UNIVERSITY OF GLASGOW

LAKE WAVES AND GRAVEL BEACH VARIATION, LOCH LOMOND SCOTLAND

LYDIA R. PIERCE

Department of Geography and Topographic Science

Faculty of Science

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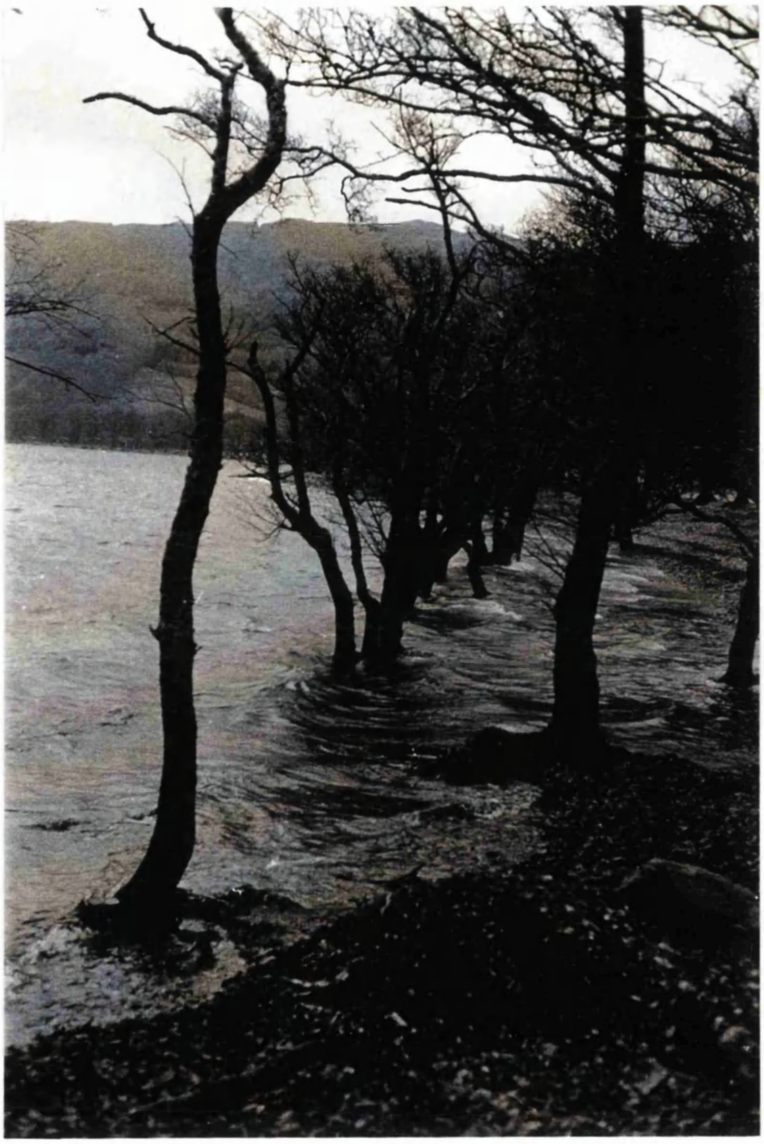

Frontispiece: Waves and high water levels at Milarrochy Bay January 1994.

CONTENTS

3.3 Investigating the shore zone ... 64
3.3.1 Historical evidence for shore zone change ... 64
3.3.2 The contemporary shore zone ... 65

Chapter 6

ABSTRACT

Lake waves and gravel beach variation, Loch Lomond Scotland.

Keywords: beach variation; gravel beaches; lake beaches; waves; sediment budget; restricted fetch..

Beaches respond morphologically to changes in wave conditions, water level and sediment supply. As coastal sediment stores, which reflect the terrestrial hydrological process balance, beaches are very sensitive to environmental change. However, controls on beach variability are not yet fully understood. In comparison to sand or mixed sand/gravel beaches, gravel beach response to environmental changes is muted. Low-energy gravel beach adjustments to external controls remain poorly understood. This research investigates gravel beach variation within a relatively low energy upland lake environment in mid-high latitudes (Loch Lomond).

To assess the nature of the lake wave climate, waves were recorded throughout 1994 and statistical and spectral analysis performed. The wave climate is distinctive, characterised by small amplitude, high frequency waves and periods of calm. Water levels fluctuate and showed clear seasonal trends with bi-annual periods of rapid rise/fall. Water levels are a fundamental control on beach variability, both in rates of fluctuation and in that they provide the underlying control on the effects of waves.

The research was largely field-based and gravel beach variability was examined with respect to morphological and sedimentological change and sediment budgets for two beaches were calculated. Fluvial sediment delivery was modelled from peak monthly stage. Cliff recession and beach morphology were surveyed to show highly variable longshore beach characteristics which are closely related to beach elevation, exposure and sediment supply. Sections of beach represented by individual profiles type showed profile types may persist from month to month. Sedimentology was examined for the sub-aerial and sub-aqueous beach into the offshore. Cross beach offshore fining was observed, with a clear abrupt limit to coarse sediment in the nearshore.

Fluvial discharge exerts a significant control on beach development as it affects sediment entrainment and delivery, distribution and storage within the beach. Water level is also significant in sediment redistribution. The deltas are major sediment stores within the beach sediment budgets often for long time periods (years). At high water levels deltaic sediments are often below wave base and are therefore not entrained and transported. This limits sediment availability for beach morphological readjustment and shore defence.

This research is important for the understanding of sediment-poor, low energy beach behaviour and response to changing environmental conditions. The research has implications for modelling lake gravel beach sediment transport and storage mechanisms. It also highlights the need for appropriate management strategies for lake coastal environments.

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LIST OF FIGURES

Chapter 5

Chapter 6

LIST OF TABLES

LIST OF PLATES

Chapter 5

LIST OF APPENDICES

Chapter 1 INTRODUCTION

Beaches respond morphologically to changes in wave conditions, water level and sediment supply, but gravel beach response is muted in comparison to sand or mixed sand/gravel beaches (Dingler 1981; Kirk 1975, 1980). Investigation of the parameters influencing change, and the scales over which that change occurs is necessary to understand beach variability.

Beaches as sediment stores at coastal margins reflect the terrestrial-hydrological process balance, and are very sensitive to environmental changes. Significant controls on beaches (e.g. tides, winds, waves. water levels, currents) are not yet fully understood (e.g. Pirazzoli 1989; Komar 1991; Carter 1992; French 1993). Beaches experiencing a reduced sediment supply are recessional, whereas those with a surplus of sediment are accretional and often progradational (e.g. Clayton 1980). Water level rise also causes beaches to retreat (e.g. Hands 1979; Bruun 1962; Dean and Maurmeyer 1983), which is a specific response to environmental conditions.

