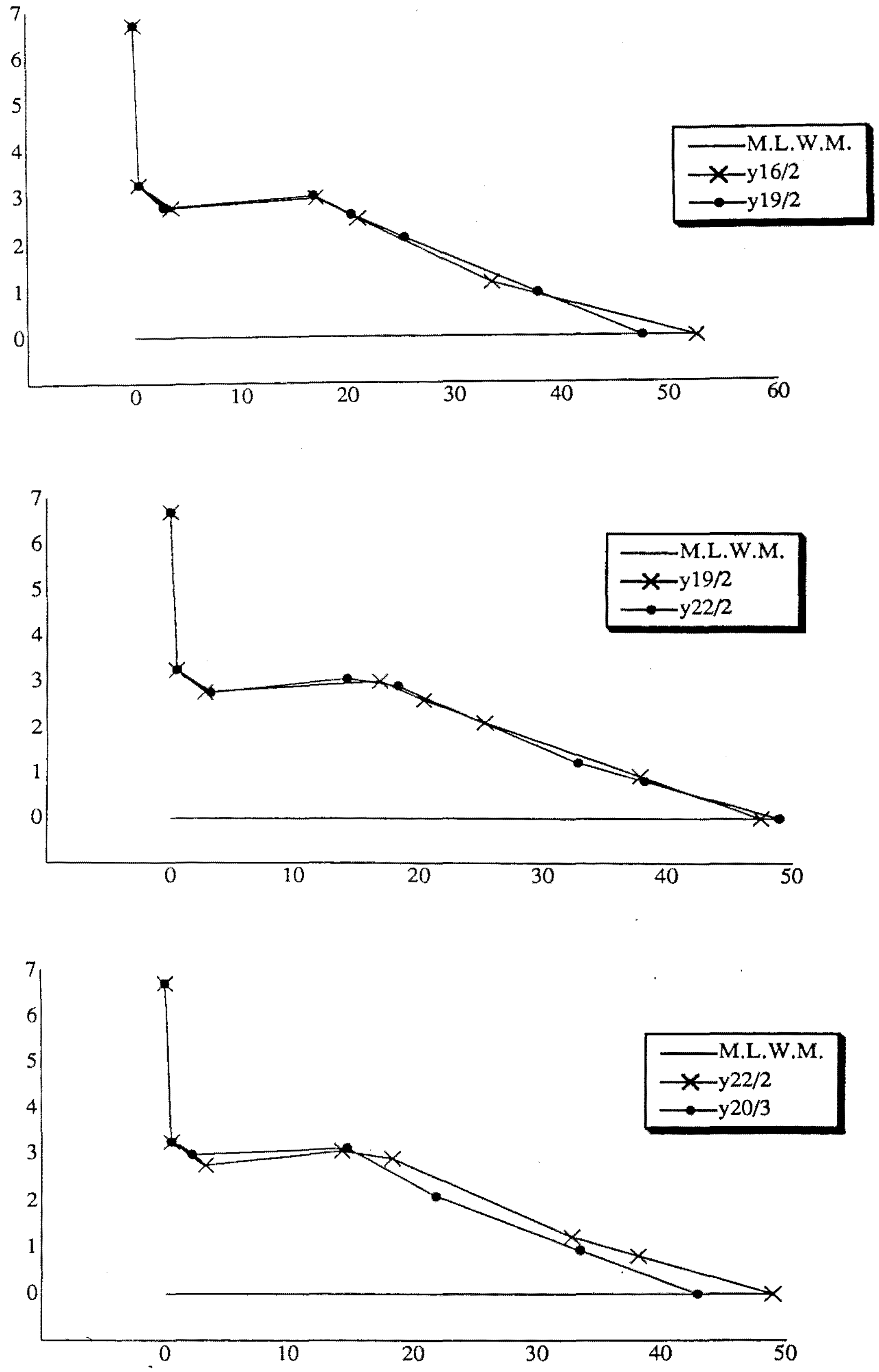


Fig. 5.25: Profile 3 Variations. February 16 to March 20.
Note: indicates rocks.

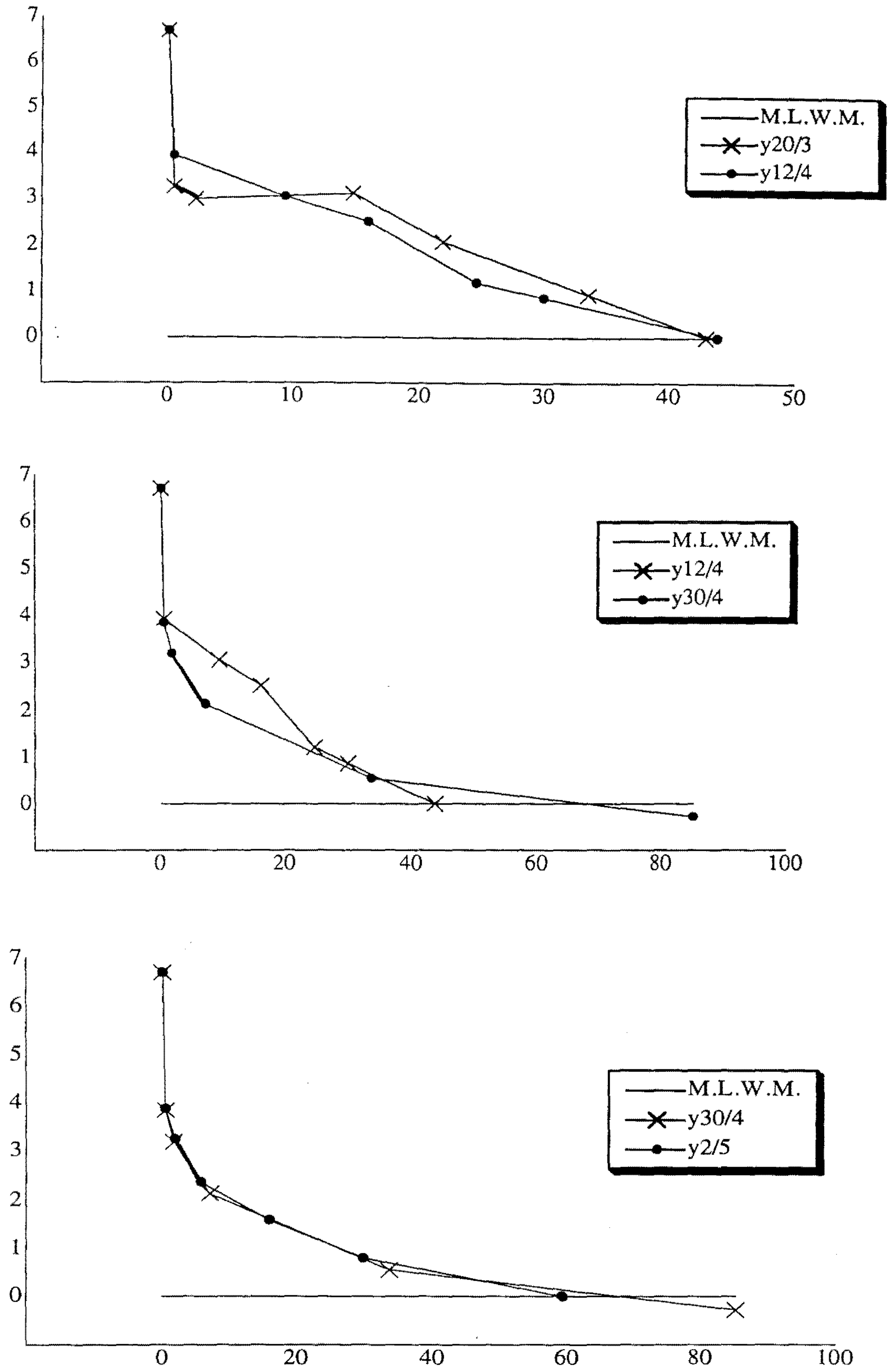
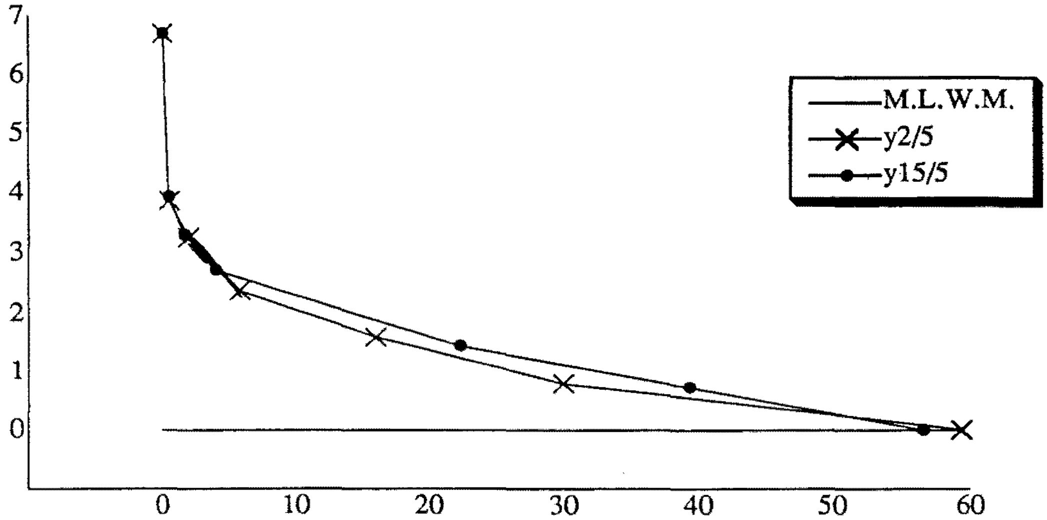


Fig. 5.26: Profile 3 Variations. March 20 to May 2.
Note: indicates rocks.



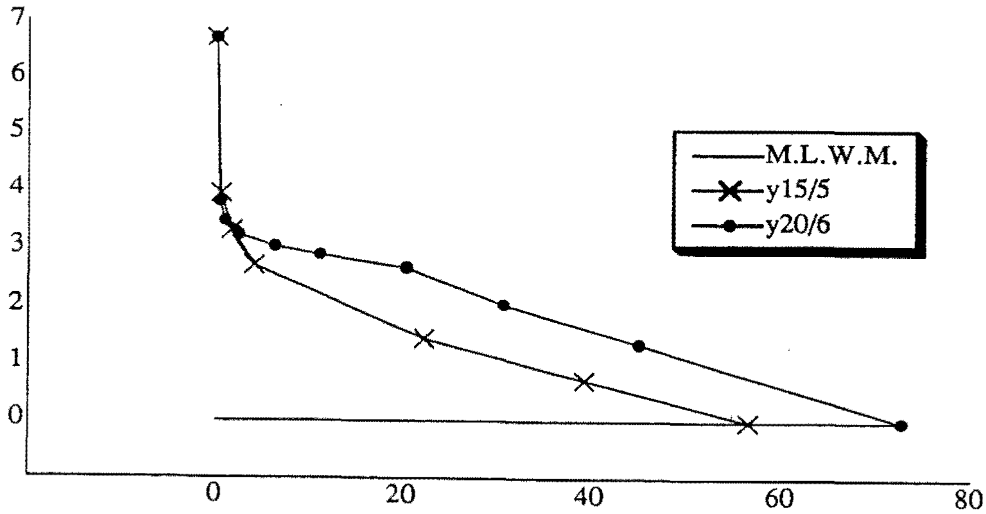


Fig. 5.27: Profile 3 Variations. May 2 to June 20.
Note: indicates rocks.

Table 5.4: Summary of Wave Conditions during Profile 3 Accretion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Dec. 20 - Jan. 4 (+42.65m³)				
S(14)	0.5 - 2m	0.8m	0.00118 - 0.01907	0.00661
ESE(10)	0.5 - 2m	1.3m	0.00353 - 0.01430	0.00835
Jan. 26 - 27 (+3.2m³)				
S	---	2m	0.01775 - 0.02773	0.02274
ESE	1 - 1.5m	1.3m	0.01331 - 0.01387	0.01359
May 2 - 15 (+9.34m³)				
S(13)	1 - 2.5m	1.8m	---	---
SSE(2)	2 - 2.5m	2.3m	---	---
ESE(2)	---	1m	---	---

Plate 5.1: St. Clair Beach June 20 after strong accretion.
Note rocky base of the western, (closest), end of beach.

Table 5.5: Summary of Wave Conditions during Profile 3 Erosion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Jan. 19 - 26 (-3.51m³)				
S	1 - 2.5m	1.6m	0.00512 - 0.02773	0.01158
ESE(1)	---	1m	---	0.01387
Jan. 27 - Feb. 8 (-10.47m³)				
S	0.5 - 3m	1.8m	0.00414 - 0.03419	0.01738
ESE(5)	0.5 - 2.5m	1.3m	0.00414 - 0.02850	0.01235
Feb. 10 - 11 (-3.58m³)				
S	---	0.5m	0.00321 - 0.00371	0.00346
Feb. 22 - Mar. 20 (-8.16m³)				
S(23)	0.5 - 2.5m	1.7m	0.00431 - 0.01603(16)	0.01082
SSE(2)	1.5 - 2m	1.8m	0.00962 - 0.02474	0.01718
ESE(15)	1 - 2.5m	1.6m	0.00476 - 0.02108(9)	0.01014
Mar. 20 - Apr. 12 (-7.24m³)				
S	0.5 - 4m	1.8m	0.00454 - 0.02375(14)	0.01095
SSE(2)	1.5 - 2m	1.8m	0.01300 - 0.02474	0.01887
ESE(2)	---	1m	0.00593 - 0.00828	0.00710
Apr. 12 - 30 (-13.39m³)				
S(18)	0.5 - 3m	1.9m	0.00379 - 0.02327(15)	0.01218
ESE(3)	1 - 2m	1.7m	0.00887 - 0.01515(2)	0.01234

5.4.4 PROFILE 4

Profile 4 was situated just to the east of the St. Kilda Surf Lifesaving Clubrooms and is backed by a single dune atop of which is the start of John Wilson Memorial Drive. The sand envelope had a maximum volume change of 28.85m³ for Profile 4. From the sweep zone, Fig. 5.28, it can be seen that most of this change was restricted to the foreshore, with the backshore remaining fairly stable. This also shows up on the EDA, Fig. 5.29, with most variation taking place below the 4 meter contour. The EDA also shows that the profile was reasonably stable throughout the study period, which is reflected in the small maximum volume change. The pattern of accretion and erosion through the study period can be seen more clearly in the volume plot, Fig. 5.30, which shows five main accretionary peaks, and four main erosional valleys.

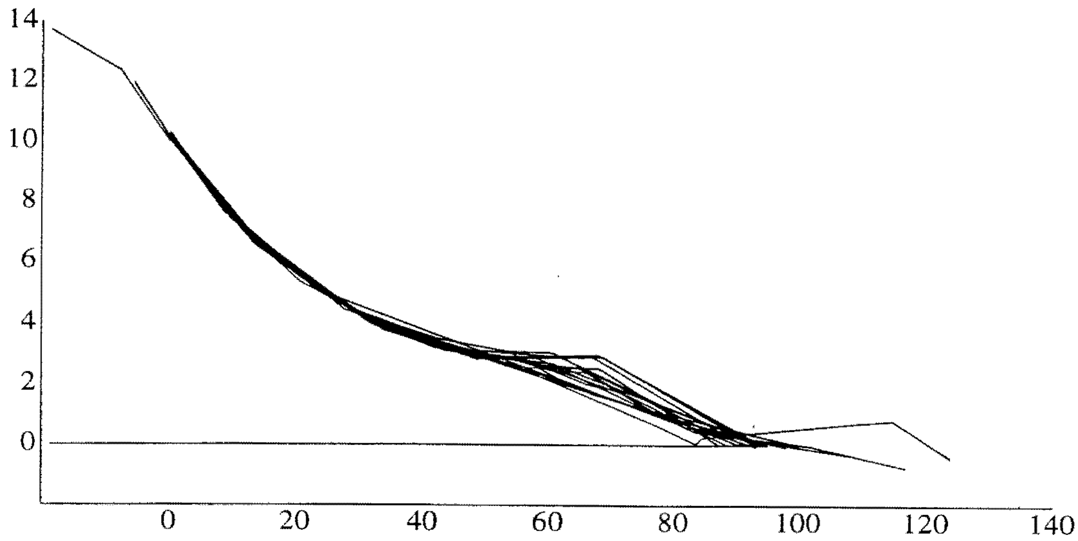


Fig. 5.28: Profile 4 Sand Envelope. December 20 1993 to June 20 1994.

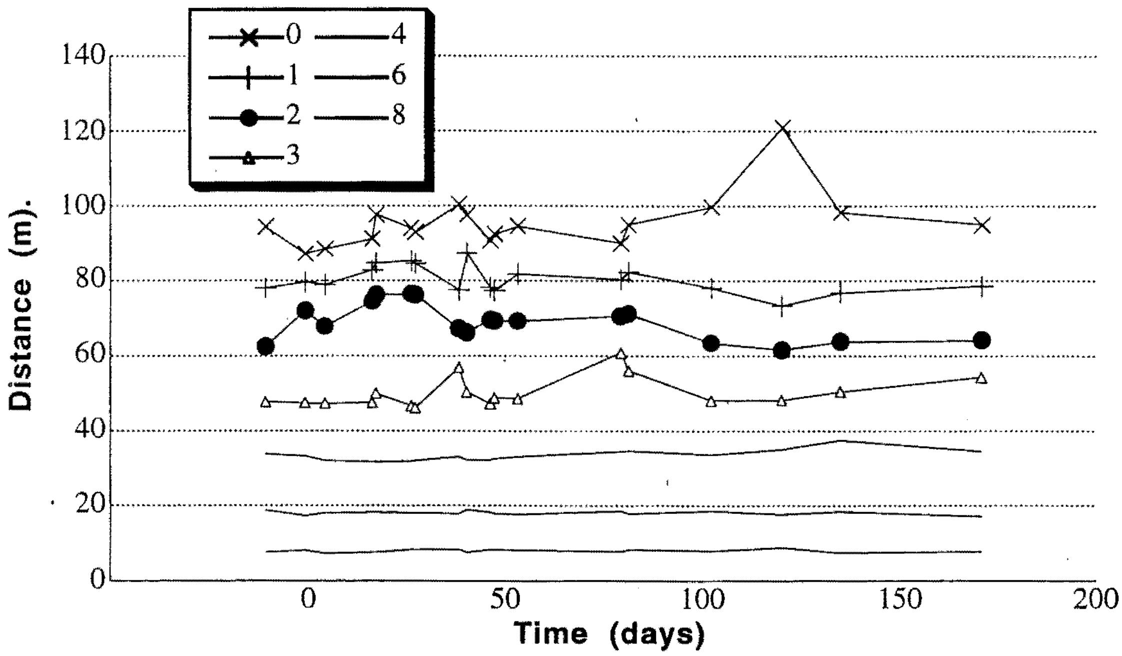


Fig. 5.29: Profile 4 Excursion Distance Analysis.