The precise mechanisms and time-scales governing coastal change are complicated by a number of factors, not least by the range of beach types. Gravel beaches range from the sediment rich (e.g. Hardy 1964; Carr 1969; Bluck 1967; Fisher 1984; Forbes *et al.* 1995) to ones with low sediment supply rates (e.g. Hansom 1979) and are subject to a wide variety of wave conditions. Universal calibration of beach response to changes in environmental conditions is difficult because of the many interacting parameters and the variety of techniques employed in the evaluation of net sediment balance. Whilst beach behaviour in high energy, gravel beaches (e.g. Carter and Orford 1984; Orford 1987; Forbes *et al.* 1995) has been researched over a variety of time-scales in recent years, lower energy regimes have been largely neglected. Gravel-rich barrier island beaches subject to high energy conditions are known to evolve slowly, punctuated by episodes of rapid reorganisation (at length scales of 1-10 km and time-scales of 10-100 years) (Forbes *et al.* 1995), yet lower energy gravel beach adjustments to external controls remain poorly understood. Overall, cycles of gravel beach development and change are far from clear, due largely to the difficulties of field-measuring and predicting imperfectly understood gravel transport and sedimentation. This research aims to investigate *gravel beach* variation within the relatively low energy *lake* environment. Beach variation within spatial and temporal controls is addressed, with particular reference to wave conditions.

1.1 Lake environments

In lakes, process energy operates at a generally lower level than marine systems, and this allows easier, higher resolution definition of change. As a result, lakes provide a good research environment. As most are non-tidal, this aids identification of controls on beach variability. However, as some lake systems undergo periods of rapid water level change, this provides an opportunity for process-response analysis. For the most part, lakes provide a natural analogue for marine systems leading to a greater understanding of low energy beach dynamics. However the scale of individual lakes varies widely from ponds to inland seas (Table 1.1), thus their energy systems show considerable variation which can be reflected in coastal dynamics (Carter 1988). Small lakes have different sedimentation patterns reflecting the lower energy hydrological regime (Sly 1978). The disadvantage of the lake-marine analogue is that generally lower sediment supplies and re-working of that sediment may give more complex sedimentation patterns than at the marine coast where greater supplies are available. Apart from research on large lakes e.g. the USA/Canadian Great Lakes (e.g. Davidson-Arnott 1979; Hands 1979, 1983) and Swedish lakes (e.g. Norrman 1964) which are closer to marine systems in size, there is a dearth of lake beach data (Alrousal 1986) especially in the UK, making a case for further investigation.

1.2 Aims of the research

This research aims to investigate lake coastal zone variation via:

1. defining the wave climate (water levels constitute part of this),
2. determining the nature of shore zone variability,
3. identifying relationships between nearshore and shore processes and forms, and
4. calculating an annual beach sediment budget.

These are outline aims and further explanation is given in chapter 2.

1.3 The research area

To investigate gravel beach variability an accessible, relatively low-energy lake field-site undergoing relatively rapid morphological change (<10 years) was required. As such coastal variability had been identified at Loch Lomond (e.g. Tivy 1980; Pender 1991; Dickinson 1991) it was selected for this research (refer to section 3.1.1). The upland catchment is in mid-high latitudes, approximately 56^0 3 N 4^0 28 W. The Loch (lake) lies 28 km to the north-west of Glasgow, Scotland (Fig. 1.1). It is the largest freshwater lake in Great Britain 33 km long and 7 km wide at its' widest point and in excess of 150 m deep in places. The Highland Boundary Fault traverses the Basin which is characterised by both extensive glacial erosion and deposition throughout the area (Rose 1981). The Loch extends from low lying wetland in the south, to the Highlands in the north (Fig. 1.2). It occupies an overdeepened basin with rocky cliff shorelines and mountains exceeding 900 m in the north. Further south the shore is characterised by numerous small bays with rocky headlands and gravel beaches and the wetland Endrick marshes.

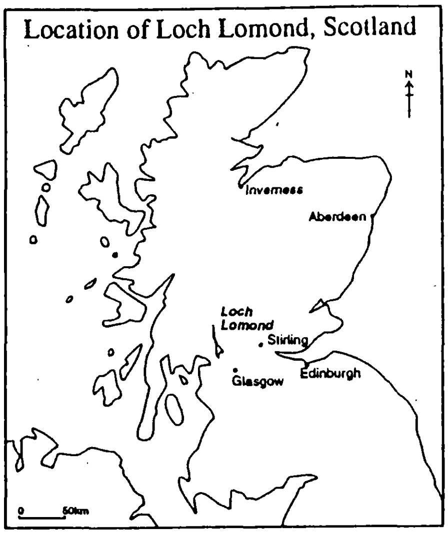


Fig. 1.1 Location of Loch Lomond Scotland

Lake Name	**Length (km)**	**Width (km)**
Black Sea	1100	600
Superior	563	483
Huron	331	294
Michigan	494	190
Tanganyika	676	48
Erie	338	92
Malawi	579	80
Chad	224	144
Vattern	137	19
St Clair	42	39
Geneva	72	13
Loch Lomond	33	7
Windermere	16	1.5

Table 1.1 Selected examples of salt and freshwater lake sizes
Within the international context, Loch Lomond is a relatively small lake with a relatively low energy regime.
(Sources: Hutchison 1957; Sly 1978)