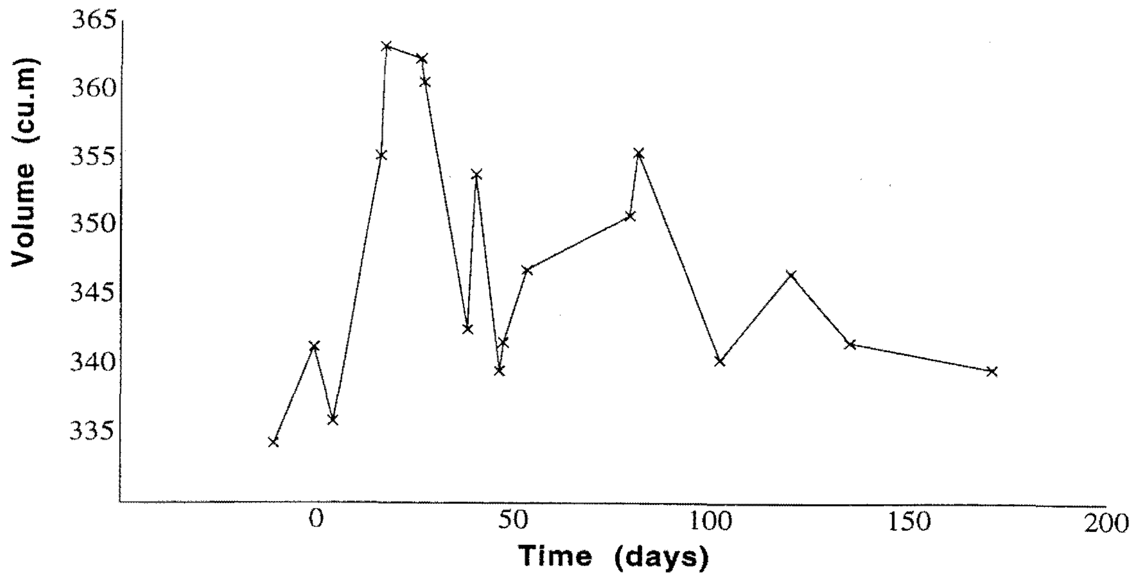


Fig. 5.30: Profile 4 Volume Changes.

Between December 20 and 30 the profile accreted, (+6.99m³), with the formation of a berm, Fig. 5.31. This berm was eroded, (-5.39m³), by January 4 but subsequently rebuilt, (+19.26m³) by January 16, Fig. 5.31. The profile then remained stable through to January 27, Fig. 5.32, before eroding, (-17.96m³), by February 7, Fig. 5.33. By February 9 a small berm had accreted, (+14.24m³), but was eroded, (-14.24m³), by February 15, Fig. 5.33. A stable profile on February 16, was followed by accretion, (+5.25m³), by February 22 and March 20, (+3.89m³), and 22, (+4.62m³), but erosion, (-15.02m³), by April 12, Figs. 5.34, 5.35. By April 30 the upper foreshore had experienced erosion but deposition on the lower foreshore resulted in a volume increase, (+6.26m³), for this period, Fig 5.35. By May 15 the reverse had occurred with accretion on the upper foreshore, but erosion of the lower foreshore ridge, (Fig. 5.36), resulting in a lower profile volume, (-5.04m³). The profile on June 20 was similar to the previous survey of May 15, (Fig. 5.36).

Table 5.6 is a summary of the wave conditions present during the eight significant accretionary events of Profile 4. The table shows no distinct conditions to dominate the accretion events with swells from all three direction, breaker heights large and small, and both flat and steep waves.

Table 5.7 is a summary of the wave conditions present during the five significant erosion events of Profile 4. The erosion events were mostly dominated by larger steep south swells.

Table 5.6: Summary of Wave Conditions during Profile 4 Accretion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Dec. 20 - 30 (+6.99m³)				
S(9)	0.5 - 2m	0.7m	0.00118 - 0.01907	0.00613
ESE(8)	1 - 2m	1.4m	0.00353 - 0.01308	0.00901
Jan. 4 - 16 (+19.26m³)				
S	0.1 - 1.5m	0.6m	0.00032 - 0.01272	0.00616
ESE(2)	---	1m	0.00322 - 0.00530	0.00426
Jan. 16 - 17 (+7.99m³)				
S	1 - 2m	1.5m	0.01272 - 0.01775	0.01523
Feb. 7 - 9 (+11.21m³)				
S	---	0.5m	0.00414 - 0.00602	0.00510
Feb. 16 - 22 (+5.25m³)				
S(4)	1 - 2m	1.4m	0.00629 - 0.01282	0.00942
SSE(4)	1 - 3m	2m	0.00962 - 0.02932	0.01859
Feb. 22 - Mar. 20 (+3.89m³)				
S(23)	0.5 - 2.5m	1.7m	0.00431 - 0.01603(16)	0.01082
SSE(2)	1.5 - 2m	1.8m	0.00962 - 0.02474	0.01718
ESE(15)	1 - 2.5m	1.6m	0.00476 - 0.02108(9)	0.01014
Mar. 20 - 22 (+4.62m³)				
S(2)	1.5 - 2m	1.8m	0.01242 - 0.01734	0.01488
SSE(2)	1.5 - 2m	1.8m	0.01300 - 0.02474	0.01887
ESE(1)	---	1m	---	0.00828
Apr. 12 - 30 (+6.26m³)				
S(18)	0.5 - 3m	1.9m	0.00379 - 0.02327(15)	0.01218
ESE (3)	1 - 2m	1.7m	0.00887 - 0.01515(2)	0.01234

Table 5.7: Summary of Wave Conditions during Profile 4 Erosion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Dec. 30 - Jan. 4 (-5.93m³)				
S	0.5 - 2m	0.8m	0.00379 - 0.01282	0.00731
ESE(2)	0.5 - 1m	0.8m	0.00501 - 0.00641	0.00571
Jan. 27 - Feb. 7 (-17.96m³)				
S	0.5 - 3m	1.8m	0.00414 - 0.03419	0.01738
ESE(5)	0.5 - 2.5m	1.3m	0.00414 - 0.02850	0.01235
Feb. 9 - 15 (-14.24m³)				
S	0.5 - 2m	1m	0.00321 - 0.01421	0.00730
last 3 days				
S	1 - 2m	1.5m	0.01088 - 0.01421	0.01206
Mar. 22 - Apr. 12 (-15.02m³)				
S	0.5 - 4m	1.8m	0.00454 - 0.02375(13)	0.01046
ESE(2)	---	1m	0.00593 - 0.00828	0.00710
Apr. 30 - May 15 (-5.04m³)				
S(15)	0.5 - 2.5m	1.7m	---	---
SSE(2)	2 - 2.5m	2.3m	---	---
ESE(4)	1 - 2m	1.5m	---	---

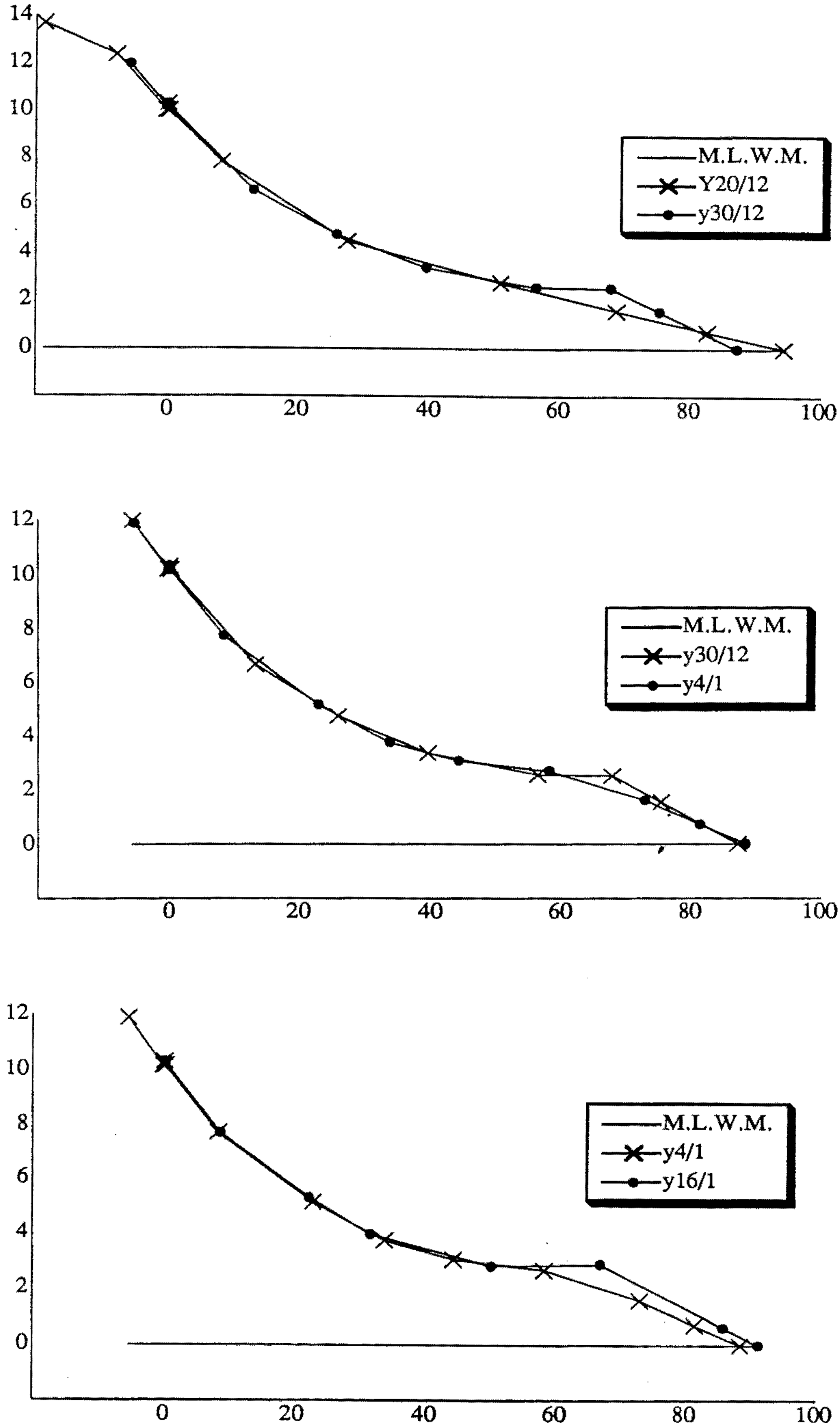


Fig. 5.31: Profile 4 Variations. December 20 to January 16.

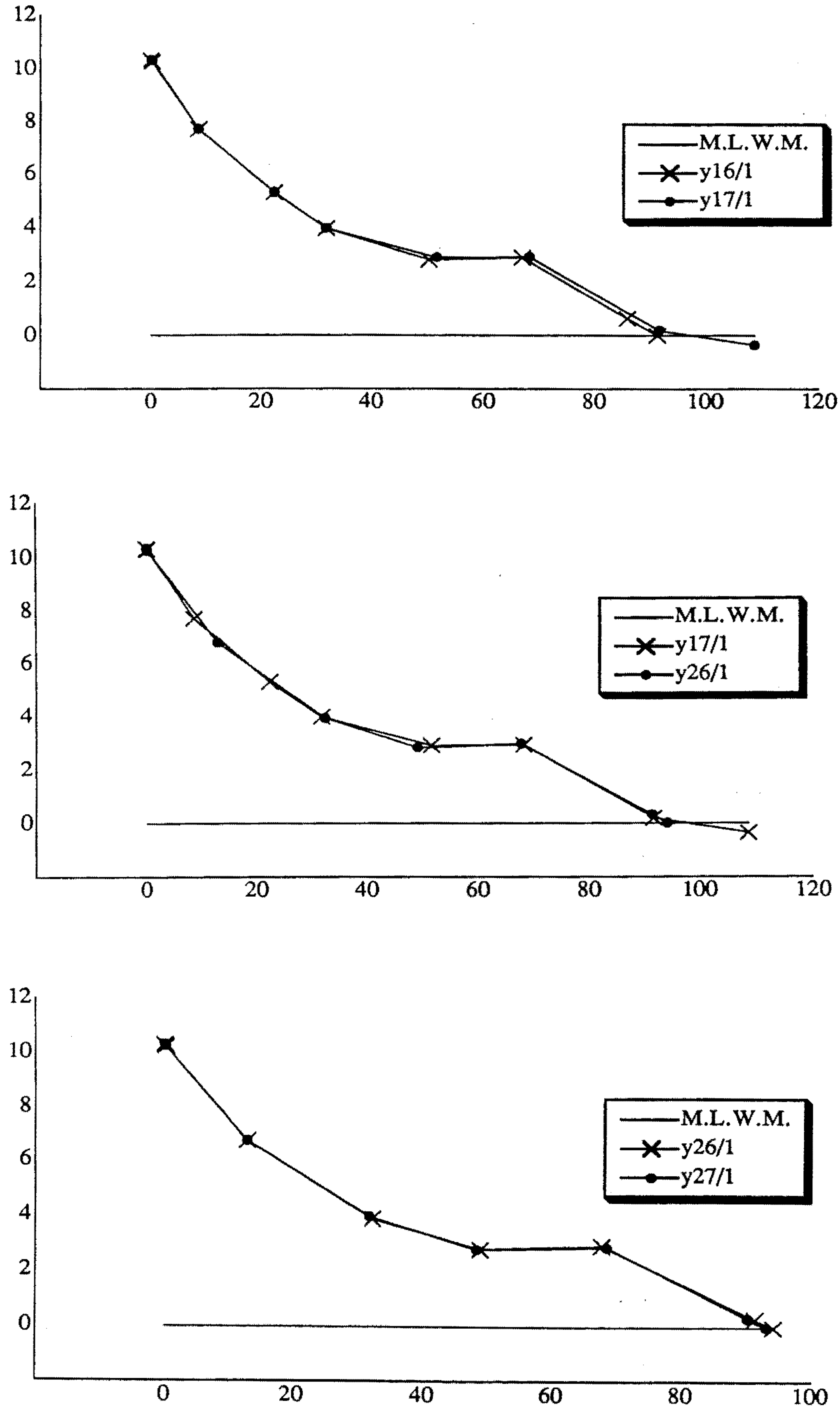


Fig. 5.32: Profile 4 Variations. January 16 to 27.

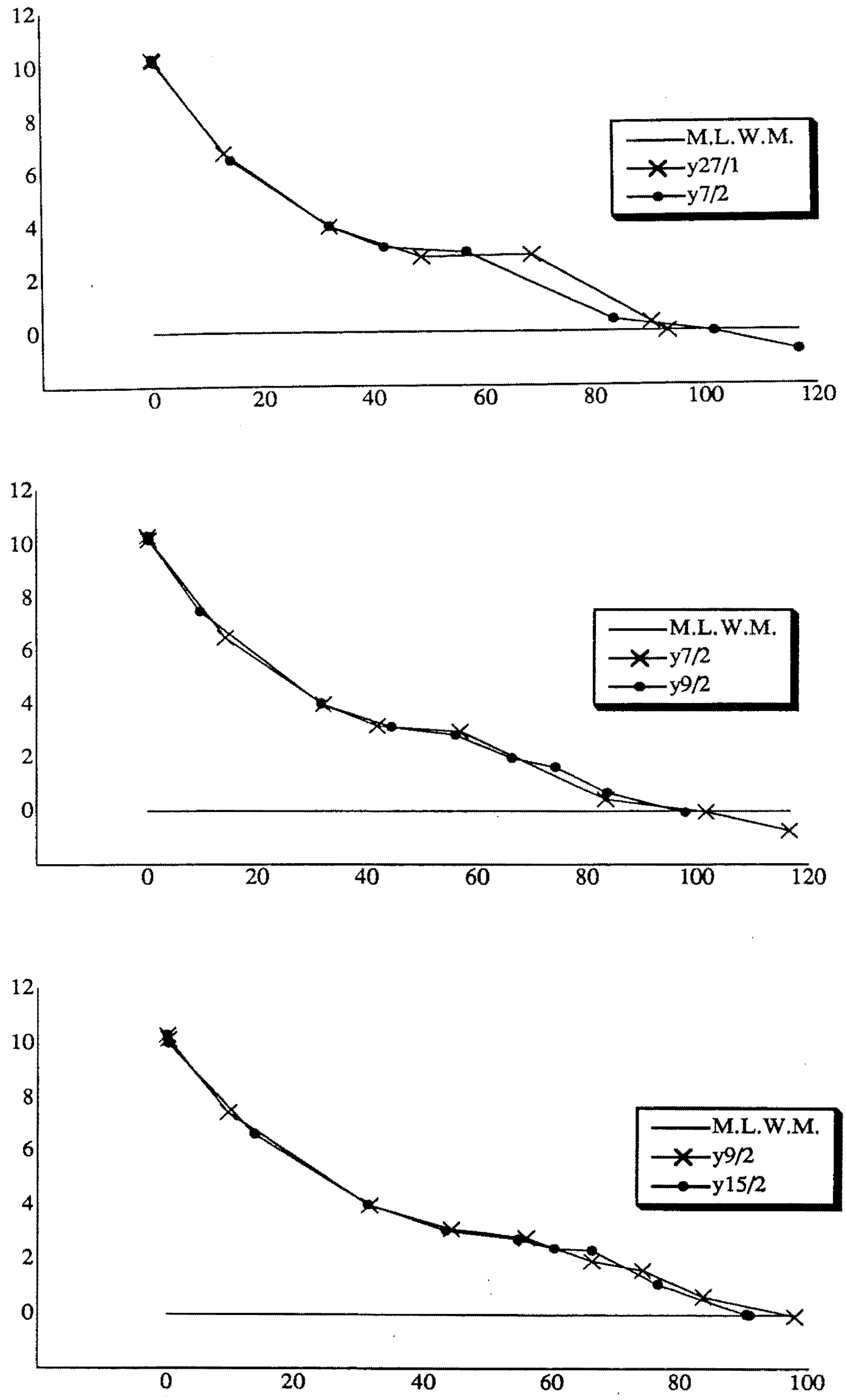
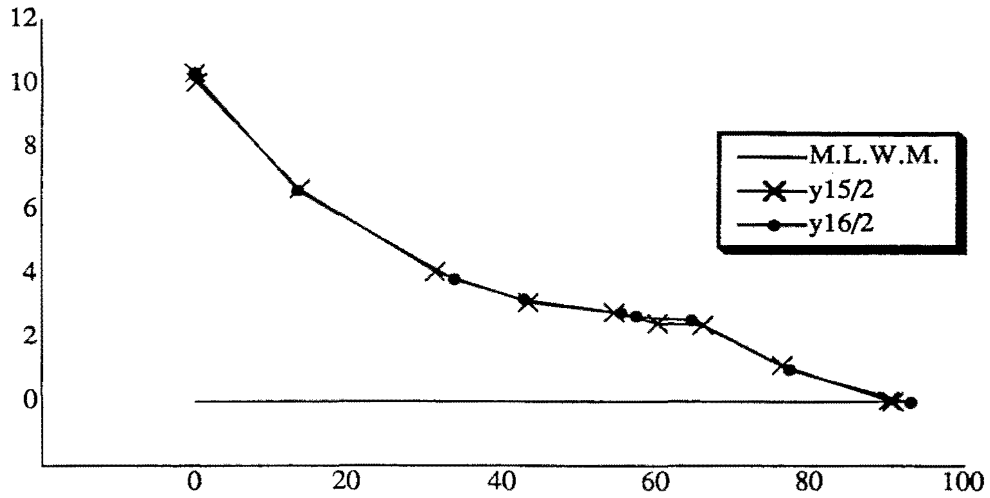
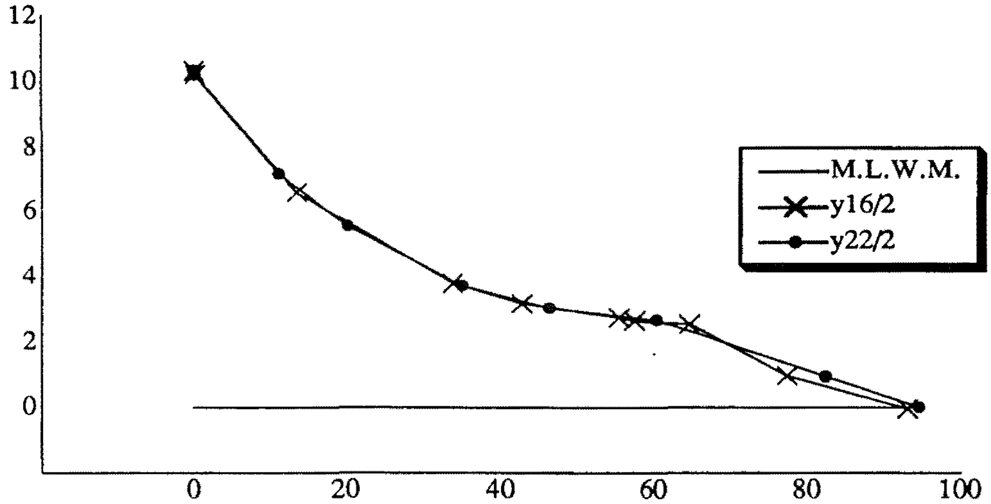


Fig. 5.33: Profile 4 Variations. January 27 to February 15.





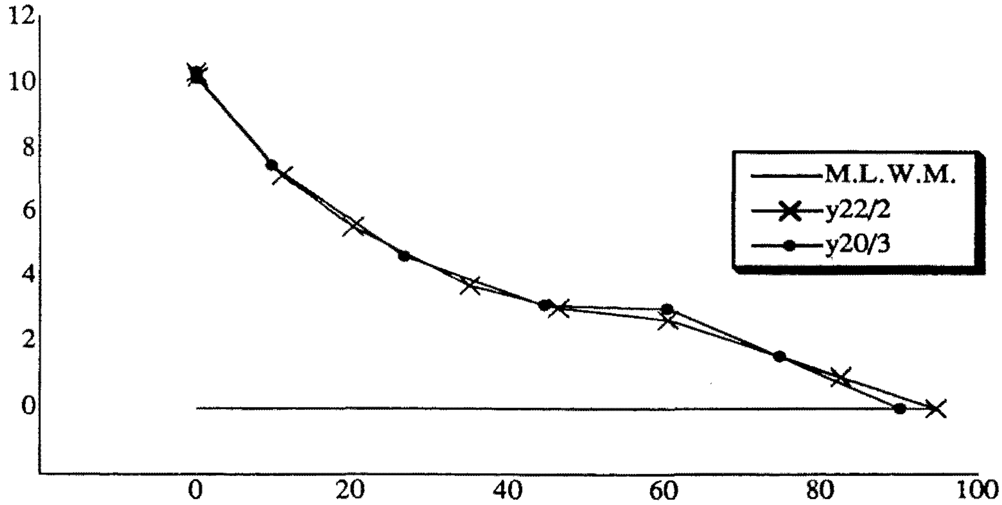


Fig. 5.34: Profile 4 Variations. February 15 to March 20.

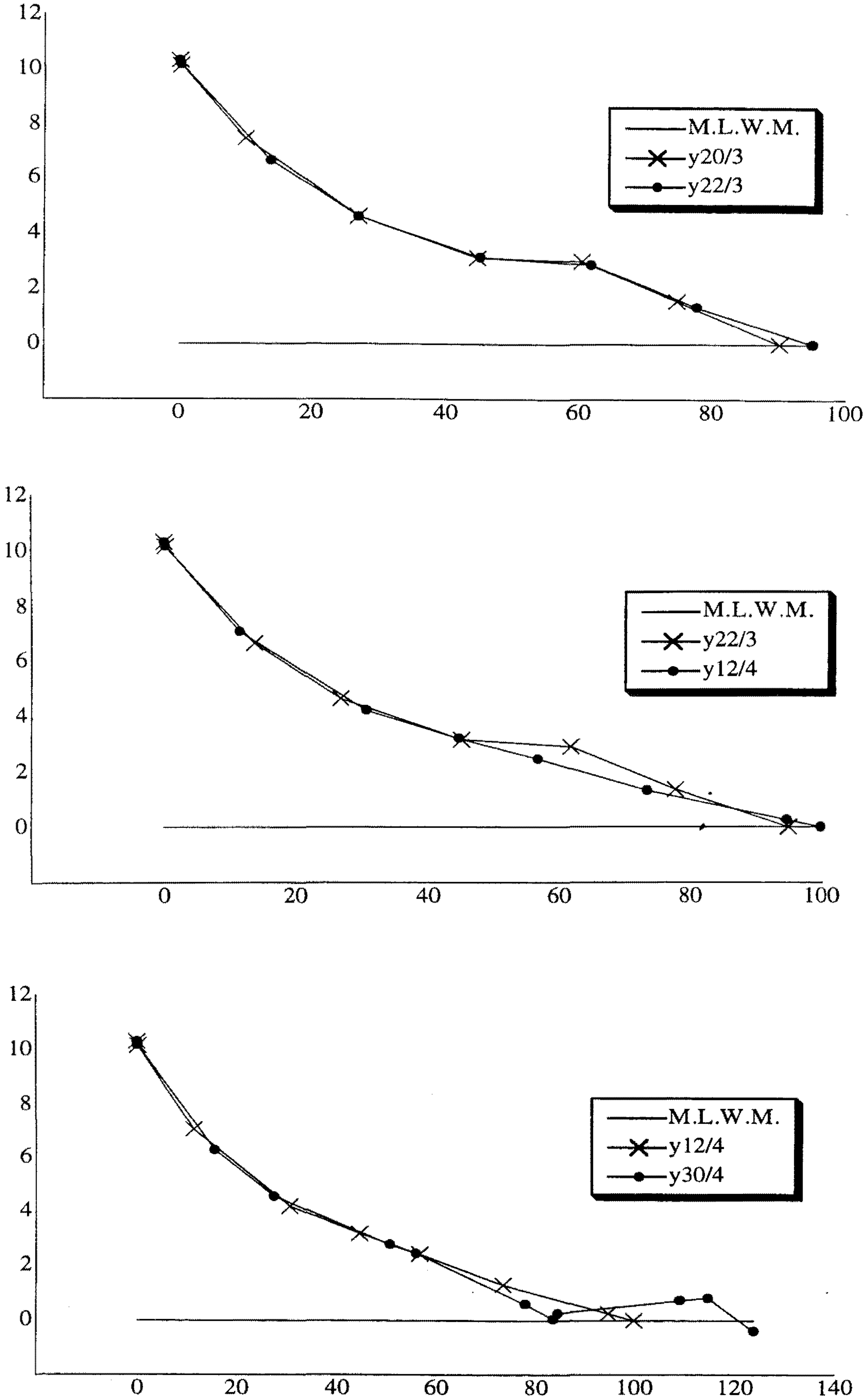
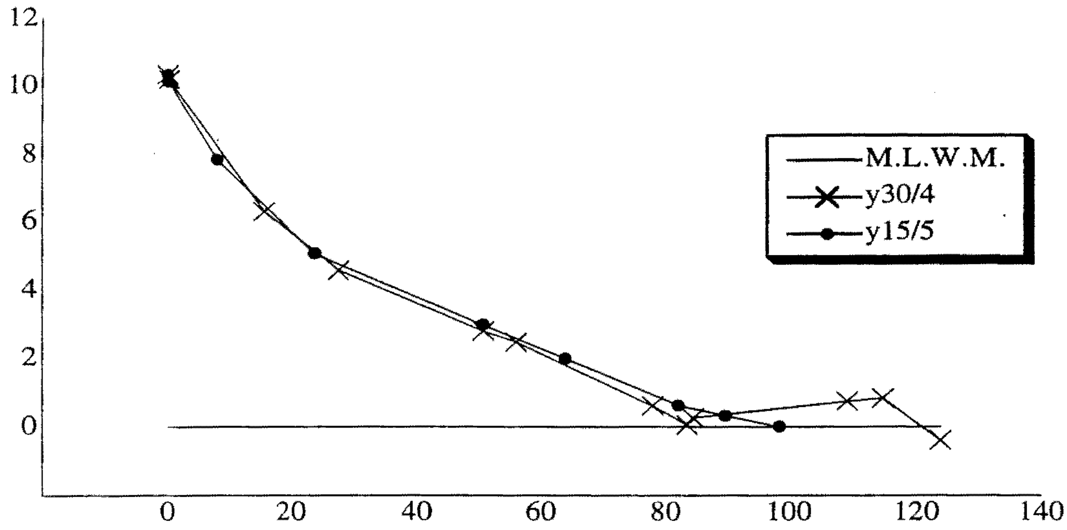


Fig. 5.35: Profile 4 Variations. March 20 to April 30.



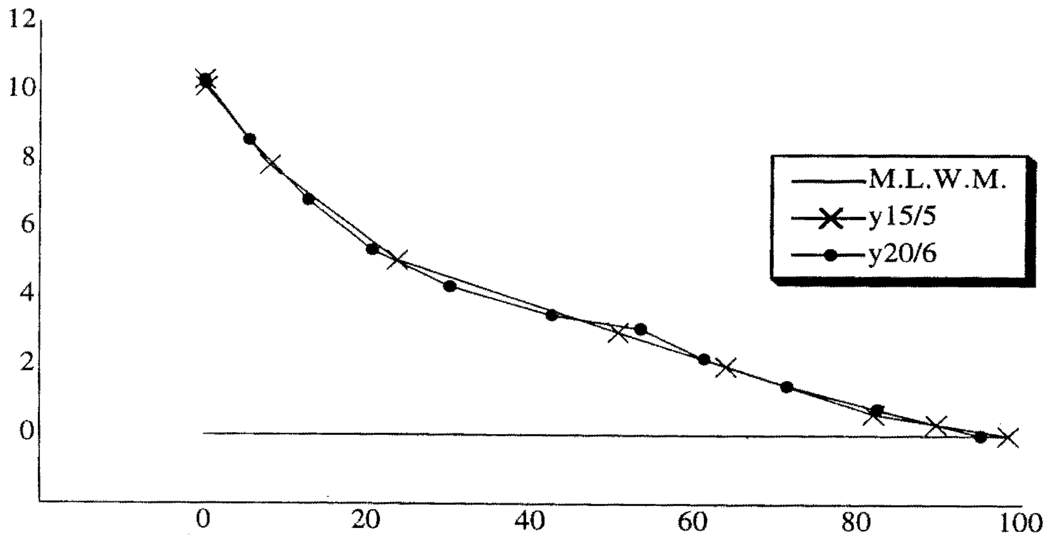


Fig. 5.36: Profile 4 Variations. April 30 to June 20.

4.4.5 PROFILE 5

Profile 5 was situated at the western end of Tomahawk Beach, but east of the lagoon outlet, and was backed by a well vegetated dune system. The sand envelope had a maximum volume change of 106.09m³ for Profile 5. The sweep zone plot, Fig. 5.37, showed that the amount of profile variation decreased from a lower foreshore maximum to a backshore minimum. This also shows up on a lower foreshore maximum to a backshore minimum. This also shows up on the EDA, Fig. 5.38, with most changes occurring below the 3 meter contour, and with the 0 meter contour showing the most amount of variation. The width of the beach varied from 70 to 155 meters. The EDA also shows a general trend of accretion up until March 21, day 80, followed by erosion to May 15, day 135, and a final period of accretion. This is also shown more clearly on the volume plot, Fig. 5.39.

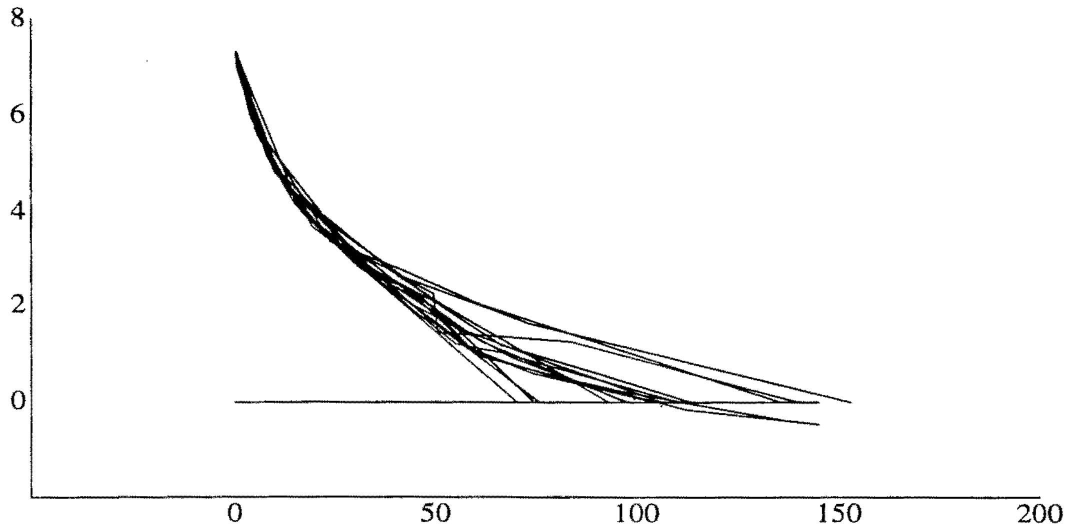


Fig. 5.37: Profile 5 Sand Envelope. December 20 1993 to June 20 1994.

Thus from December 20 the profile accreted, (+34.01m³), through to January 26, Figs. 5.40, 5.41, but was then eroded, (-9.5m³), by February 7, Fig 5.41. The profile then again accreted, (+92.06m³), through to March 21, Figs. 5.41, 5.42. The erosion, (-33.18m³), of the profile by March 22, Fig. 5.43, was due to heavy rains on the previous days filling the Tomahawk Lagoons and subsequently scouring the outlet channel, (see Plates. 5.2, 5.3). The scoured channel was present on March 21, but it was not until March 22, when the head of the channel migrated east, over the profile that, the profile was affected. The profile then also eroded further, by April 12, (-36.34m³), April 30, (-12.06m³), and May 15, (-27.16m³), before finally accreting, (+89.28m³) by June 20, Figs. 5.43, 5.44.

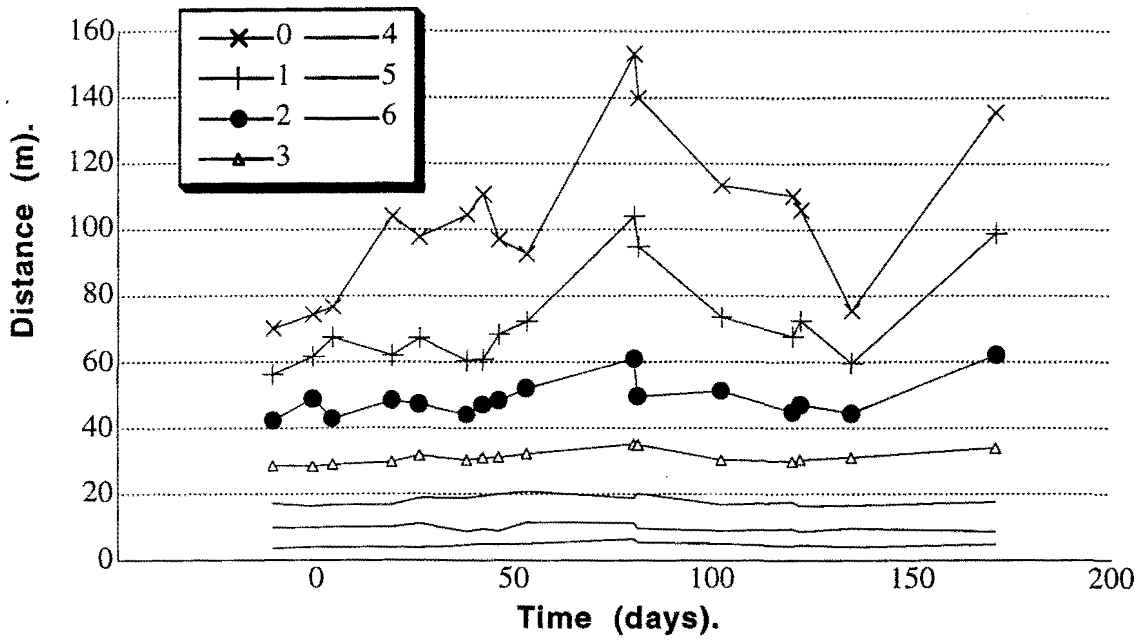


Fig. 5.38: Profile 5 Excursion Distance Analysis.

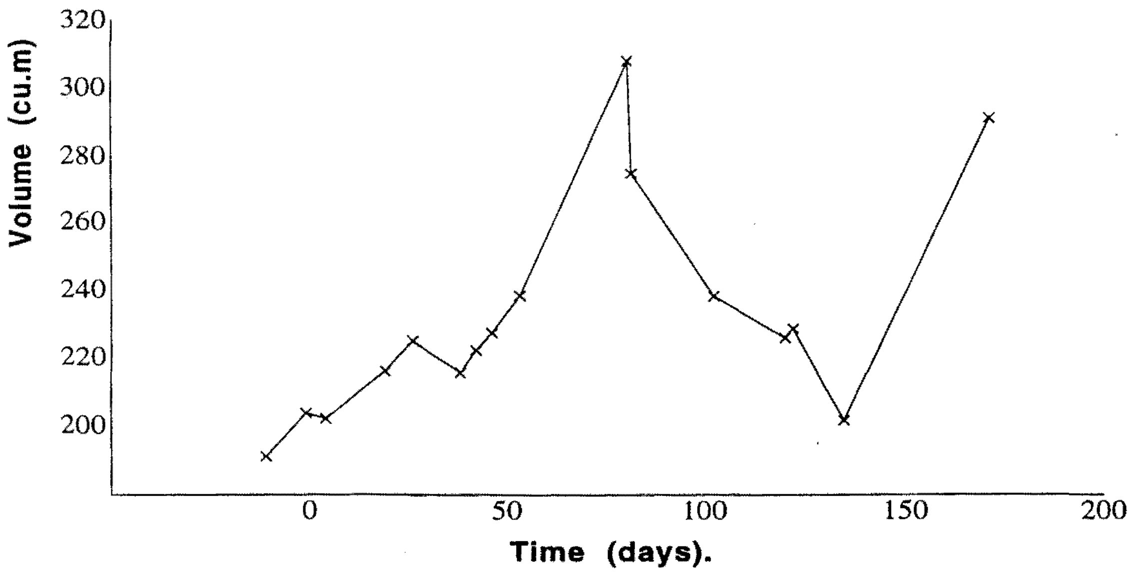


Fig. 5.39: Profile 5 Volume Changes

Plate 5.2: Scour of the Tomahawk Lagoon Outlet Channel, March 22.

Plate 5.3: The Outlet Head after migrating east over the Profile 5 site.

Table 5.8 shows a summary of the wave conditions for the significant erosion events of Profile 5. From this it can be seen that the erosion events were mostly dominated by larger steep south swells.

Table 5.9 is a summary of the wave conditions present during the first six accretionary events of Profile 5. Again the last accretionary event was not included due to its extra long time period. Thus from Table 5.9 it can be seen that the first five accretion events were dominated by small flat south swells. The first event also had a significant amount of east-southeast swell present as well. The last two accretion events were dominated by larger steeper south swells, but also had present significant amounts of south-southeast, and east-southeast swell, respectively as well.