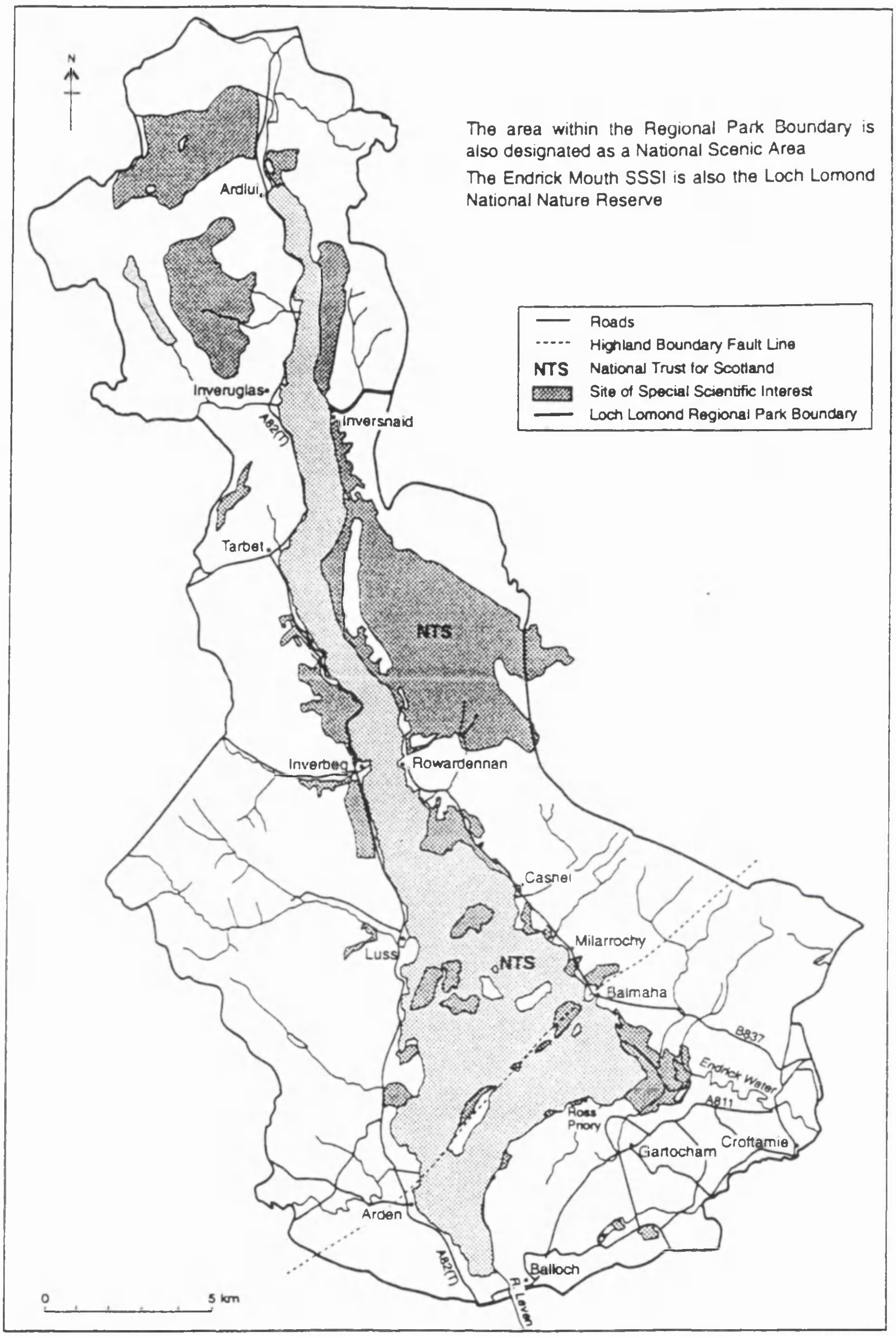


Fig. 1.2 The Loch Lomond Catchment.

Twenty sites within the catchment are Sites of Special Scientific Interest (SSSIs) for geological and biological reasons. 253 hectares are on the RAMSAR List (1971) as wetland areas for international conservation. In 1980 much of the area was given a National Scenic Area designation. The catchment is managed by the Loch Lomond Regional Park Authority which is funded by local authorities and the Scottish Office.

1.4 Outline of thesis

1.4.1 Approach to the research

This work is focused on field-based investigations into coastal processes and forms: lake waves, water levels and beach variability supported by laboratory analysis. The study is based on research at the meso-scale, over 1 year (1994). After field data collection, data were then analysed and described and the main trends highlighted.

1.4.2 Thesis structure

This section outlines how the research is presented in this thesis.

Chapter 2 provides a selective review of the geomorphological coastal literature (marine and lacustrine) relevant to the aims of this research. The nomenclature used is explained and the theoretical background and approaches to research are described. The significance of the scale of the lake environment is highlighted. Ascertaining lake shore zone sensitivity to nearshore and shoreline processes is fundamental to the approach. Gaps in the literature are highlighted and the context and contribution of this research is explained. The spatial limits of the research units are defined to be the nearshore and shore zones together with the components of the coastal system.

Chapter 3 details the methods used for data collection. The methods used to measure and analyse variables in the nearshore and shore zones are explained and their limitations recorded.

Chapters 4 and 5 present the results and analysis of the research. Chapter 4 reports the findings from the nearshore zone investigations, and chapter 5 the findings from the shore investigations. The split between them being purely for ease of handling. These chapters include the wave climate results for 1994, water level variation, sedimentological variation (temporal and spatial) and beach morphological change.

Chapter 6 is devoted to a discussion of the results. The strengths and weaknesses of the investigations and the implications of the findings are discussed. The contribution of the research at Loch Lomond is set in the context of the broader international context of lacustrine and marine coastal geomorphology. The overall research findings are summarised and evaluated, the wider implications of the research discussed and suggestions for further research are presented.

Chapter 7 is a short chapter presenting the main conclusions and the contribution of the work.

Chapter 2 LITERATURE REVIEW

2.0 Introduction and rationale

This chapter provides a selective review of the lacustrine and marine coastal literature, in relation to the aims introduced in chapter 1. The present state of knowledge is reviewed and approaches to geomorphological investigation are discussed.

Lakes have a significant global distribution, the largest 29 freshwater lakes alone comprising over 573 445 km^2 of the earth's surface. They form integral parts of drainage systems for water storage and act as sediment filters and sinks. Within the drainage basin they represent relatively 'closed' natural systems. Although geologically transitory, the relatively low energy systems of most lakes, and shorter response times to environmental change make them particularly suitable for monitoring and process research. Lakes are of environmental and economic importance as reservoirs, as environments supporting ecosystems providing food, and for recreational activity.

The lake environment and the processes acting within it are influenced by the basin size and form, orientation and climatic conditions (Boyce 1974; Brunsden and Doornkamp 1977; Sly 1978). Compared to oceans, the small size of most lakes restricts the generation and development of long period wind generated waves. This keeps energy levels much lower than those of marine systems. Consequently sorted coarse sands and gravels tend to be restricted to lake coastal regions of shallower water, where wave base affects their transportation. Coastal responses to process changes are likely to show different scales and types of response where energy regimes are low (Carter 1988; Sly 1995). Such responses are reflected in beach sediments, shore erosion or progradation. To date in small lakes, these changes are largely undocumented. As the lake coast is a sensitive indicator of environmental change, coastal variability provides the focus for this research.

The external characteristics of lakes which determine their response to climatic factors are mean and maximum depth, fetch, basin shape, exposure to wind and geology. Lakes also respond in a variety of ways to other controls such as air temperature, humidity, radiation, air stability and for frozen lakes to ice thickness, albedo and snow depth (Zenkovitch 1967; Ragotzkie 1978). All these characteristics affect the thermal regime of a lake and this affects primarily fine sediment transport and deposition. Thermal stratification with seasonal mixing depends on climatic conditions. A temperate to cold lake such as Loch Lomond exhibits some stratification, with spatial differences in duration and extent (Slack 1957). In Summer, with the increase in solar radiation, the lake water stratifies into an upper layer of relatively uniformly warm water, the epilimnion, which develops its own circulation structures.

Many of the processes acting on lake shores are similar to those of sea coasts, as illustrated by Norrman (1964) at Lake Vattern, Sweden and Hands (1982) and Davidson-Arnott (1989) in the Great Lakes. However there are differences as most lakes are not tidal and therefore have limited or absent littoral zones. In general, because of their smaller size, lakes are very responsive to variations in energy input and this is reflected in shore behaviour. As short fetches limit swell wave development, wave generation can occur right up to the shore. Lake waves can be unstable and spilling over wide surf zones (Carter 1988). Lake systems are essentially closed or nearly closed (Hutchinson 1957; Brunsden *et al.* 1977) such that drainage basins constantly infill with sediment. As the ratio between land drainage and lake area tends to be high, lake sedimentation rates can be significantly higher than marine rates (Sly 1978). All these factors point towards distinct characteristics which warrant separate consideration of lake coasts.

2.1 The lake coastal environment

This research examines the lake coastal environment from a geomorphological perspective, i.e. the coastal zone landforms and their sensitivity. Fig. 2.1 illustrates the extent of the lake coastal area (after CERC 1984; Carter1988; Goudie *et. al.* 1990). Definitions of the main features of this figure are:

Backshore The area of beach, (and cliff and vegetation, where present), landwards of the high water mark. The area is characterised on gravel beaches by one or more storm ridges. On a sandy beach, by a flat or gently sloping landwards area.

Beach The zone of unconsolidated sediment at the margin between land and water, usually of sand size or above. The sediment is derived from rivers or other sources, and moved by waves and currents to form a beach.

Berm A beach ridge, usually referring to the large back ridge.

Breaker zone The area in the nearshore where waves break. The extent of this area depends on the magnitude of the waves.

Foreshore The area of beach 'lakewards' of the high water mark. Foreshore zones can show different configurations and slopes depending on beach sediments and wave energies. A step is often present, caused by the final wave plunge before breaking.

Offshore Zone The deepwater area 'lakewards' of the beach, extending out from the breaker zone.

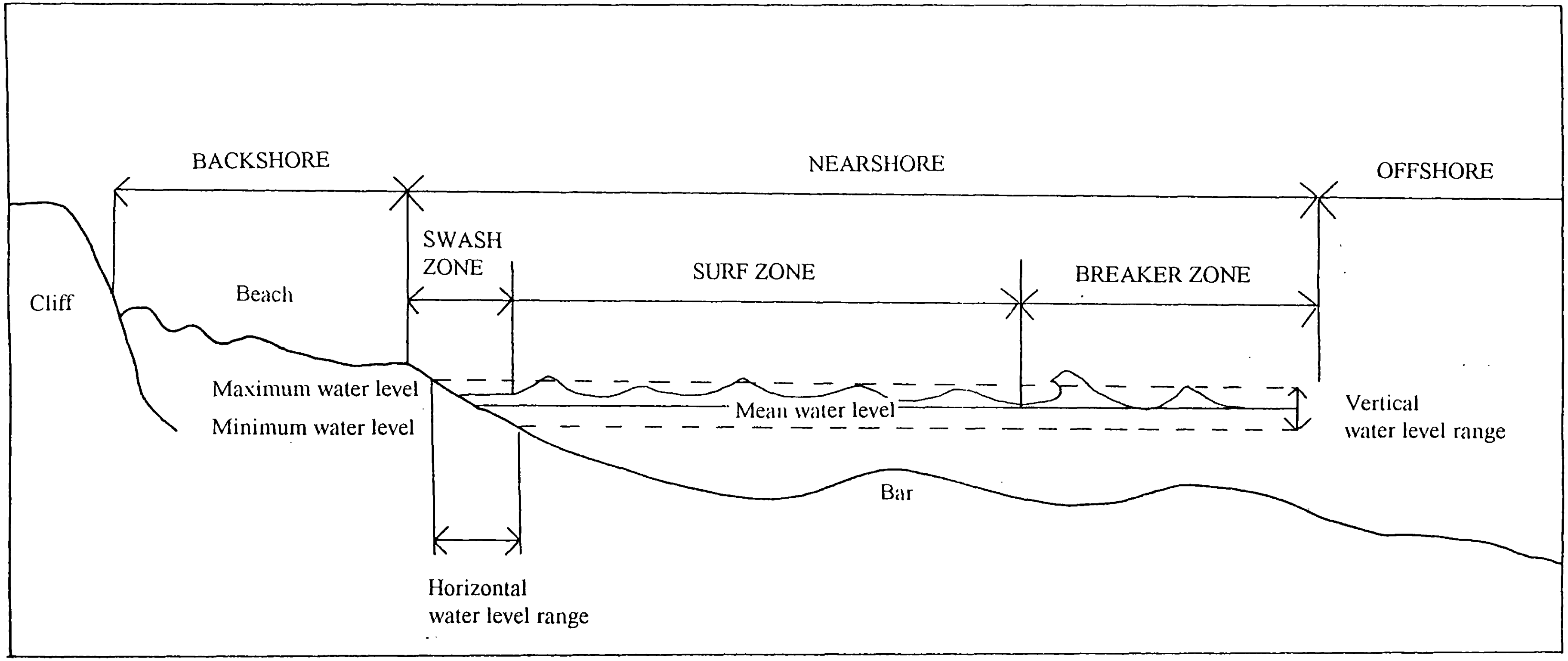


Fig. 2.1 The lake coastal zone: see text for definitions (adapted from CERC 1984)

Surf zone is the area in the nearshore between the breaker and swash zones, characterised by broken waves moving towards the sub-aerial beach. Longshore currents develop in this area.