Table 5.8: Summary of Wave Conditions during Profile 5 Erosion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Jan. 26 - Feb. 7 ($-9.02m^3$)				
S	0.5 - 3m	1.8m	0.00414 - 0.03419	0.01818
ESE(6)	0.5 - 2.5m	1.3m	0.00414 - 0.02850	0.01260
Mar. 22 - Apr. 12 ($-36.34m^3$)				
S	0.5 - 4m	1.8m	0.00454 - 0.02375(13)	0.01046
ESE(2)	---	1m	0.00593 - 0.00828	0.00710
Apr. 12 - 30 ($-12.06m^3$)				
S(18)	0.5 - 3m	1.9m	0.00379 - 0.02327(15)	0.01218
ESE (3)	1 - 2m	1.7m	0.00887 - 0.01515(2)	0.01234
May 2 - 15 ($-27.16m^3$)				
S(13)	1 - 2.5m	1.8m	---	---
SSE(2)	2 - 2.5m	2.3m	---	---
ESE(2)	---	1m	---	---

Table 5.9: Summary of Wave Conditions during Profile 5 Accretion Events

Swell Direction	Wave Height Range	Wave Height Mean	Steepness Range	Mean Steepness.
Dec. 20 - 30 (+12.64m³)				
S(9)	0.5 - 2m	0.7m	0.00118 - 0.01907	0.00613
ESE(8)	1 - 2m	1.4m	0.00353 - 0.01308	0.00901
Jan. 4 - 9 (+13.95m³)				
S	0.1 - 2m	0.8m	0.00032 - 0.01775	0.00733
ESE(2)	---	1m	0.00322 - 0.00530	0.00426
Jan. 19 - 26 (+9.02m³)				
S	1 - 2.5m	1.6m	0.00512 - 0.02773	0.01158
ESE(1)	---	1m	---	0.01387
first 4 days				
S	1 - 2m	1.5m	0.00596 - 0.00821	0.00660
Feb. 7 - 11 (+6.76m³)				
S	---	0.5m	0.00321 - 0.00602	0.00444
Feb. 11 - 15 (+5.16m³)				
S	0.5 - 2m	1.2m	0.00321 - 0.01421	0.00865
Feb. 15 - 22 (+10.91m³)				
S(5)	1 - 2m	1.5m	0.00629 - 0.01421	0.01037
SSE(4)	1 - 3m	2m	0.00962 - 0.02932	0.01859
Feb. 22 - Mar. 21 (+69.23m³)				
S(24)	0.5 - 2.5m	1.7m	0.00431 - 0.01734(17)	0.0112
SSE(3)	1.5 - 2m	1.7m	0.00962 - 0.02474	0.01579
ESE(15)	1 - 2.5m	1.6m	0.00476 - 0.0218(9)	0.01014

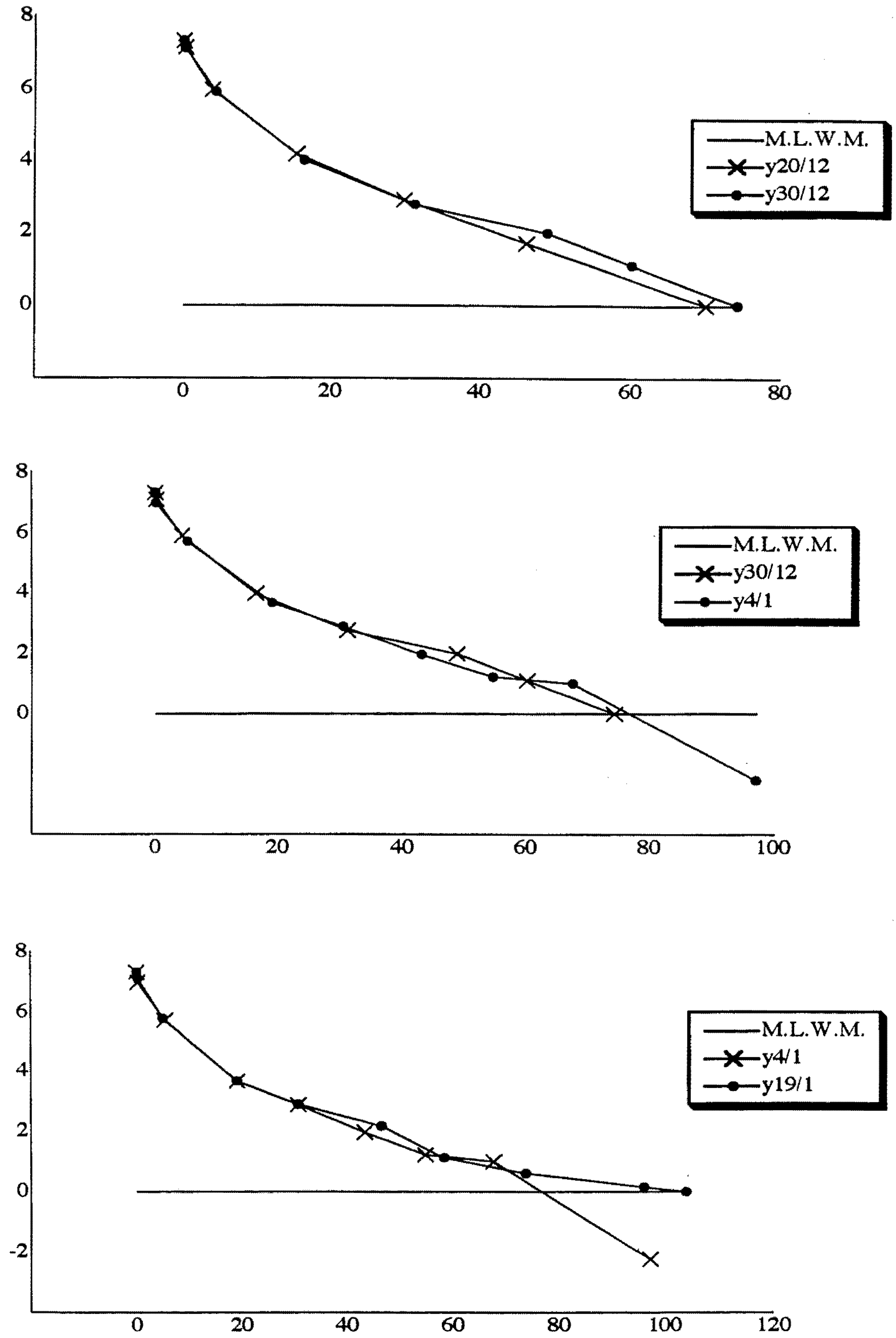


Fig. 5.40: Profile 5 Variations. December 20 1993 to January 19 1994,

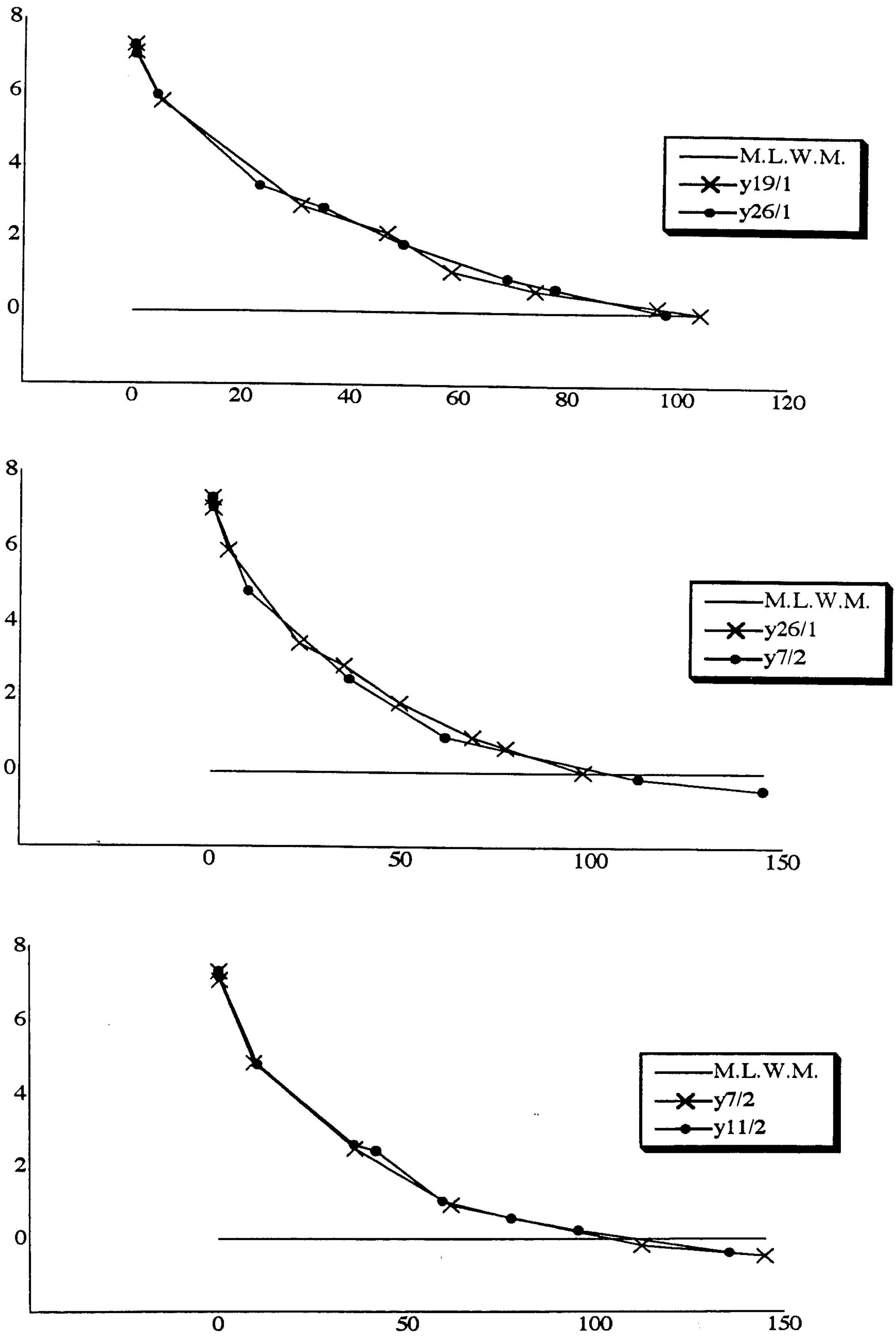


Fig. 5.41: Profile 5 Variations. January 19 to February 11.

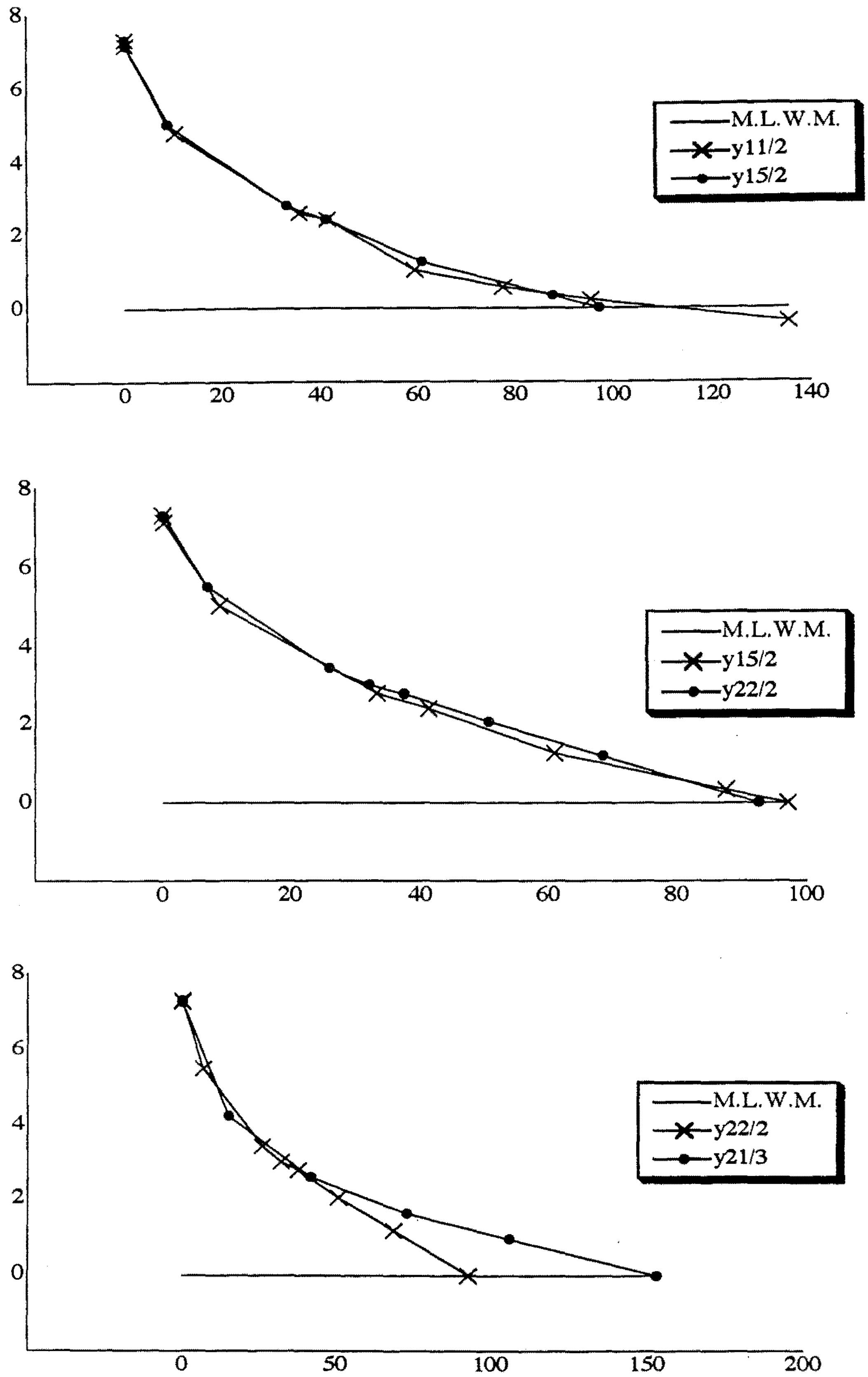


Fig. 5.42: Profile 5 Variations. February 11 to March 21.

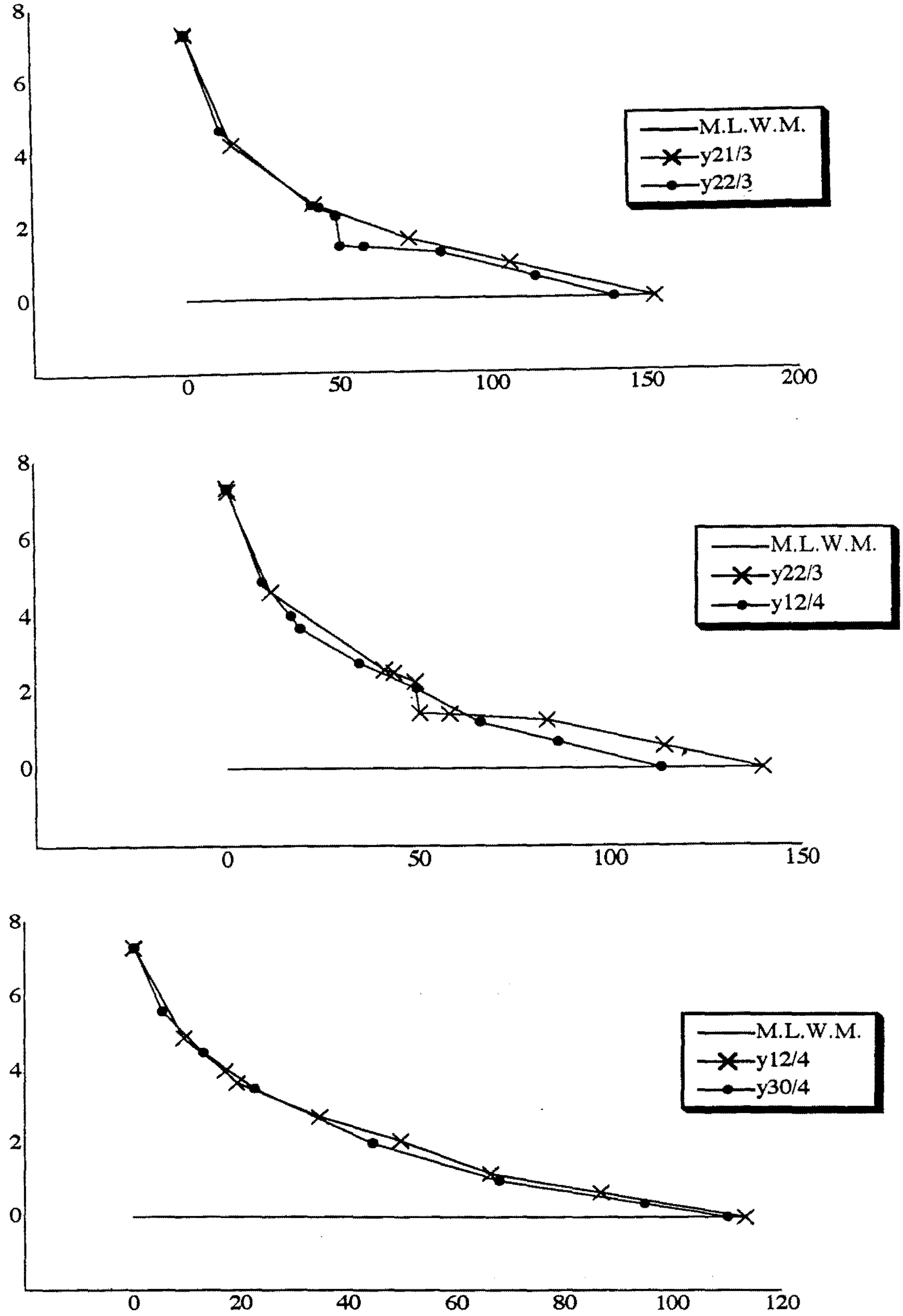


Fig. 5.43: Profile 5 Variations. March 21 to April 30.

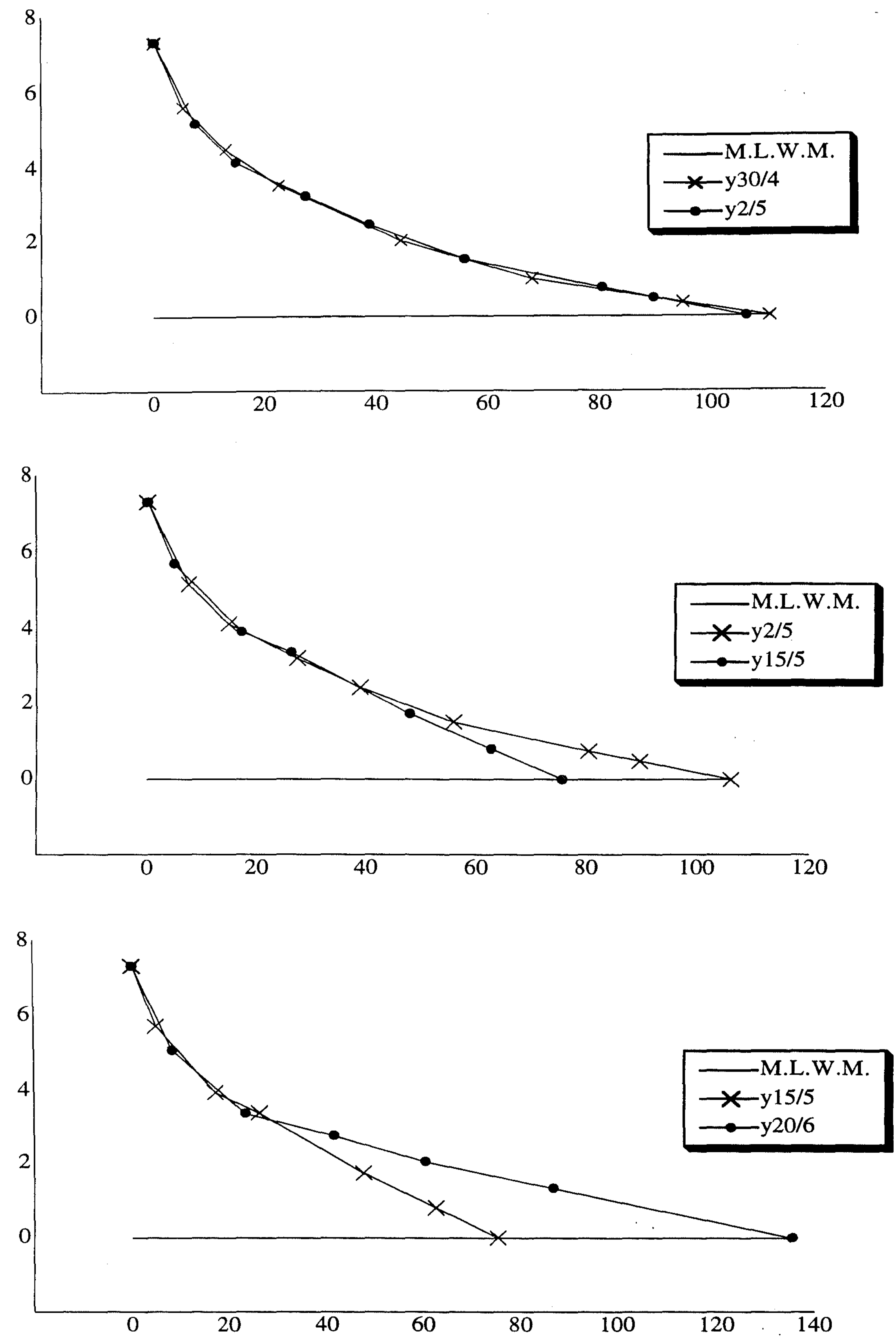


Fig. 5.44: Profile 5 Variations. April 30 to June 20.