Swash zone In a marine environment, the area of beach between high and low water marks, over which waves break. It is the area of the shore which experiences swash and backwash of waves. In a lake this area of beach occurs between maximum and minimum water levels and its' extent and position depends on wave and water level conditions. This is sometimes referred to as the littoral zone.

The coastal environment is continually modified by the interplay of the various processes and components. The energy inputs are principally from waves, and beach forming sediments can be from rivers, glaciers, from cliffs or shore platform erosion and from biological sources such as leaf litter. It can be helpful to consider coastal dynamics within the framework of a system, with inputs, throughputs and outputs and a variety of feedbacks. Within a geological framework, variation in process energies causes variation within the shore zone. Figure 2.2 illustrates the coastal system with the inter-linking processes and variables. This diagram includes sediments and energy sources but not morphology. Alternative system representations are possible.

2.2 Coastal classification and scale

Many of the differences between marine and lacustrine coasts may be dependent on the different process scales involved. To place the lake coast in the broader perspective, brief reference to marine coastal classifications will be made. Hansom (1988) identifies three main groups of coast classification based on variation in: 1) sea/water level; 2) structure; 3) processes. Sea level changes have led to the definition of emergent and submerging coasts (e.g. barrier islands or fjords). Structural variation definitions of coasts relate to plate tectonic theory. Process classifications are related to wave energy modification of coastal features. In many ways the latter type of classification is the most helpful in understanding lake coastal systems because it is the energy variable, which has the most significant effect on coastal behaviour.

Scale is an important parameter in coastal geomorphology (Schwartz 1968; Pethick 1984; Davidson-Arnott 1989) and relationships between process variables may vary temporally and spatially. Large scale change (temporal or spatial) may be a combination of different processes at smaller scales. Schumm and Lichty (1965) describe cyclic time (usually 10^6 years) graded time (usually 10^1-10^4) years and steady time (usually 10^{-1} year i.e. approximately a month) in geomorphology. Relationships between processes which exist in the long-term (e.g. in graded

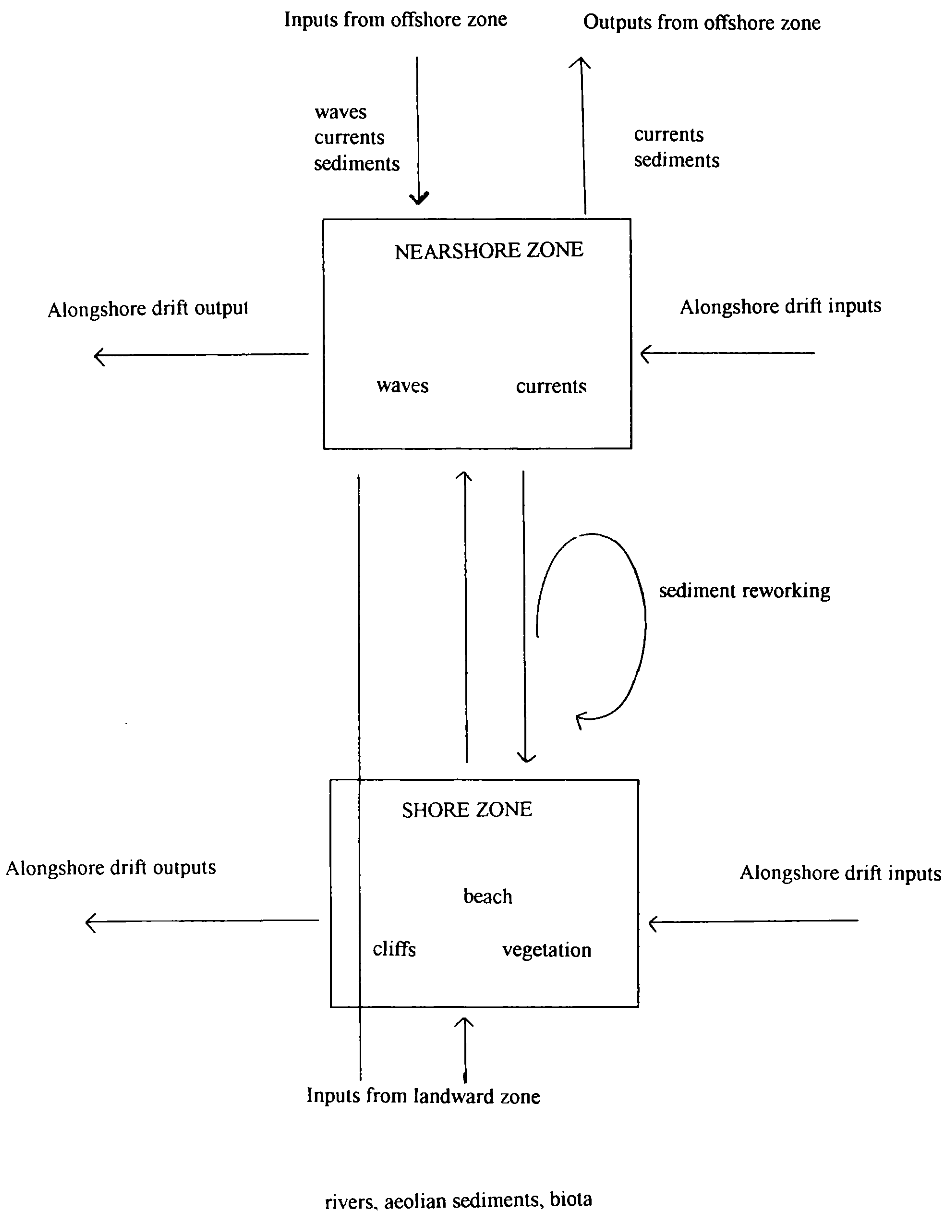


Fig. 2.2 A simple coastal system:
showing sediment transfer and energy sources in the shore and nearshore zones

time) may not be detectable in the short term (steady time). An example is provided by Fig. 2.3 which shows hypothetical scales of water level variation. When viewed at different temporal scales, the pattern may be quite different. The scale at which coastal processes are measured is important for both understanding and interpretation. Throughout this work reference will be made to the temporal and spatial scale of study and the implications of this are discussed in section 6.5.1.

2.3 Coastal Processes

This section comprises a review of nearshore and shore coastal processes. These are significant in the characterisation of the coastal area. Definition of process controls (e.g. waves and water levels), scales of those controls and thresholds which cause significant system responses are important for understanding coastal zone operation. Beach behaviour, sediment transport and inter-linkages between various variables within the coastal system are discussed.

2.3.1 Waves and wave theory

Waves are identified as the principle source of energy affecting the coast (e.g. Kinsman 1965; May and Tanner 1973, 1975; Davidson-Arnott and Pollard 1980), and therefore are fundamental to investigations of shore and nearshore dynamics. This section introduces wave hydrodynamics and wave theory in some detail, as waves constitute an important part of this research.

Most deep water waves form by gravitational forces of the sun, but the moon, planetry movement and earthquakes can also cause waves. A wave forms when the water surface is disturbed, (Darbyshire 1952). Energy and momentum, (as wave form) are transferred through the water mass. Wave energy is dispersed by radial, inertial and convective means (Carter 1988), but most is not lost until waves enter shallower water and are affected by bathymmetry. In lakes most waves are wind generated. Although a relationship between wind and waves was identified by Aristotle (384-322 BC), details of this relationship remains unclear. Essentially wind friction and pressure differences cause waves to generate (e.g. Jeffreys 1925; Darbyshire 1953, Kinsman 1965).

Waves can be described in a variety of ways. Munk (1951) classified scales of waves (Fig. 2.4). Geometrically waves can be variously described: e.g. height, peak to trough (H); amplitude (H/2); wavelength (L). Process definitions include period, (T), the time in seconds for successive wave crests to pass a fixed point; frequency (1/T); celerity or wave velocity (C); wave energy (E). Wave parameters of an idealised two-dimensional wave are illustrated by Fig. 2.5.

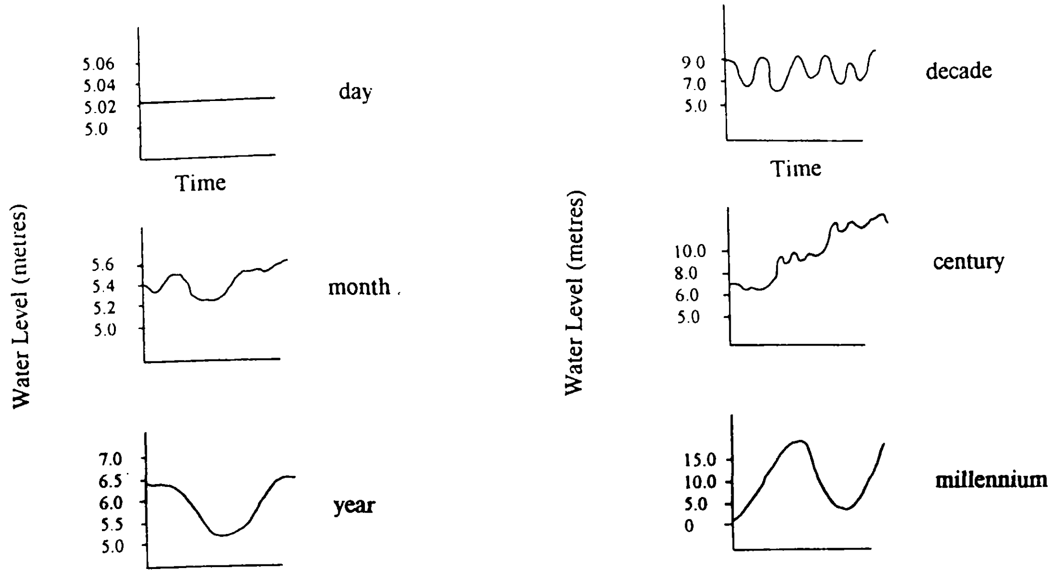


Fig. 2.3 Scales of environmental change

For example: water level. When water level change is viewed over different temporal scales, the range and frequency of that change varies. Variation evident at one scale may be masked at another. The scale at which phenomena are measured is therefore significant.

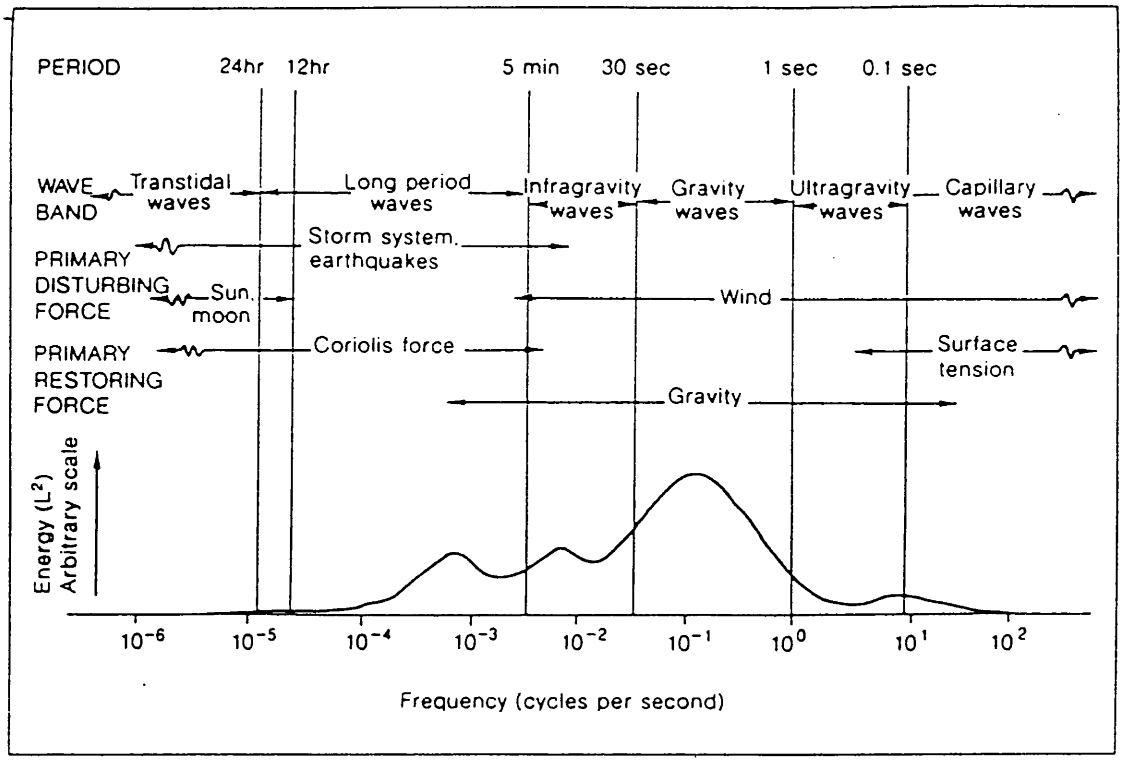


Fig. 2.4 Classification of scales of waves (after Munk 1951; Kinsmnan 1965). Note the most frequently occurring gravity waves in the coastal environment.