5.4.6 WAVE HEIGHTS

Table 5.10 showed that for south swells the erosional events had the higher average mean and maximum wave heights. The average mean wave heights of the south-southeast swells were larger for the erosion events but the average maximum wave height showed no distinct variation between the erosion and accretion events. East-southeast swells showed no distinct variation in average mean and maximum wave height between the erosion and accretion events.

Table 5.10: Average Mean and Maximum Wave Heights for the Erosion and Accretion Events with respect to Swell Direction.

	South		South-southeast		East-southeast	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Accretion	1.3	1.92	1.82	2.25	1.28	1.67
Erosion	1.55	2.67	2.1	2.3	1.29	1.66

5.4.7 WAVE STEEPNESS

Table 5.11 shows that there was no distinct variation in the average wave steepness between the erosion and accretion events, but that the erosional wave steepness average tended to be slightly higher.

Table 5.11: Average Mean Wave Heights Steepness for the Erosion and Accretion Events with respect to Swell Direction.

	South	South-southeast	East-southeast
Accretion	0.00976	0.01770	0.00936
Erosion	0.01151	0.01803	0.01070

Figs. 5.45 and 5.46 show a comparison of the observed wave steepness values to the critical wave steepness as predicted by the Dean (1973) equation. From this it can be seen that the observed wave steepness values are almost allways greater than the critical wave steepness as predicted by the Dean (1973) equation.

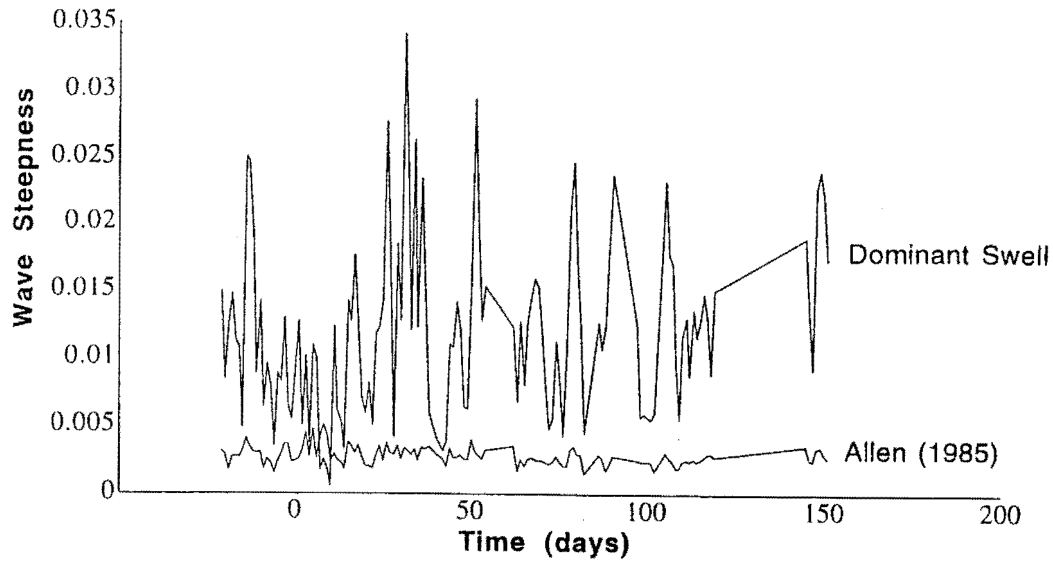


Fig. 5.45: Comparison of observed wave steepness values of the dominant swell to those predicted by the Dean (1973) equation.

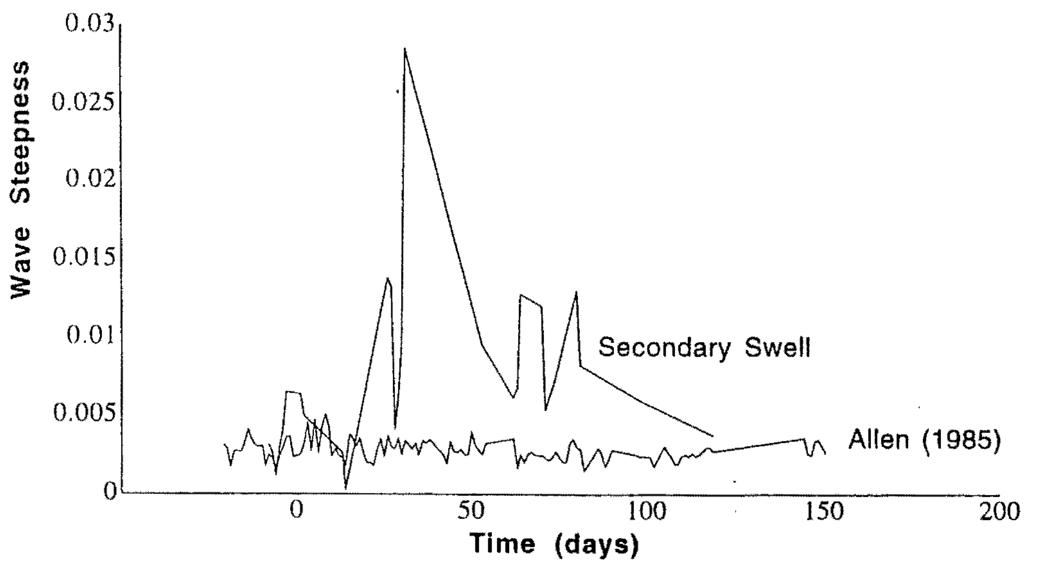


Fig. 5.46: Comparison of observed wave steepness values of the secondary swell to those predicted by the Dean (1973) equation.

5.4.8 WINDS

Fig. 5.47 shows the wind roses for the four main erosion events, January 27 to February 7, March 20 to April 29, (two events), and May 3 to 14. Common to all three windroses is an indication of extended periods of strong southwesterly winds.

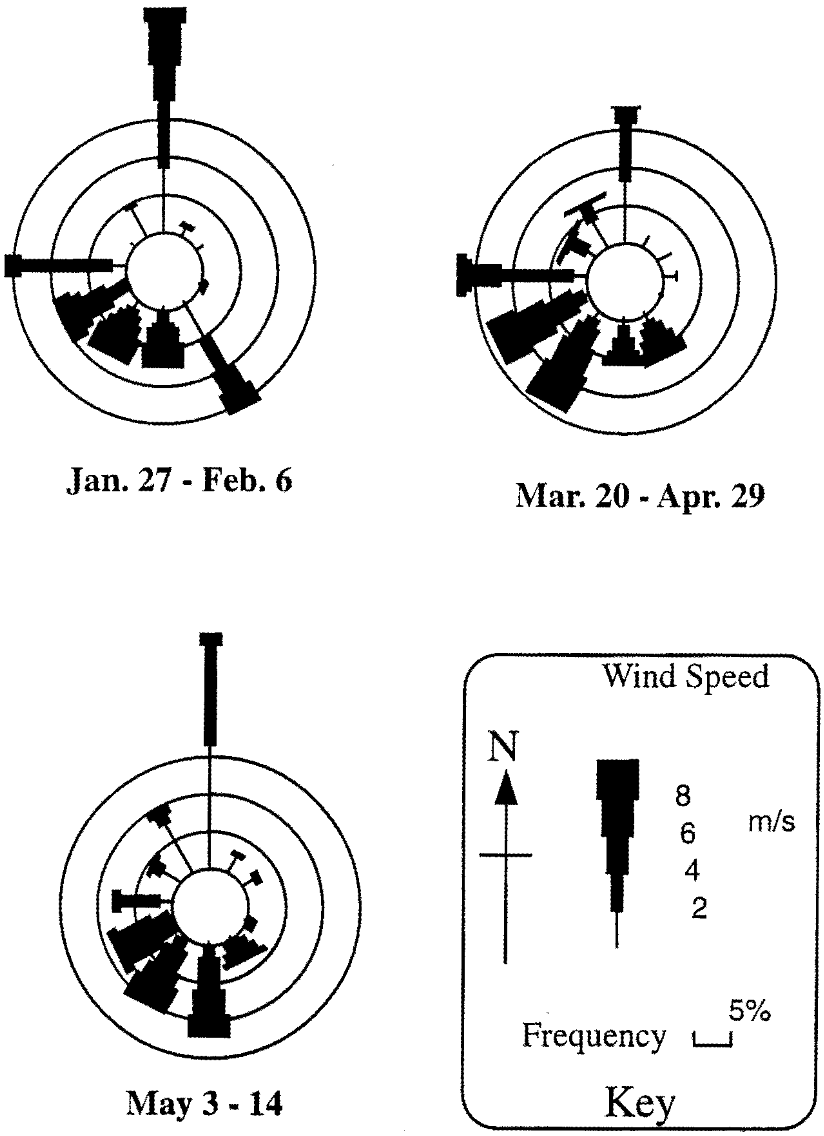


Fig. 5.47: Main Erosional Events windroses.

Fig. 5.48 shows the windroses for the two main accretion events. For the first event data was missing from December 22 (1500) to 29 (1800). However Table 3.1, page 57 in Chapter 3, tells us that six of these missing days had north to northeast gradient winds. Thus this accretional period had a predominance of north to northeasterly winds, and an almost complete absence of southwest winds. The second accretional event had a greater prevalence of northerly winds, than that indicated for the erosional events. Although strong southwest winds occurred for about 8% of the time, from the June windrose it can be seen that the second half of this accretional period was completely devoid of southwest winds.

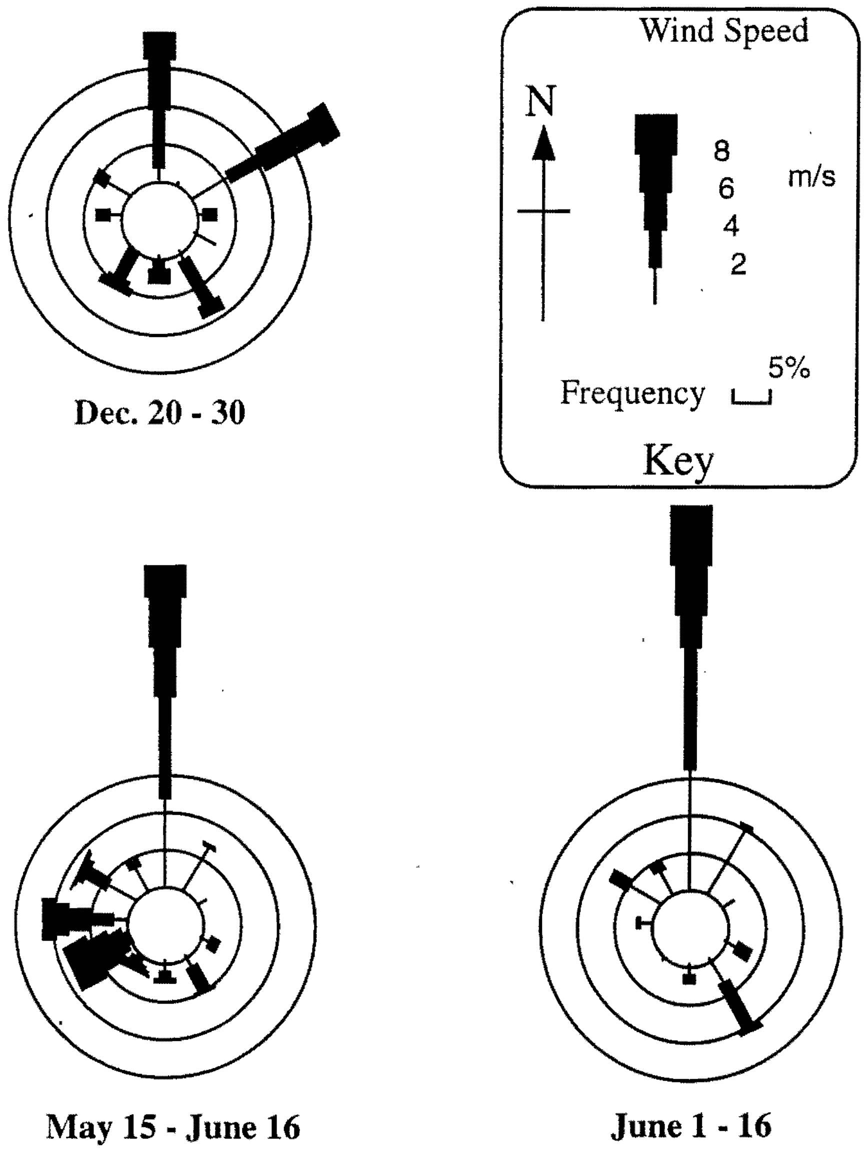


Fig. 5.48: Main Accretional Events Windroses.

5.4.9 BEACH STATE

From Fig 4.49 it can be seen that the dimensionless Dean parameter predicted the beaches to be mostly intermediate states, and occasionally dissipative.

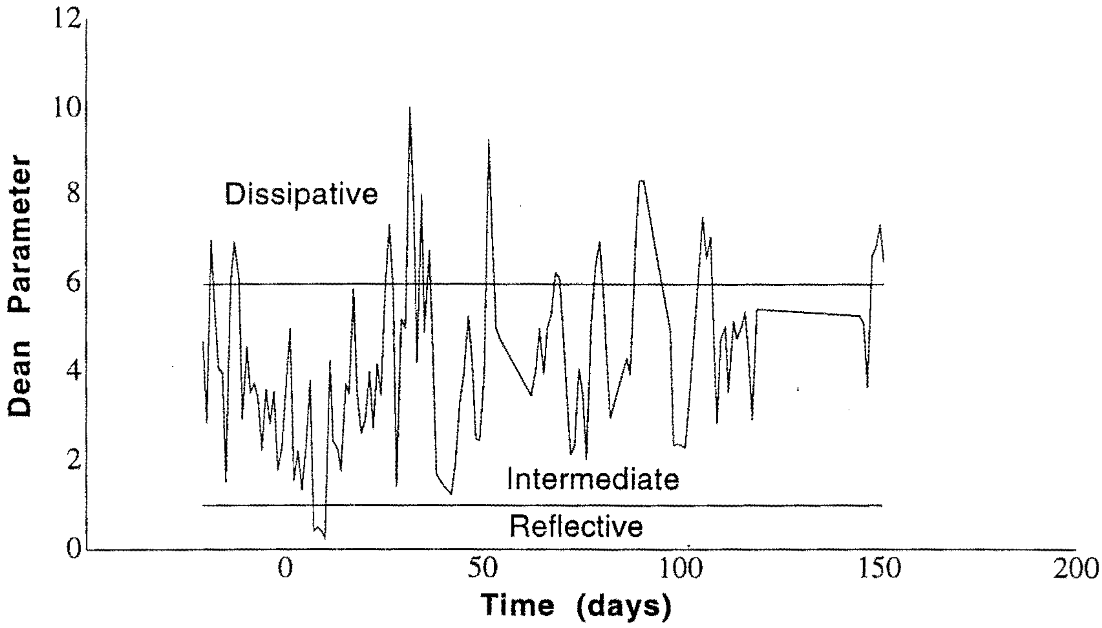


Fig. 5.49: Distribution of the dimensionless Dean Parameter.

5.5 DISCUSSION

5.5.1 THE DEAN (1973) CRITICAL WAVE STEEPNESS EQUATION

To compare the critical wave steepness prediction ability of the Dean (1973) equation, used by Allen (1985), the predicted critical steepness values were compared to the actual steepness values of the observation data. Thus from Figs. 5.45 and 5.46, it can be seen that observation wave steepness values were nearly always larger than the critical wave steepness predicted by the Dean equation. For the dominant swell, the observation wave steepness values were only less than the predicted critical wave steepness on 4 of the 171 days of observations, January 7 to 10. These were all days of south swell of 0.1 meter wave heights, with periods ranging from 5 to 10.5 seconds. For the secondary swell the observation wave steepness values were only less than the predicted critical wave steepness on 2 days, December 26 and January 14. These days were south swells of 0.5 and 0.1 meter wave heights and 16.5 and 14.1 second wave periods respectively.

According to the theory these results indicate that the beaches should have been continuously eroding throughout the study period. Clearly this was not the case with all five profiles having both accretional and erosional phases.

The mean fall velocity of $0.04ms^{-1}$ used in the equation was gained by rapid sediment analysis of sediments collected on May 1 which gave a mean sediment size of 1.75 phi. This is similar to, but slightly larger than, the mean sediment size of 1.96 phi given by Hodgson (1966) for St. Clair - Ocean Beach. The higher mean value obtained here was probably due to the collection of sediments after a major erosional event which would have tended to leave coarser sediments on the beaches. A smaller mean sediment size would have resulted in a lower fall velocity value and therefore an even greater disparaty between the two data sets. Thus the critical wave steepness equation of Dean (1973) was not applicable to observation data and the beaches of the south coast of the Otago Peninsula.

Allen (1985) gained a 96% agreement with the predicted critical wave steepness associated with erosional beach profiles. From this it was suggested that the equation could be more widely used for local planning and engineering design by identifying which wave parameters would result in erosion of the beach concerned. Clearly the present results show that this is not the case, showing that individual coastal problems should be probably be treated on their own merits, and with an understanding of the local environmental conditions, and systems involved.

One reason for the difference in the results of Allen (1985) to those found here is likely to stem from variations in the wave heights between the two studies. The Allen (1983) study was also carried out on a medium sand beach, but here waves were mostly less than 1 meter in height, peaking at 1.98 meters. For the south coast of the Otago Peninsula, the observed mean wave height was

1.6 meters, with wave heights peaking at 4m. This finding is thus consistent with the work of Iwagaki and Noda (1963) and others who consider that the critical wave steepness is related to the scale of the waves in relation to the mean sediment size. However the diagram presented by Iwagaki and Noda (1963), Fig. 5.50, suggests that for a constant sediment size increases in wave height result in lower critical wave steepness values. This is not the case with the present finding. Assuming a similar sediment size, valid as both studies were conducted on medium sand beaches, the critical wave steepness for the Dunedin beaches would be expected to be below that predicted by the Dean (1973) equation, as the equation fits the Allen (1985) data which had significantly lower wave heights. Again this is clearly not the case with the observed wave steepness values being consistently greater than the predicted Dean (1973) value, not smaller as predicted by Iwagaki and Noda (1963). The findings of Iwagaki and Noda (1963) were by way of wave tank experiment. The findings presented here suggest that there is still a need for more field investigations into critical wave steepness and its relationship to the scale of the wave heights to the mean sediment size. Is there a universal model, or does the relationship vary between different natural coastal environments?

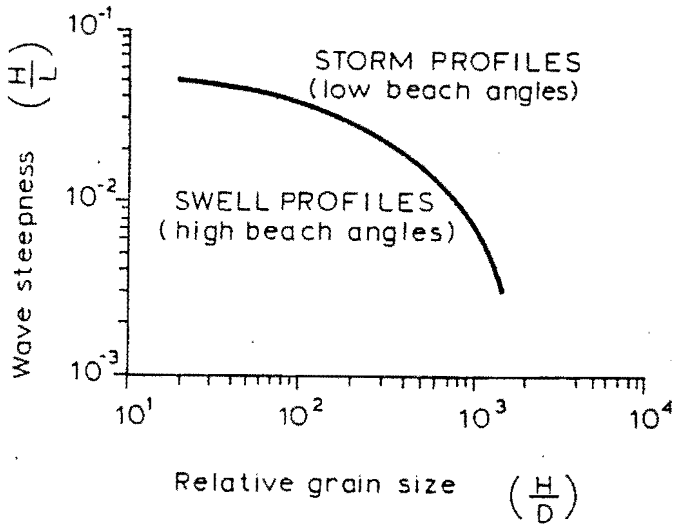


Fig. 5.50: The critical wave steepness required for the transition from swell to storm profiles is dependent on the relative grain size of the beach sediments in relation to the wave height.
(after Iagaki & Noda, 1963; *in* Pethick, 1984)

It must also be remembered that the predominant form of a beach is related to the predominant nature of the waves arriving at it. If the typical wave environment is composed of predimantly steeper waves then it is probable that the beach will accrete under steeper wave conditions than that of a similar beach which predominatly experiences flat waves, as the beach profile attempts to adjust so as to attain an equilibrium with the incoming waves.

Allen (1985) applied a constant of 2 within the Dean (1973) equation instead of the 1.7 applied in the original equation. The reason for this was that the original equation of Dean (1973) was for the deep water critical wave steepness. Allen (1985) applied a constant of 2 to allow for the 20% increase in breaker heights, (used in the study), due to shoaling, in relation to the deep water wave heights that the equation was designed for. Thus another possible reason for the failure of the equation to fit the present data is that the increase of the breaker height in relation to the offshore wave height may be larger than 20%. This would result in the observed wave steepness values tending to be greater than the Dean (1973) predicted critical wave steepness. However the St. Clair - Ocean and Tomahawk beaches, are only open to direct swell approach from the south to southeast. The two most predominant directions in the offshore swell record are the southwest and the northeast and the refraction of these swells would result in a decrease of the wave heights, therefore reducing the discrepency between offshore and inshore wave heights. This is especially so for the heavily refracted northeast swell. The equation did not work with the Tomahawk inshore wave data suggesting that deepwater wave data may be required. The most thorough way to test the Dean (1973) equation would be through the utilisation of deep water wave data which could be collected from a waverider bouy.

5.5.2 DATA LIMITATIONS

The variable nature of the times between surveys plus the long duration of some survey periods made it impossible to make a detailed critical assessment and demarcation of the differences in wave parameters between the erosion and accretion events. The factors of water table height, wind and wave set up, and the effects of storm surge, all variables which affect profile variation were not assessed. Also the profiles did not extend into the nearshore environment, where most of the coastal geomorphic activity takes place.

The effects of this were shown from January 9 to 16 when small 0.1 to 0.5 meter waves allowed for suveying of the immediate nearshore zone, for Profile 3. Thus for Profile 3 in Figs, 5.20 and 5.22, it can be seen that while the foreshore remained stable that considerable change was occuring within the nearshore, with the landward migration of a trough and bar system.

These types of constraints are however not new to coastal field investigations, the coastal environment having a range of complex and interdependent process variables, creating a complicated environment. Despite of these limitations some distinct patterns were still apparent within the collected data for the present study. These are based on the assumption that within the long periods between surveys that accretion over the survey period must indicate a dominance of accretionary conditions, and that erosion over the survey period must indicate a dominance of erosional conditions.

5.5.3 EROSIONAL EVENTS

From the results in Tables 5.1 to 5.9 it appeared that the erosion events were associated with periods of larger south swells. The results of the analysis of mean maximum and mean mean wave heights of the individual events in Table 5.10 also showed this. Thus the average mean wave height and average maximum wave height of the east-southeast and south-southeast swells showed no distinct variation between the erosion and accretion events. The south swell on the other hand had larger erosional average mean wave heights and average maximum wave heights, compared to the accretion events. Thus from this it can be tentatively concluded that erosion of beach profiles was asssociated with increased southerly swell heights. Ignoring Profile 4 the erosional events of Profiles 1, 2, 3, and 5, were all dominated by south swells. For fifteen of the eighteen erosional events where periods were recorded the mean wave steepness, during the erosion period was greater than 0.009. From this it can therefore be

Plate 5.4: St. Clair on March 21.

Plate 5.5: St. Clair on March 21.

Plate 5.6: St. Clair on April 30.

Plate 5.7: St. Clair on April 30.

concluded that the erosional events were predominantly associated with periods of larger south swells with wave steepnesses greater than 0.009. Plates 5.4 to 5.7 show the erosion that took place from March 21 to April 30.

5.5.4 CRITICAL WAVE STEEPNESS

The mean wave steepness showed no distinct variation between erosion and accretion events, Table 5.11. The failure to gain a distinct critical wave steepness demarcating the point between erosion and accretion was most probably a result of the long durations between surveys, between which there is likely to have been both erosion and accretion conditions. Thus to gain a distinct critical observed wave steepness it would appear that more frequent surveying of the beach profiles is required than that carried out in this study.

However from the erosional events it was clear that the mean wave steepness was typically greater than 0.009. This is similar to the critical wave steepness of 0.008 attained in other studies of medium sand beaches (Allen, 1973: Psuty *et al*, 1980). Thus the question asked is **"Is the wave steepness a critical factor in accretion at St Clair?"**

5.5.5 ACCRETION AT ST. CLAIR

Profile 5 and the St. Clair profile sites are in similar geographical positions, on their respective beaches, that is at the western ends of their embayed beaches. The accretion events for these profiles can be split into two categories with respect to the south swell wave steepness. The events with south swell mean wave steepness values less than 0.009 could be expected to be associated with accretion due to the flat and therefore accretional nature of these waves. The events with south swell mean wave steepness values greater than 0.009 on the other hand might at first appear unusual. However all of these accretional events have significant occurences, greater than 50%, of south-southeast and east-southeast swell. This is where the beach profile problem must be expanded from two-dimensions to its actual three-dimensional prespective. The south-

Plate 5.8: St. Clair on April 30.

Plate 5.9: St. Clair on June 20.

southeast and east-southeast swells result in longshore currents flowing west along the beaches, thus transporting sand into the western profile sites from the east. The western headlands of both beaches, then act in a similar fashion to that of groynes blocking the west flowing current, thus reducing its velocity and causing rapid deposition of sand at the western ends of the two beaches, resulting in accretion of the profiles.

Further support for this comes from the final surveys of June 20, (Plates 5.8 & 5.9), with all 4 profiles showing that marked accretion had taken place. The New Zealand Meteorological Service Forecasts, Appendix 1, show the first 20 days of June were dominated by 11 days of predominantly 2 meter east swells and 4 days of 1 to 2 meter southeast swell. Thus the strong accretion here was associated with easterly swells, which would have set up longshore currents flowing to the west, and transporting sand into the western end of the beaches, where Profiles 1, 2, 3, and 5 were situated.

For Profile 3 the initial accretion event between December 20 and January 4 was associated with the formation of a prominant berm on the upper foreshore. From Table 5.4 it can be seen that this accretional period not only had a strong presence of east-southeast swells, but that these and the south swells present all tended to be flat, with mean wave steepness less than 0.009. This would therefore indicate that the accretional waves were associated with the berm building as is stated in the literature (King, 1972: Komar, 1976). This berm also showed up on later surveys of Profile 1 and 2. Profiles 4 and 5 also accreted during this period of accretional waves.

The last accretion event shown by the June 20 survey was not associated with the formation of a prominant berm. Thus the profiles accreted while maintaing an erosional storm profile. Also Profile 4 was stable but tending slightly erosional during this period. This would possibly indicate that the dominant easterly quarter swells responsible for the accretion on Profiles 1, 2, 3, and 5 were not distinctly accretional in nature. Thus in a similar fashion to the findings of Shepard (1950) in Southern California it would appear that the accretion of the western beach end profiles was due to an excess of sand being transported into the area by longshore currents in relation to that eroded by the probable steep erosional nature of the waves, rather than being deposited by flat accretional waves.

These results would therefore indicate that it is the direction of wave approach that is the most important factor with respect to accretion at St. Clair. Small flat south swells may result in minor accretion, but the most important factor which results in substantial accretion at St. Clair is the longshore transport of sediment into the area from the east, as a direct result of easterly quarter swell approach. They also indicate that there is the possibilty that the erosion of St. Clair would be assisted by longshore transport away from the area under times of southerly swell.

5.5.6 INFLUENCE OF WINDS

Further evidence for this comes from the analysis of the wind data for the main erosional and accretional events. The main erosional events all show the presence of extended periods of strong southwesterly winds. It was observed that extended periods of strong southwesterly winds tended to increase the longshore velocities of the littoral zone, therefore enhancing the transport of sand to the east, away from the western corner of St. Clair. It also should be noted that the more normal approach of the southerly waves compared to the oblique approach of the easterly quarter swells, especially the east-southeast, would result in a lower longshore impulse for the south swells, when considering the direction of swell approach alone. It is thus considered here that while south swells do create eastward flowing longshore velocities, it is the enhancement of these longshore velocities under extended strong southwesterly conditions that is considered to be most influential in the longshore transportation of sand away from St. Clair. The strong infux of sand into St. Clair by easterly quarter swells however is considered to not rely so strongly on any wind enhancement of the longshore velocities, due to the greater oblique approach of these swells, although any wind enhancement would be beneficial to accretion in the western corner.

The extended periods of strong southwesterly winds are also probably likely

Plate 5.10: Development of a hole in the footpath atop the seawall at St. Clair.

Plate 5.11: Same hole, beginning to cave in. No fill under asphalt.

to enhance erosion for several other reasons as well. Firstly they tend to be onshore in nature, for the south coast of the Otago Peninsula, therefore increasing the probability of enhanced seaward flowing bottom return currents, thus encouraging the erosion of sand from the foreshore. The southwest winds have also be shown in Chater 4 to be associated with increased southerly swell wave heights and decreased wave periods, therefore creating larger steeper waves and furthur increasing the erosional potential. Also they are generated by the presence of deep low pressure systems within the study area, which along with the enhanced wind and wave set up would also result in a tendency for increased water level elevations, therefore exposing more of the beach system to the already erosional conditions. These findings thus agree with the earlier observations of Elliot (1958) in that the strong southwesterly winds and their influence on the predominant inshore southerly swell of the Otago area result in erosional conditions.

While the accretional events were associated with a predominance of northerly winds, Fig. 5.48, the more striking feature is the near absence of any southwesterly winds. Also substantial periods of northerly winds, (18 - 31%), were still observed within the erosional events. It is therefore considered here that although the offshore northerly winds probably enhance accretional conditions, that it is the absence of extended periods of strong southwest winds and their associated wave conditions that is of greater importance in allowing the beach to accrete.

5.5.7 THE ST. CLAIR SEAWALL

The appearance of holes in the footpath atop, (Plates 5.10 & 5.11), of the St. Clair seawall during the strong erosional events of March and April were associated with the exceptionally low levels of Profile 2, Figs 5.15 and 5.16, (see also Plates 5.12 & 5.13). As the profile erodes the presence of the seawall prevents a supply of sand from the backshore from nourishing the eroding foreshore. This is then compensated by an increased drop in the height of the foreshore in front of the seawall. The extremely low foreshore then allows for fill to be eroded out from behind the seawall through gaps at the base of the

Plate 5.12: Seawall in the vicinity of Profile 2. February 9.

Plate 5.13: Seawall in the vicinity of Profile 2. April 30.

Plate 5.14: March 21. Toe of structure has eroded.

Plate 5.15: April 30. Structure has collapsed.

seawall. These gaps having been recently replugged after the strong erosional events can be seen in Plate 5.16. Subsequently holes begin to appear in the footpath after the event as the cavity at the base of the seawall is propagated upward with the fall of upper fill under the influence of gravity.

The footpath holes were clustered around the Profile 2 site with its extremely low foreshore. In the vicinity of Profile 1 it appears that the rocky base forms a lower limit to erosion, protecting the base of the seawall and therefore preventing the erosion of any fill from behind it. It did not however prevent the collapse of the coastal defence structure just to the west, (Plates 5.14 & 5.15). No footpath collapse was observed along the eastern end of the seawall in the vicinity of profile 3. This can be explained by the fact that the foreshore was not eroded to the low levels of Profile 2. Plate 5.17 also shows this with the sand backed on the seawall protecting the seawall base along its eastern section.

5.5.8 ST. KILDA

Profile 4 was unique in that it is situated in the middle of St. Clair - Ocean Beach. Apart from Profile 1 whose volume changes are restricted by its stable rock base Profile 4 shows a maximum volume change that is less than half that of the other four profiles. This would suggest that the central area of St. Clair - Ocean Beach is more stable than the western corner and therefore possibly not as dramatically influenced by changes in the longshore drift direction as the western corner. From this it would be interesting to compare profile change variation between the western and eastern ends of the beaches to see if accretion at one end is associated with erosion at the other and vica versa. Tables 5.6 and 5.7 also show no clear distinction between the mean wave steepness values most probably due to the extended intervals between surveys.

Plate 5.16: Seawall in the vicinity of Profile 2. April 30.
Note replastered cracks at base of seawall.

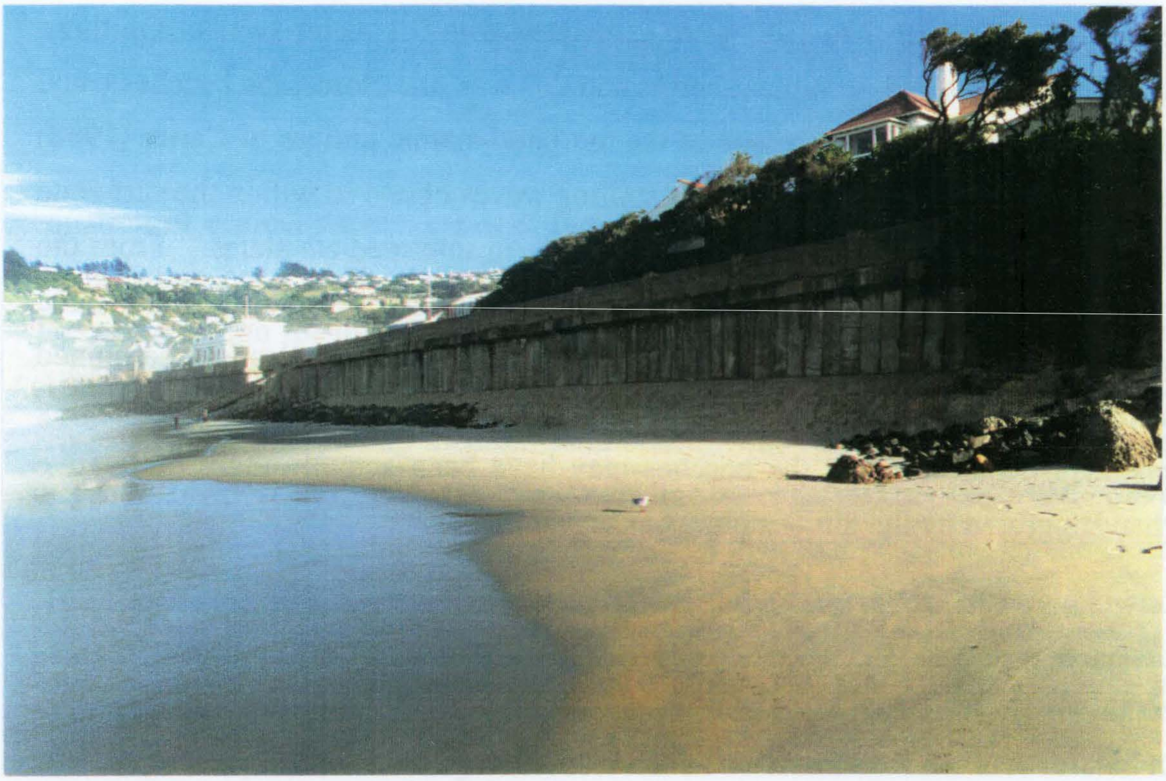


Plate 5.17: Base of seawall in the vicinity of Profile 3 protected by sand. May 2.

5.5.9 THE SOUTH FACING SPITS

The strong accretion of the western ends of the two study beaches due to longshore sand transport under easterly quarter swells also helps to explain the southfacing spit tips on the Otago Peninsula. The inlets are considered to be confined to the southern corners of the beaches as this is where the dominant southerly swells are the most refracted and decayed. Thus this is the zone of lowest wave energy where the inlet can maintain an opening to the sea. From the above findings it can also be seen that longshore velocities generated by northeast and east swell would be capable of creating the south facing spit tips, and therefore also helping to push the inlet openings into the southern corners.

5.5.10 MORPHODYNAMICS

Fig. 4.49 showed that the dimensionless Dean Parameter predicted the beaches to be mostly of intermediate states. The four days of reflective conditions, (January 7 to 10), were associated with 0.1 meter swells. On these days the profiles had prominant berms and this was the closest the beaches came to reflective states. Comparison to the morphodynamic indices of Carter (1988) suggested that with the two to three spilling waves observed within the surf zone on these days that the beaches were probably in intermediate states. From the morphodynamic indices (Carter, 1988), the predominance of more than three rows of waves within the surfzone on most days of data collection, combined with the high percentage of spilling waves and absence of purely plunging breakers, indicates that the beaches may have been actually more dissipative than suggested by the dimensionless Dean parameter.

5.6 CONCLUSIONS

The Dean (1973) equation was developed for deep water wave steepness. Allen (1985) compensated for this, by using a 20% larger constant, to apply the model to inshore wave data. It has been shown here that the Dean (1973)

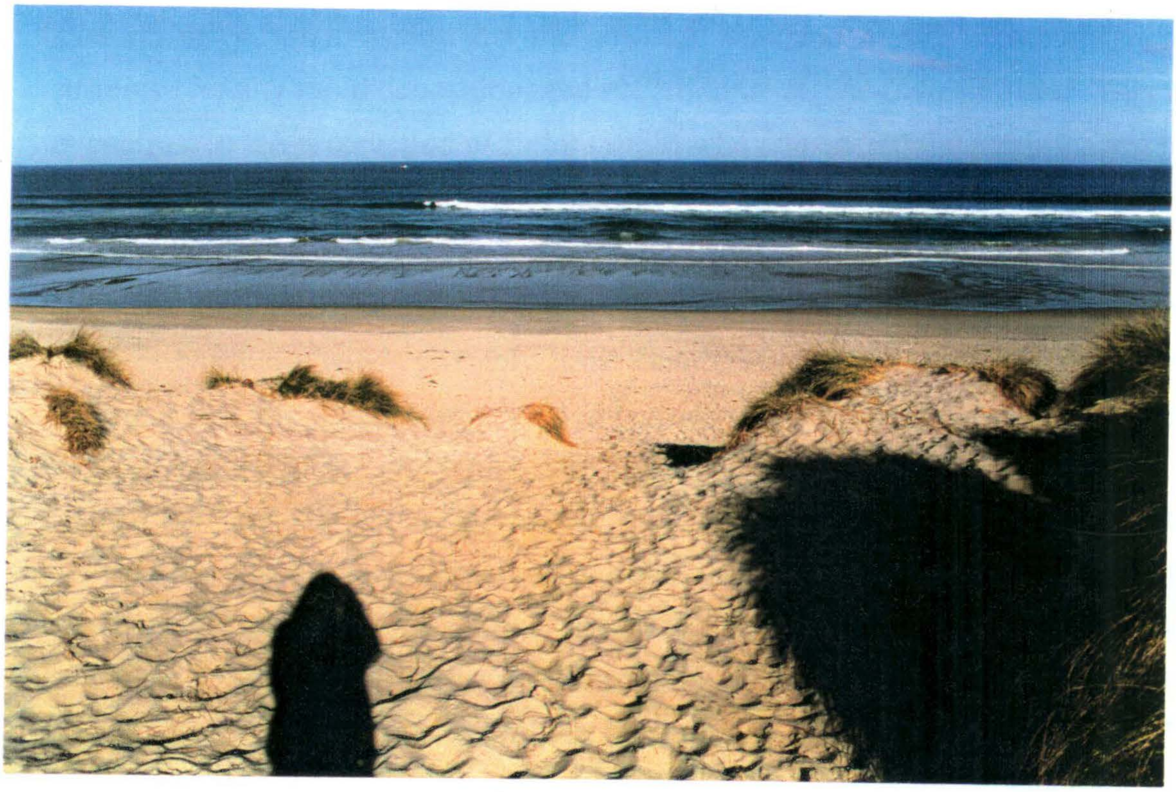


Plate 5.18: St. Kilda Profile showing prominant lower foreshore berm of April 30.

equation of critical wave steepness does not apply to the medium sand beaches of the south coast of the Otago Peninsula, when inshore wave data are used. The main reason for this, (in comparison to the high correlation found by Allen (1985) between the predicted critical wave steepness, of inshore wave data, and erosional events of another medium sand beach), was considered to be the larger wave heights experienced on the Dunedin beaches. The observed wave steepness values were almost always far greater than that predicted by the Dean (1973) equation. This is opposite to that predicted by the model of Iwagaki and Noda (1963) which shows that an increase in wave height for a constant sediment size decreases the critical wave steepness. It is therefore proposed here that the critical wave steepness observed on a natural beach is also related to the predominant waves that the beach experiences, and that those beaches which recieve typically steeper waves will also be observed to have higher critical wave steepness values. The response of a beach also depends on its initial state. Also to furthur test the Dean (1973) equation for Otago beaches it is considered that deepwater wave data needs to collected.