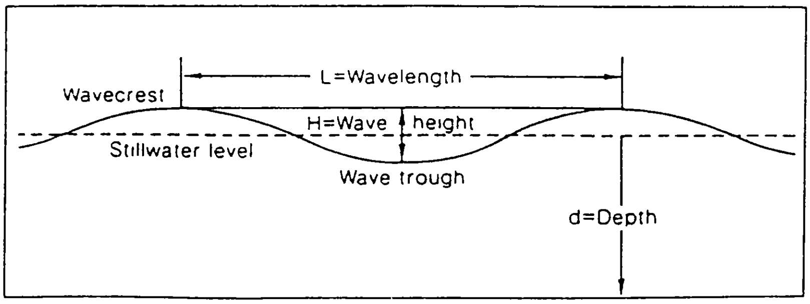


Fig. 2.5 Wave parameters

Waves are highly variable in type, their characteristics being affected by wind velocity and duration, as well as fetch (the distance over which winds blow). In lakes, fetch is the main limiting factor in wave development which is a primary difference from marine wave climates, which have much longer distances of open water over which waves can develop. Where the fetch is long enough, a condition of wave equilibrium develops. This is known as a 'fully developed sea,' where theoretically wave sizes should remain constant. In reality this rarely occurs as wind conditions are highly variable. However, a fully developed sea with a range of wave sizes or *wave field* is more common (Bearman 1989). Gravity waves can be categorised into two states: seas and swell. 'Seas' are when waves are in the generating area and are affected by wind. Swell is when waves are outwith the generating area and no longer subject to significant wind action (CERC 1984).

The following section introduces a brief summary of wave theory which is important for selecting appropriate wave recording methods and understanding nearshore processes. Fuller accounts are given by Tucker (1964), Kinsman (1965), CERC (1978) and Komar (1976). Pethick (1984) describes three classical theories, none of which, individually, fully explains wave dynamics.

1. Airy (1845) (or Linear, or Small amplitude) wave theory, which applies to deep water waves.

2. Stokes' (1880) wave theory, which is the most widely applicable to all water depths, but is highly complex.
3. Solitary wave theory which applies to shallow water waves.

Airy wave theory is reliable descriptor of most waves. It describes oscillatory or nearly oscillatory wave motion (Fig. 2.6). The movement of wave form across the water surface causes the orbital rotation of water particles beneath it, which decreases with depth beneath the surface. Airy wave theory predicts the relationship between the orbital diameter and wave height. This is particularly important when examining methods of wave recording. The relationships between wave parameters are derived from Airy wave theory and assume deep water conditions. An important relationship is between wave length and period:

$$L = \frac{g.T^2}{2\pi} \,.\, r \tag{2.1}$$

$$r = tanh \frac{2\pi d}{L} \tag{2.1a}$$

where L = wave length; h = wave height (m); g = acceleration due to gravity (m s^{-2}); T = wave period (secs.); d = water depth (m) ; r = the complex variable, affected by water depth.
A simpler and commonly used form of this can be derived for deep water (eq. 2.1b). Where for deep water ($d>>L$) if, and only if r tends towards 1, eq. 2.1a becomes 2.1b.

$$L = 1.56\,T^2 \qquad (2.1b)$$

The energy of a wave per unit wave crest, can be described by the following equation:

$$E \text{ (energy)} = 1/8 \rho g H^2 \qquad (2.2)$$

where ρ = water density (kg m^{-3}); H = wave height (m).
This combines potential energy (due to wave deformation above still water level) with kinetic energy due to orbital particle movement below the wave form. The rate at which this energy moves is related to the velocity (celerity) of the wave form (Pethick 1984). Group wave behaviour is different from single wave behaviour, as within a group individual waves move theoretically twice as fast as the group. Group wave velocity is an expression of wave energy transfer (P, J m sec^{-1}) through the group and expressed as:

$$P = ECn \qquad (2.3)$$

where E = energy (J); Cn = group wave velocity (m s^{-1})
This is essentially a description of the power of a group of waves.

Wave steepness (S) is given by the ratio

$$S = H_0/L_0. \qquad (2.4)$$

where $_0$ denotes deep water, $(d > L_0/4)$.
The steepness of waves affects how they break on the shore and this affects sedimentation and morphology at the shore. Waves steeper than 0.14 become unstable and collapse. Waves steepen on entering shallow water on approach to the shore until they become unstable and break (at the 'break point'). Three types of breaker are identified: surging, spilling, and plunging (Galvin 1972). Surging breakers occur close to steep beaches where waves have low steepness. The wave peaks as if to break, but the base of the wave surges up-beach leaving the crest to collapse. Spilling breakers tend to occur some distance from the shore on flat beaches, producing a foaming surf band. Plunging breakers occur on steep beaches as the beach gradient induces

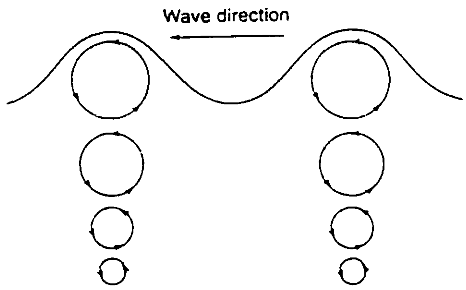


Fig. 2.6 Orbital movement of water beneath each passing wave crest. The size of the orbit decreases with depth.

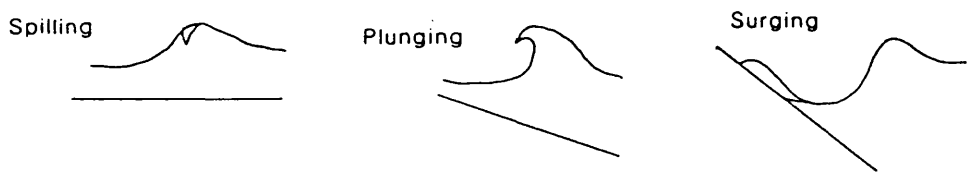


Fig. 2.7 Wave breaker types (after Galvin 1968; Clark 1979). These are associated with different beach steepnesses, spilling with flat beaches, plunging with steep beaches and surging with very steep beaches.