Despite the apparent limitations of the data collected within the present research the erosional and accretional cycles that occur at St. Clair have been identified, quantified, and successfully linked to the wave and wind environments.

The findings of this research agree with the earlier work of Elliot (1958) in that erosion has been shown to be associated with periods of southwesterly weather, along the south coast of the Otago Peninisula. Thus erosion of the beach profile at St. Clair is primarily associated with the passage of deep low pressure systems, from the southern ocean, over the region from the southwest. These bring the onset of strong onshore southwesterly winds for the south coast of the Otago Peninsula. Extended periods of strong southwest winds have been shown to be associated with larger waves with shorter periods therefore creating large steep erosional wave conditions on the south coast of the Otago Peninsula. The extended periods of strong southwest winds have also been observed to enhance longshore currents flowing to the east along the study beaches. The location of St. Clair in the western corner of the St. Clair - Ocean Beach results in these enhanced longshore currents transporting sand out of the area and therefore accentuating the erosion experienced.

In the most western corner of St. Clair the depth of the erosion appears to be limited by the presence of a stable rocky profile base. The most dramatic erosion at St. Clair is centered in the central area of the seawall. Here the natural retreat of the beach is most prevented by the seawall resulting exceptionally low profiles. These low profiles result in the exposure of the base of the seawall which in turn allows fill to be eroded out from behind the seawall. These erosional cavities then propagate up to become holes in the footpath atop the seawall.

The main periods of accretion at St. Clair are primarily associated with a strong presence of easterly quarter swells which create strong longshore velocities transporting sand west, along St. Clair - Ocean Beach. The western location of St. Clair means that the adjacent headland blocks these longshore currents creating rapid deposition, and accretion of the St. Clair profiles. This is in contrast to the proposition of Elliot (1958) who considered the modification of the predominant southerly swell by northerly winds to be primarily responsible for accretion. Accretion also occurs during periods of small flat south swells, but tends to be minor in comparison to that experienced with the easterly quarter swells. Northerly winds probably assist the accretion phases but it is considered here that it is the absence of extended periods of strong southwesterly weather that is the more beneficial to the accretion of the beaches.

The Tomahawk profile was situated in a similar geographical position to St. Clair that is in the western corner of the adjacent beach, which explains the similarities in profile variations that were observed.

The St. Kilda profile was situated in the center of St. Clair - Ocean Beach, and was considered to be not as affected by variations in the longshore current directions. This shows up in the fact that it was by far the most stable of the profiles showing the lowest maximum volume change, (excluding Profile 1 with its rocky base).

A definite critical wave steepness was not able to be attained due to the inconsistent survey base, and the fact that the St. Clair and Tomahawk profiles accretional periods were influenced primarily by alongshore sand transport rather than the steepness of the waves. However the erosional events had mean wave steepness greater than 0.009 which is similar to 0.008 quoted for other medium sand beaches.

CHAPTER SIX

CONCLUSIONS

6.1 CONCLUSIONS

The research conducted within this thesis has examined the nature of the variations that occur within the beach profile at St. Clair Dunedin. These profile changes have subsequently been linked to changes in the wind and wave environments and the results compared to both previous local work and to the theories and models of the accepted literature.

With most profile change theoretical concepts and models having been developed by two-dimensional laboratory based wave tank experiments there is a real need to back the theory up with field based research. Assessment of the theoretical models within the field helps point to where future research might be directed. Also the diverse range of natural coastal environments, necessitates that local fieldwork is carried out when dealing with local problems, such as erosion and accretion at St. Clair, so that the unique local coastal geomorphic characteristics are fully understood.

Within this context the research had four main aims which were:

1) To record, observe and quantify the two main process elements, the wave and wind environments, and from this assess their potential influence on geomorphic change at the coast in relation to the accepted models and theory discussed above.

2) To determine and quantify the nature of the fluctuations of the beach profile at St. Clair Beach.

3) To relate the beach profile fluctuations at St. Clair to changes within the wave and wind energy environments. Are the earlier observations of Elliot (1956) that erosion and accretion is controlled by the modification of the predominant southerly swell by the local winds correct? Does the Dean (1973) critical wave steepness equation apply to the St. Clair beach, and can a critical wave steepness be determined above which the beach erodes and below which the beach accretes? What role if any does variation in the direction of longshore transport play in the erosion accretion cycles at St. Clair?

4) To compare the St. Clair profile fluctuations to those of the other nearby sites of St. Kilda, and Tomahawk beaches.

The research was undertaken on the St. Clair - Ocean and Tomahawk Beaches which are situated on the south coast of the Otago Peninsula. The Otago Peninsula interupts the general northeast - southwest trend of the greater Otago coastline. The Otago Peninsula is the eroded remains of a late Tertiary Shield Volcano which now forms an irregularly embayed coastline of sandy beaches interdispersed between rugged cliffed volcanic headlands. The medium beach sands are predominantly quartzo - feldspathic, of Haast Schist provenance, having been initially supplied by the Clutha River and subsequently transported and dispered north by a predominant northward longshore drift within the littoral system. Situated on the edge of Dunedin City the St. Clair - Ocean and Tomahawk Beaches have also been dramatically influenced within their most recent history by human activities and the subsequent management policies and practices implaced.

The wind environment was assessed by comparing the Tomahawk wind data, (collected during the study), to the local long term Taiaroa Head wind records. The Taiaroa Head long term wind record shows a strong bimodal distribution of predominant but light north to northeast winds over strong southwest to southerly winds. The absence of northeast winds from the Tomahawk record, in favour of northerlies, was considered to be the result of local topographic influences at the Tomahawk data collection site. Thus the dominance of predominantly light notherly winds within the monthly, seasonal, and total Tomahawk records was consistent with the Taiaroa Head record. The west-southwest and south-southwest winds obtained stronger velocities for longer periods than the other wind directions, but did not appear to be quite as prominant as that indicated by the Taiaroa Head record. This was considered to be due to a number of different factors but mostly due to the different increments used in windrose construction (30° as opposed to 45°), the short nature of the Tomahawk record, and local topographic influences. From the distribution frequency of wind speeds and directions, combined with personal observations, and morphological evidence it was concluded that strong onshore winds, most importantly the southwesterly, had the strongest impact on the aeolian transport of sand along the south coast of the Otago Peninsula. Also the extended periods of strong southwesterly weather were observed to enhance longshore current velocities in the easterly directions along the south coast of the Otago Peninsula.

The sea states reported for the Chalmers forecast area were shown to overestimate the size of the sea in comparison to the predicted swell heights. This was thus in contradiction to the definition that the sea state refers to the average of the highest one-third waves. The reason for this was found to be related to the fact that the reported sea state was directly related to the highest forecast windspeed, and that the other two important factors of fetch length and wind duration appeared to have not been considered. Some clarification is thus needed as to what the reported sea state is from the N. Z. Met Service. Thus rather than a reiteration of the predominant swell height the inshore sea states were recorded as the state of the sea surface between the predominant swells. This is considered to be a more sound method, as it gives an indication of the sea state as a separate entity to that of the predominant swells.

The bimodal nature of the wind environment is reflected in the bimodal distribution of the offshore wave climate with a year round predominant southwest swell and a secondary northeast swell whose frequency of occurence peaks in the summer months. Swell direction approach for the St. Clair - Ocean and Tomahawk Beaches is restricted by wave refraction to just west of south to the east-southeast. South swells predominate the inshore wave record. The approach of refracted offshore southwest swell just to the west of south on St. Clair - Ocean Beach results in eastward flowing longshore currents, being generated. These are further enhanced by extended periods of strong southwesterly winds. Thus the predominance of the southwest direction in both the offshore wave record and the wind record was taken to confirm a net longshore drift to the east. This is consistent with the regional sediment dispersal pattern. The less frequent east-southeast and south-southeast swells result in a reversal of the longshore currents, causing them to flow to the west.

The wave data showed that the wind direction at the time of observation influenced the wave characteristics. Thus southerly orientated winds, (southwest, south, & southeast), tended to favour higher energy shorter steeper waves, having increased heights, and lower periods. The northerly orientated winds, (northwest, north, & northeast), tended to favour lower energy flatter waves, having decreased heights and increased periods.

Erosion at St. Clair was shown to be associated with extended periods of strong southwest winds, as was proposed by Elliot (1958). Southwest winds result from the passage of deep low pressure systems over the region from the Southern Ocean. The extended periods of strong southwest winds are associated with steep erosional inshore southerly swells, having increased heights and decreased periods. The enhancement of longshore currents by the southwest winds results in sand being transported to the east away from the western corner of St. Clair thus further accentuating the erosional conditions. Thus erosion at St. Clair is the result of large steep southerly swells transporting sand offshore and enhanced longshore currents transporting sand to the east away from the the western St. Clair corner under extended periods of strong southwest winds.

The most dramatic erosion at St. Clair is focussed in central area of the seawall where the natural retreat of the beach under erosional conditions is most prohibited. This results in exceptionally low profiles which in turn allows for the erosion of fill from behind the concrete face of the seawall.

While northerly winds probably do assist accretion as proposed by Elliot (1958) it is considered that the extended absence of periods of strong southwest winds, and their associated erosional conditions, that is of greater importance in allowing the beach to substantially accrete. Small flat south swells result in only minor amounts of accretion. The main accretion at St. Clair however results from sand being transported into the western corner by westerly flowing longshore currents set up by easterly quarter swells. Under these conditions the beach can rapidly accrete. Accretion under steep wave conditions, shown by the beach accreting while maintaining a storm profile, indicates that the amount of sand moving alongshore into the area under these conditions is greater than that moved offshore by the erosional waves.

The Tomahawk profile experienced similar phases of variation to those occuring at St. Clair. This is attributed to the similarities in their geographical positions, in the western corners of adjacent embayed beaches.

The central area of St. Clair - Ocean Beach was not as dramatically affected by variations in the longshore current direction, compared to the western St. Clair corner, being the most stable of the profiles.

A definite critical wave steepness was not able to be calculated due to the inconsistent survey base, and the fact that the St. Clair and Tomahawk profiles accretional periods were influenced primarily by alongshore sand transport rather than the steepness of the waves.

The critical wave steepness equation of Dean (1973) as applied successfully by Allen (1985) for inshore wave data on a medium sand beach, does not apply to the medium sand beaches of the south coast of the Otago Peninsula. The reason for this is considered to be due to the south coast of the Otago Peninsula being exposed to considerably larger waves than the Allen (1985) beach. The observed wave steepness values were almost always far greater than that predicted by the Dean (1973) equation. Thus given the success of the equation with the smaller wave data of Allen (1985) this is opposite to that predicted by the model of Iwagaki and Noda (1963) which shows that an increase in wave height for a constant sediment size decreases the critical wave steepness. As the response of a beach also depends on its initial state it is considered that those beaches which receive typically steeper waves will also be observed to have higher critical wave steepness values.

6.2 FURTHER RESEARCH

Within the Otago area there are plenty of opportunities for the further extension of the research that was conducted in this thesis.

The critical wave steepness equation of Dean (1973) was shown to not apply to the Tomahawk observation data. However the equation was originally developed for use with deepwater wave steepness. Thus further examination of the Dean (1973) critical wave steepness equation might best be aimed at deep water wave parameters collected with the likes of a wave rider bouy. From this the offshore wave steepness values could be compared to inshore observed wave steepness. This may help explain the observed discrepencies.

The collection of deep water data would provide a more detailed insight into the offshore Chalmers wave climate. This could also be compared to simultaneously collected inshore data, to gain a better understanding of the relationship between the offshore and inshore Chalmers wave climates. Also a continued collection of daily shore based observations and of the Chalmers coastal forecast area swell reports, if built up over many years would provide a valuable long term wave record that is at present missing for the Chalmers area.

No measurements of longshore currents were made in this study. With the importance of the local longshore currents in the erosion and accretion cycles having been pointed out an examination of the actual values of longshore velocities would help to determine more accurately the local sediment transport processes of the different swell directions. Research into the influences of the local winds, in particular southwest winds, on the longshore velocities would also be beneficial to further the understanding of Otago inshore sand movements.

The results of this research have provided an small insight into the nature of sand movements on the Otago coast. There much that is still unknown. Initially further research into sand movements on the Otago coast might be based on comparisons of the St. Clair variations to those of other sites, such as the eastern end of St. Clair - Ocean Beach. Later the installation of a greater number of perminant relocatable profile baselines at various sites throughout Otago would help to determine a more regional picture of littoral sand transport. Given the importance of sand movements on the inner continental shelf and within in the nearshore littoral zone in shaping the present sandy areas of coastline this line of research could be seen as valuable to gain an understanding of what future changes might take place, especially given the now dramatically reduced bedload of the dominant Clutha River sediment source.

The research has also shown that there is still a need for more field based coastal research. The relationships between the scale of the wave height in relation to the mean grain size, and its effect on the critical wave steepness between different coastal environments should be looked into, as it appears to differ from that predicted from wave tanks. Also the relationship between the mean wave steepness and the critical wave steepness between similar beaches is an area which might be addressed.

Plate 6.1: Tomahawk Sunset.

ACKNOWLEDGEMENTS

The completion of this thesis would not have been possible without the input and help of many people, to all I thank heaps.

Thanks to Professor Bob Kirk for his supervision for the year, and whose ideas, inputs, suggestions and draft comments proved invaluable.

Thanks to Allan Worthington and the Otago Regional Council for the beach profile plans, and to Allan Worthington, Murray Harris, and the Otago Regional Council, and Richard Mitchell, and the Dunedin City Council, for the loan of local papers.

Also thanks to other thesis students for company during the long haul, and to Linda for pasting heaps of diagrams.

Thanks to Tane, Joanna, and Nikki Tokona for providing an awesome summer house from which to conduct my fieldwork and for their hospitality and friendship throughout the year. Special thanks to Tane for helping out with feildwork, collection of obs, and the seeking out of filthy barrels. May more be found this summer.

Also thanks to all the hard core Dunnos crew. Go hard or go home!

A big thanks to my mother and father for their most generous support and encouragement over the last five years of univeristy. Also thanks to Janine and Andy over in Aus.

Lastly and most definitely not leastly I would like to thank Lisa for providing me with the initial inspiration to attend university and for the wonderful friendship which we have shared over numerous years.

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APPENDIX ONE

NEW ZEALAND MET. SERVICE CHALMERS COASTAL AREA SWELL FORECAST

Key:			
Swell Direction	0 = no swell reported	1 = southwest swell	
	2 = south swell	3 = southeast swell	
	4 = east swell	5 = northeast swell	
Sea State	1 = calm	2 = smooth	
	3 = slight	4 = moderate	
	5 = rough	6 = very rough	
	7 = high		

December 1993.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
11	1	2	0	0	3
12	1	2	0	0	5
13	1	3.5	0	0	5
14	2	3	0	0	5
15	2	2.5	0	0	3
16	1	1.5	0	0	3
17	1	2.5	0	0	5
18	1	2	5	2	5
19	1	2.5	5	2.5	5
20	1	2.5	5	1.5	4
21	1	1.5	5	1.5	5
22	4	2.5	0	0	5
23	4	3	1	2	5
24	4	2.5	0	0	5
25	4	2	0	0	5
26	4	1.5	0	0	6
27	5	1.5	1	1	5
28	5	1.5	0	0	3
29	5	1	0	0	4
30	5	1	1	1	3
31	1	1.5	5	1	1

January 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	5	1.5	0	0	5
2	1	1	5	1	5
3	5	1.5	1	1	6
4	5	1	0	0	4
5	1	3.5	5	1	6
6	1	2.5	5	1	4
7	5	1.5	0	0	5
8	5	1.5	0	0	6
9	5	1.5	0	0	4
10	5	1.5	0	0	5
11	5	1.5	0	0	4
12	1	1.5	5	1	4
13	1	1.5	5	1.5	4
14	5	1.5	1	1	6
15	5	1	0	0	5
16	1	2.5	0	0	5
17	1	3	0	0	5
18	1	2.5	5	1	5
19	5	1.5	0	0	5
20	1	1.5	5	1	4
21	5	1	0	0	5
22	5	1	0	0	4
23	1	1.5	5	1	4
24	1	2	5	1	5
25	1	2	5	1	4
26	1	2	0	0	3
27	2	3.5	0	0	3
28	2	2	0	0	5
29	1	2	0	0	3
30	1	2.5	0	0	6
31	1	3.5	0	0	5

February 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	1	3.5	0	0	4
2	1	3.5	0	0	5
3	2	2.5	0	0	5
4	1	2.5	0	0	5
5	1	2	0	0	4
6	2	1.5	0	0	3
7	1	1.5	0	0	3
8	5	1.5	0	0	4
9	5	1	0	0	3
10	5	1	0	0	4
11	5	1	0	0	3
12	0	0	0	0	5
13	0	0	0	0	5
14	1	2.5	0	0	3
15	2	1	0	0	3
16	1	2	0	0	3
17	2	1	0	0	3
18	0	0	0	0	4
19	2	1	0	0	5
20	3	3	0	0	5
21	3	2	0	0	4
22	3	1	0	0	4
23	1	2	4	2	4
24	4	2	0	0	3
25	5	1.5	0	0	3
26	5	1	0	0	3
27	5	2	1	1	3
28	5	2	0	0	5

March 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	5	2	0	0	4
2	2	2	5	1	5
3	1	2	4	2	4
4	1	3	4	2	5
5	1	2	2	2	5
6	5	2	0	0	6
7	1	3	0	0	6
8	1	3	0	0	6
9	1	3.5	0	0	5
10	1	4	0	0	3
11	2	2	5	2	5
12	5	3	0	0	5
13	5	2	0	0	5
14	5	2	0	0	5
15	5	2	0	0	3
16	5	1.5	0	0	5
17	5	1	0	0	3
18	2	2	0	0	5
19	2	3	0	0	6
20	2	3	0	0	6
21	2	3	0	0	4
22	2	1	0	0	3
23	2	3	0	0	6
24	2	3	0	0	6
25	2	3	0	0	5
26	2	2	0	0	4
27	1	3	0	0	5
28	1	2	0	0	6
29	1	3	0	0	5
30	1	3	0	0	4
31	1	3	0	0	6

April 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	1	4	0	0	5
2	1	2	5	1	5
3	1	2	0	0	5
4	1	2	0	0	5
5	1	2	0	0	3
6	1	2	0	0	4
7	2	1	0	0	4
8	0	0	0	0	5
9	5	1	0	0	4
10	5	1	0	0	3
11	5	1	0	0	3
12	5	1	0	0	3
13	2	1	5	1	5
14	1	3	0	0	7
15	1	3	0	0	3
16	1	4	0	0	6
17	1	3	0	0	3
18	1	2	0	0	5
19	1	1.5	0	0	5
20	1	2	0	0	7
21	1	4	0	0	6
22	1	4	0	0	7
23	1	4	0	0	6
24	1	5	0	0	6
25	1	4	0	0	6
26	3	3	0	0	5
27	1	3	0	0	3
28	1	2	0	0	5
29	1	2	0	0	5
30	1	1	0	0	4

May 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	0	0	0	0	3
2	1	1	0	0	5
3	1	2	5	1	5
4	1	2	0	0	4
5	1	3	0	0	5
6	1	2	0	0	3
7	1	2	0	0	3
8	1	1	5	1	3
9	0	0	0	0	3
10	4	3	0	0	5
11	4	3	0	0	5
12	2	2	4	2	5
13	1	2	0	0	3
14	1	3	0	0	3
15	1	2	0	0	5
16	1	4	0	0	7
17	1	5	0	0	7
18	1	4	0	0	5
19	1	2	0	0	5
20	1	2	0	0	5
21	1	2	0	0	5
22	1	2	0	0	5
23	1	1	0	0	4
24	1	2	0	0	5
25	2	1	5	1	4
26	5	1	0	0	4
27	5	1	0	0	5
28	5	1	0	0	5
29	1	2	5	1	6
30	1	3	5	1	6
31	1	3	0	0	5

June 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	3	2	0	0	3
2	2	1	0	0	4
3	3	2	0	0	3
4	3	1	0	0	3
5	2	1	0	0	3
6	2	1	0	0	3
7	4	2	0	0	5
8	4	2	0	0	4
9	4	2	0	0	3
10	4	2	0	0	5
11	4	2	0	0	4
12	4	2	0	0	5
13	3	1	0	0	3
14	4	1	0	0	5
15	4	2	0	0	5
16	4	2	1	1	3
17	4	2	0	0	3
18	4	1	0	0	4
19	5	1	0	0	4
20	1	2	5	1	5
21	1	3	0	0	3
22	1	4	0	0	6
23	1	4	0	0	4
24	1	3	0	0	5
25	1	1	0	0	4
26	2	2	0	0	4
27	2	3	0	0	5
28	2	3	0	0	6
29	2	4	0	0	6
30	2	4	0	0	6

July 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	2	4	0	0	5
2	2	4	0	0	5
3	1	3	0	0	5
4	1	2	0	0	5
5	1	2	0	0	6
6	1	2	0	0	6
7	1	3	0	0	3
8	1	4	0	0	6
9	1	4	0	0	6
10	1	4	0	0	6
11	1	4	0	0	6
12	1	4	0	0	6
13	1	4	0	0	5
14	1	2	0	0	4
15	1	1	0	0	4
16	1	2	0	0	5
17	5	2	0	0	4
18	5	2	2	1	3
19	1	2	5	2	3
20	1	2	0	0	5
21	1	3	5	1	5
22	1	3	5	1	5
23	2	3	4	1	5
24	2	2	4	1	3
25	5	2	0	0	5
26	5	3	0	0	6
27	5	4	0	0	6
28	4	4	0	0	5
29	4	4	5	1	3
30	4	3	0	0	3
31	4	3	0	0	5

August 1994.

Day	Swell Direction	Swell Height	2nd. Swell Direction	2nd. Swell Height	Sea State
1	4	3	0	0	6
2	5	3	0	0	6
3	5	3	0	0	5
4	5	3	0	0	3
5	5	2	0	0	3
6	2	1	5	1	3
7	2	1	0	0	5
8	5	1	0	0	5
9	1	4	5	1	6
10	1	4	0	0	6
11	1	4	0	0	6
12	1	4	0	0	5
13	1	2	0	0	6
14	1	1	0	0	6
15	1	2	0	0	6
16	1	3	0	0	5
17	1	2	0	0	5
18	1	3	0	0	5
19	1	3	3	1	5
20	1	4	0	0	5
21	1	4	0	0	3
22	1	2	5	2	5
23	1	2	0	0	5
24	1	2	0	0	5
25	1	3	3	1	5
26	1	3	0	0	6
27	1	3	0	0	4
28	1	2	0	0	5
29	1	2	0	0	5
30	1	2	0	0	6
31	1	2	0	0	5

APPENDIX TWO

TOMAHAWK SHORE BASED WAVE OBSEVATIONS

Key: Swell Direction:	0 = no swell	2 = south swell	
	3 = south-southeast swell		
	4 = east-southeast swell		
Breaker Type:	0 = spilling	1 = plunging	
	2 = spill-plunge		
Wind Direction:	1 = N	2 = NE	3 = E	4 = SE
	5 = S	6 = SW	7 = W	8 = NW
Sea State:	0 = calm (glassy)	2 = calm (rippled)	
	3 = slight	4 = moderate	
	5 = rough	6 = very rough	
	7 = high		
Column:	1 = day	2 = swell direction	
	3 = breaker height	4 = 2nd swell direction	
	5 = 2nd breaker height	6 = breaker type	
	7 = wind direction	8 = sea state	
	9 = period	10 = wave steepness	
	11 = 2nd wave steepness		

December 1993.

1	2	3	4	5	6	7	8	9	10	11
11	2	1.5	0	0	0	7	2	8	0.01502675	-
12	2	1	0	0	0	8	1	8.7	0.00847062	-
13	2	4	0	0	2	0	0	14.3	0.01254128	-
14	2	2	0	0	0	6	3	9.3	0.01482579	-
15	3	1.5	0	0	0	5	3	9.2	0.01136238	-
16	3	1.5	0	0	0	1	0	9.4	0.01088402	-
17	2	0.5	0	0	0	6	2	8.1	0.004886	-
18	2	1.5	0	0	2	6	2	6.2	0.02501852	-
19	2	2	0	0	0	6	4	7.2	0.02473539	-
20	2	2	0	0	2	1	0	8.2	0.01907024	-
21	2	1	0	0	0	6	2	8.5	0.00887393	-
22	4	1.5	0	0	0	3	4	8.2	0.01430268	-
23	4	2	0	0	0	3	3	14.1	0.00644979	-
24	4	1.5	2	0.5	0	3	3	10	0.00961712	0.0032
25	4	1.5	2	0.5	2	2	2	11	0.00794803	0.0026
26	4	1.5	2	0.5	2	2	2	16.5	0.00353246	0.0012
27	4	1.5	2	0.5	2	1	1	10.4	0.00889157	0.003
28	4	1	2	0.5	0	2	2	8.8	0.0082792	0.0041
29	4	1	2	0.5	0	2	2	7	0.01308452	0.0065
30	2	0.5	0	0	0	2	2	7	0.00654226	-
31	2	1	0	0	0	2	2	10.8	0.00549675	-

January 1994.

1	2	3	4	5	6	7	8	9	10	11
1	2	2	4	1	0	3	3	10	0.01282283	0.0064
2	2	0.5	4	0.5	0	1	1	8	0.00500892	0.005
3	2	0.5	0	0	2	1	2	5.6	0.01022228	-
4	2	0.5	0	0	0	1	1	9.2	0.00378746	-
5	2	0.5	0	0	0	6	3	5.4	0.01099351	-
6	2	1.5	0	0	2	1	2	9.8	0.01001366	-
7	2	0.1	0	0	0	0	0	6	0.00178095	-
8	2	0.1	0	0	0	0	0	5	0.00256457	-
9	2	0.1	0	0	0	0	0	6	0.00178095	-
10	2	0.1	0	0	0	6	2	10.5	0.00058153	-
11	2	1.5	0	0	0	5	1	8.8	0.0124188	-
12	2	1	0	0	2	2	2	10.2	0.00616245	-
13	4	1	2	0.5	2	2	1	11	0.00529869	0.0026
14	4	1	2	0.1	2	1	2	14.1	0.00322489	0.0003
15	2	1	0	0	0	5	3	6.7	0.0142825	-
16	2	1	0	0	0	6	3	7.1	0.01271854	-
17	2	2	0	0	2	7	3	8.5	0.01774786	-
18	2	1	0	0	0	1	1	7.2	0.0123677	-
19	2	1	0	0	0	1	2	9.5	0.00710406	-
20	2	1.5	0	0	2	1	1	12.7	0.00596263	-
21	2	2	0	0	2	1	2	12.5	0.00820661	-
22	2	1.5	0	0	0	5	3	13.7	0.00512394	-
23	2	1.5	0	0	2	2	2	9	0.01187299	-
24	2	1	0	0	0	5	3	7.2	0.0123677	-
25	2	2.5	0	0	2	7	0	10.6	0.01426534	-
26	2	2	4	1	2	5	4	6.8	0.02773103	0.0139
27	2	2	4	1.5	2	2	2	8.5	0.01774786	0.0133
28	2	0.5	4	0.5	0	8	0	8.8	0.0041396	0.0041
29	2	1.5	4	0.5	2	8	2	7.2	0.01855154	0.0062
30	2	2	4	1.5	2	1	3	10	0.01282283	0.0096
31	2	3	4	2.5	2	6	4	7.5	0.03419421	0.0285

February 1994.

1	2	3	4	5	6	7	8	9	10	11
1	2	2.5	0	0	2	6	4	8	0.02504458	-
2	2	1.5	0	0	2	1	2	8.9	0.0121413	-
3	2	2.5	0	0	2	6	4	7.8	0.02634539	-
4	2	2	0	0	2	7	2	10.2	0.0123249	-
5	2	2	0	0	2	6	3	7.4	0.02341641	-
6	2	1.5	0	0	2	2	2	7.8	0.01580723	-
7	2	0.5	0	0	2	4	0	7.3	0.00601559	-
8	2	0.5	0	0	2	2	2	7.9	0.00513653	-
9	2	0.5	0	0	0	6	1	8.8	0.0041396	-
10	2	0.5	0	0	2	2	1	9.3	0.00370645	-
11	2	0.5	0	0	2	2	1	10	0.00320571	-
12	2	1	0	0	2	1	1	12.9	0.00385278	-
13	2	1	0	0	0	6	3	7.6	0.01110009	-
14	2	1.5	0	0	0	6	4	9.4	0.01088402	-
15	2	2	0	0	2	1	3	9.5	0.01420812	-
16	2	1.5	0	0	2	1	3	8.9	0.0121413	-
17	2	1	0	0	2	1	1	10	0.00641141	-
18	2	1	0	0	0	6	2	10.1	0.00628508	-
19	3	1	0	0	0	5	3	6.4	0.01565287	-
20	3	3	0	0	0	5	5	8.1	0.02931602	-
21	3	2.5	0	0	0	6	4	9	0.01978831	-
22	2	2	3	1.5	2	7	3	10	0.01282283	0.0096
23	2	1.5	0	0	2	6	4	7.9	0.01540958	-
24	2	1.5	0	0						
25	2	2	4	2						
26	2	1.5	4	1.5	-	-	-	-	-	-
27	4	1.5	2	1	-	-	-	-	-	-
28	2	2	4	2	-	-	-	-	-	

March 1994.

1	2	3	4	5	6	7	8	9	10	11
1	4	2	2	1	-	-	-	-	-	-
2	4	1	2	1	-	-	-	-	-	-
3	4	1	2	0.5	0	6	3	7.2	0.0123677	0.0062
4	2	2.5	4	2.5	2	8	4	15.3	0.00684717	0.0068
5	2	2	4	2	1	2	4	10	0.01282283	0.0128
6	2	2	0	0	2	1	3	12.6	0.00807686	-
7	2	2	0	0	0	6	4	10	0.01282283	-
8	2	2	0	0	2	7	4	9.4	0.01451203	-
9	2	2.5	0	0	2	8	4	10	0.01602853	-
10	2	2.5	0	0	2	1	3	10.2	0.01540613	-
11	2	2	4	2	1	2	3	10.3	0.01208674	0.0121
12	4	1.5	2	1	1	2	2	10.9	0.00809454	0.0054
13	4	1	0	0	2	2	2	11.6	0.00476472	-
14	4	1	0	0	2	2	2	10.7	0.00559998	-
15	2	1.5	4	1	2	1	2	9.2	0.01136238	0.0076
16	2	1.5	0	0	2	4	2	10.7	0.00839997	-
17	2	1	0	0	0	6	2	12.2	0.00430759	-
18	2	2.5	0	0	0	6	4	12.3	0.01059458	-
19	4	2	0	0	0	3	4	7.8	0.02107631	-
20	3	2	0	0	0	4	4	7.2	0.02473539	-
21	2	2	3	1.5	0	6	4	8.6	0.01733752	0.013
22	2	1.5	4	1	2	8	2	8.8	0.0124188	0.0083
23	2	2	0	0	2	1	2	16.8	0.00454324	-
24	2	2	0	0	0	4	3	-	-	-
25	2	2	0	0	2	7	3	-	-	-
26	2	1.5	0	0	0	5	3	-	-	-
27	2	1.5	0	0	0	7	2	8.7	0.01270593	-
28	2	1.5	0	0	0	6	2	9.5	0.01065609	-
29	2	4	0	0	0	6	5	14.3	0.01254128	-
30	2	4	0	0	0	6	5	12	0.01780948	-
31	2	3	0	0	0	6	5	9	0.02374598	-

April 1994.

1	2	3	4	5	6	7	8	9	10	11
1	2	2.5	0	0	2	1	4	-	-	-
2	2	0.5	0	0	2	6	1	-	-	-
3	2	1.5	0	0	0	6	2	-	-	-
4	2	1	0	0	0	6	2	-	-	-
5	2	2	0	0	2	7	3	-	-	-
6	2	1.5	0	0	2	7	3	-	-	-
7	2	2	0	0	2	1	3	10.1	0.01257017	-
8	2	1	0	0	2	1	2	10.6	0.00570614	-
9	2	1	4	1	2	2	2	10.4	0.00592771	0.0059
10	2	1	0	0	2	1	2	10.6	0.00570614	-
11	2	1	0	0	2	1	2	10.8	0.00549675	-
12	2	2	0	0	2	7	3	14.5	0.00609885	-
13	2	1.5	0	0	2	8	2	-	-	-
14	2	3	0	0	2	6	5	-	-	-
15	2	2.5	0	0	2	6	3	8.3	0.02326685	-
16	2	2.5	0	0	2	7	3	9.5	0.01776015	-
17	2	3	0	0	2	7	4	10.6	0.01711841	-
18	2	2.5	0	0	2	8	3	13	0.00948434	-
19	2	1.5	0	0	2	7	2	13.1	0.00560406	-
20	2	2	0	0	2	8	3	10.5	0.01163068	-
21	2	2	0	0	0	6	3	9.9	0.01308318	-
22	2	1.5	0	0	0	6	2	10.5	0.00872301	-
23	2	2	0	0	0	6	3	9.7	0.01362826	-
24	2	2	0	0	2	8	3	10.5	0.01163068	-
25	2	2	0	0	2	6	3	9.9	0.01308318	-
26	2	2	0	0	0	6	3	9.3	0.01482579	-
27	2	1.5	0	0	2	1	2	8.6	0.01300314	-
28	4	1	0	0	2	1	1	8.5	0.00887393	-
29	4	2	2	0.5	1	1	3	9.2	0.01514984	0.0038
30	4	2	2	1	-	-	-	-	-	-

May 1994.

1	2	3	4	5	6	7	8	9	10	11
1	4	1	2	0.5	3	8	2	-	-	-
2	2	2	4	1	2	2	2	-	-	-
3	2	2	0	0	0	5	3	-	-	-
4	2	2.5	0	0	2	1	3	-	-	-
5	2	1.5	0	0	0	6	2	-	-	-
6	2	1	0	0	0	1	2	-	-	-
7	2	2	0	0	0	1	3	-	-	-
8	2	2	0	0	2	1	2	-	-	-
9	2	1.5	0	0	2	2	2	-	-	-
10	2	1.5	0	0	2	1	2	-	-	-
11	3	2.5	0	0	0	6	3	-	-	-
12	3	2	2	1.5	0	5	3	-	-	-
13	2	2	0	0	0	6	3	-	-	-
14	2	2	0	0	2	1	3	-	-	-
15	2	2	4	1	2	1	3	-	-	-
16	2	2	0	0	2	7	3	-	-	-
17	2	3	0	0	0	6	4	-	-	-
18	2	2	0	0	0	6	3	-	-	-
19	2	2	0	0	2	1	3	-	-	-
20	2	2	0	0	2	1	2	-	-	-
21	2	2	0	0	2	7	3	-	-	-
22	2	2	0	0	2	7	3	-	-	-
23	2	1.5	0	0	2	1	2	-	-	-
24	2	2	0	0	2	2	3	-	-	-
25	2	1.5	0	0	0	7	3	7.1	0.0190778	-
26	4	2	0	0	2	1	2	9.8	0.01335155	-
27	4	1.5	0	0	2	1	2	10.2	0.00924368	-
28	4	2	0	0	2	1	2	7.5	0.02279614	-
29	4	2	0	0	2	6	3	7.3	0.02406235	-
30	2	2.5	0	0	0	6	4	8.5	0.02218482	-
31	2	2.5	0	0	0	6	4	9.6	0.01739207	-

APPENDIX THREE

BEACH PROFILE VOLUMES. (m^3).

Profile 1

Julian Day	Profile Volume	Volume Change
9	55.526	
12	45.618	-9.908
15	44.378	-1.24
16	35.017	-9.361
17	38.319	+3.302
19	39.039	+0.72
26	28.55	-10.49
38	29.075	+0.525
102	35.934	+6.859
120	33.918	-2.016
171	54.128	+20.21
Max Volume Change =		**26.98**

Profile 2

Julian Day	Profile Volume	Volume Change
26	39.603	
38	31.054	-8.549
39	29.851	-1.203
40	31.308	+1.457
41	37.679	+6.371
42	33.072	-4.607
47	27.532	-5.54
50	32.826	+5.29
53	46.244	+13.42
79	51.033	+4.789
81	70.345	+19.312
102	26.733	-43.61
120	13.611	-13.12
122	25.809	+12.198
135	9.7664	-16.04
171	104.97	+95.20
Max Volume Change =		**95.20**

Profile 3			Profile 4		
Julian Day	Profile Volume	Volume Change	Julian Day	Profile Volume	Volume Change
-10	55.219		-11	334.32	
4	97.866	+42.647	-1	341.31	+6.99
9	100.73	+2.864	4	335.92	-5.39
12	101.59	+0.86	16	355.18	+19.26
15	102.75	+1.16	17	363.17	+7.99
16	101.78	-0.97	26	362.26	-0.91
17	103.21	+1.43	27	360.56	-1.7
19	102.3	-0.91	38	342.6	-17.96
26	98.789	-3.511	40	353.81	+11.21
27	101.99	+3.201	46	339.57	-14.24
38	91.523	-10.47	47	341.67	+2.1
39	92.009	+0.486	53	346.92	+5.25
40	93.318	+1.309	79	350.81	+3.89
41	95.162	+1.844	81	355.43	+4.62
42	91.581	-3.581	102	340.41	-15.02
47	92.463	+0.882	120	346.67	+6.26
50	92.935	+0.472	135	341.63	-5.04
53	92.653	-0.282	171	339.65	-1.98
79	84.48	-8.164	Max Volume Change =		**28.85**
102	77.251	-7.238			
120	63.866	-13.39			
122	64.432	+0.566			
135	73.772	+9.34			
171	125.8	+52.03			
Max Volume Change =		**70.58**			

Profile 5

Julian Day	Profile Volume	Volume Change
-11	191.27	
-1	203.91	+12.64
4	202.31	-1.6
19	216.26	+13.95
26	225.28	+9.02
38	215.78	-9.5
42	222.54	+6.76
46	227.7	+5.16
53	238.61	+10.91
80	307.84	+69.23
81	274.66	-33.18
102	238.32	-36.34
120	226.26	-12.06
121	226.12	-0.14
122	228.91	+2.79
135	201.75	-27.16
171	291.03	+89.28
Max Volume Change =		**106.09**