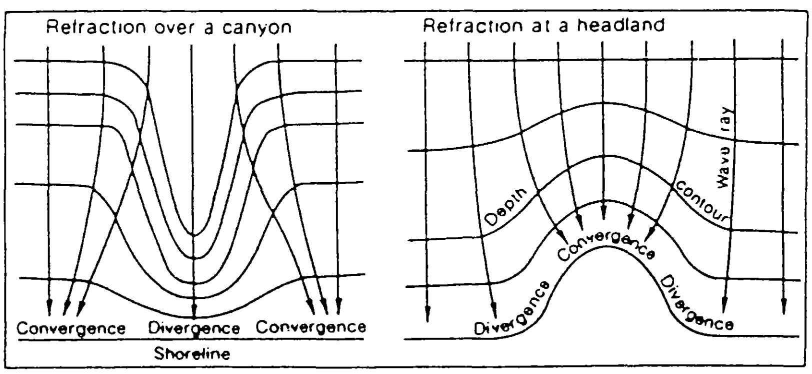


Fig. 2.8 Wave refraction showing divergence and convergence of wave orthogonals with varying bathymetry and shore plan.

plunging wave breaking (Fig: 2.7). Huntly and Bowen (1975) associate wave breaker types with beach steepness.

As incident waves enter shallow water they undergo transformations in response to changing bathymetry and the shoreline geometry. In any study of wave-beach interaction the behaviour of waves in the nearshore is critical to this understanding. Transformation of waves entering shallow water begins as minor 'bottom influences' take effect at water depths of approximately $L_0/20$. In shallow water, wave celerity is influenced by water depth rather than wave period and is given by

$$C = \sqrt{gd} \tag{2.5}$$

where d = water depth; g = acceleration due to gravity

As a wave enters shallow water, the leading edge travels at a slower velocity than the lakeward edge, causing a redistribution of energy, and causing the wave crest to bend or refract so that all parts of the wave crest are travelling at the same speed. The refracted wave crests either converge (focusing wave energy) or diverge (dispersing wave energy) on the shore. Thus wave refraction is significant for calculating wave energy at any point on the shore and hence establishing the potential for sediment movement. This provides a link between wave action and shoreline morphodynamics (CERC 1984; Pethick 1984; Viles and Spencer 1995).

Divergence or convergence of refracted waves reaching the shore produces a spatial variation of energy alongshore (Fig. 2.8). Komar (1976) describes potential alongshore power (P_L J m^{-1} s^{-1}) variation as:

$$P_L = ECn \sin \alpha \cos \alpha \tag{2.6}$$

where α is the angle the approaching wave crest makes with the shore; E = energy; Cn = group wave celerity or phase velocity. This is a useful relationship linking nearshore processes with potential shore modification.

Various methods for predicting the wave behaviour at the shoreline have been developed. These calculate wave refraction coefficients and plot incident wave rays (the line perpendicular to the direction of wave approach). From these wave power at the shore can be calculated. Furthermore using calculations based on sand transport rates (e.g. Pierson 1951; Bagnold 1963; Kinsman 1965; Komar and Inman 1970), longshore sediment transport rates can be determined. Examples of computer programmes for calculating wave refraction patterns on any given shore include: Abernethy *et. al.* (1977); WAVENRG, (May 1974); Genesis (Hanson and Kraus 1989). These are unsuitable for small lakes as they require larger swell waves. Wave refraction can be computed graphically for a whole range of wave sizes and frequencies using a template (e.g. King 1972; CERC 1977, 1984).

In this discussion, waves have generally been referred to individually or in small groups. Continuous wave records for even short periods of time provide large data sets. Statistical analyses and spectral analysis are two methods for analysis. Spectral analysis is useful both as an analytical tool and for predictive purposes. It involves converting data from the time to the frequency domain and determining the energy distribution of waves on a frequency basis. Naturally occurring waves do not have the regular and precise properties of regular sinusoidal waves. In order to describe the variance of the wave surface, wave spectra give the distribution of wave variance as a function of frequency.

The wave climate can be defined in terms of energy, the total energy being the sum of the energies of all waves (statistically this is proportional to the sum of the squares of the heights of all the waves), a measure of which is obtained by the area under the energy density spectrum (Fig. 2.9). Spectra can be described using the spectral width parameter (ε) which ranges between 0 and 1, where values closest to zero represent a regular monochromatic sea or sinusoidal, regular waves and higher values represent more mixed distributions of different wave heights and periods, closer to a fully developed sea (Tucker 1963; Draper 1967; Hardisty 1989). When ε is low the distribution of wave energy is Gaussian, and as ε increases the distributions tend toward Rayleigh distributions (Carter 1988) (Fig. 2.10).

Most published spectra are smoothed and have been derived from tank experiments with sinusoidal waves and the amount of field data in the literature remains relatively small (e.g. Chakrabarti 1987). The composite spectra which have been derived from field measurement are published as generalised models (e.g. Bretschneider 1959; Hasselmann *et al.*, 1973; Inoue 1967; CERC 1977; Pierson and Moskowitz 1964), to which any Loch Lomond wave results can be compared.

2.3.2 Wave recording methods

Wave recording methods can be divided into three categories: (1) below surface, usually pressure sensitive; (2) at the surface, direct water level or acceleration based; (3) above surface, remote recording. These have been developed largely for use on the open coast, or in wave tanks.

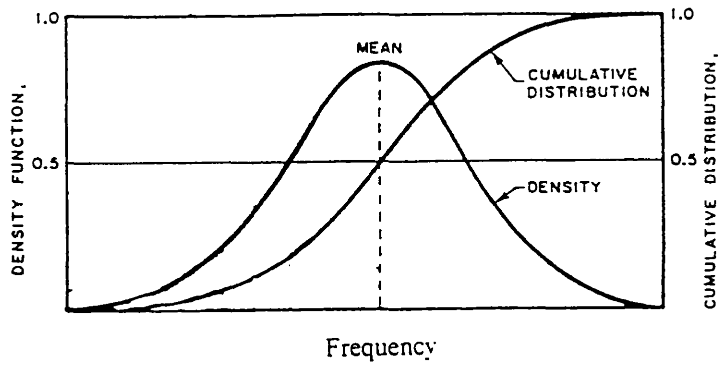


Fig. 2.9 Energy density spectrum:
The Gaussian (normal) probability distribution and the related cumulative distribution curve (adapted from Chakrabarti 1987)

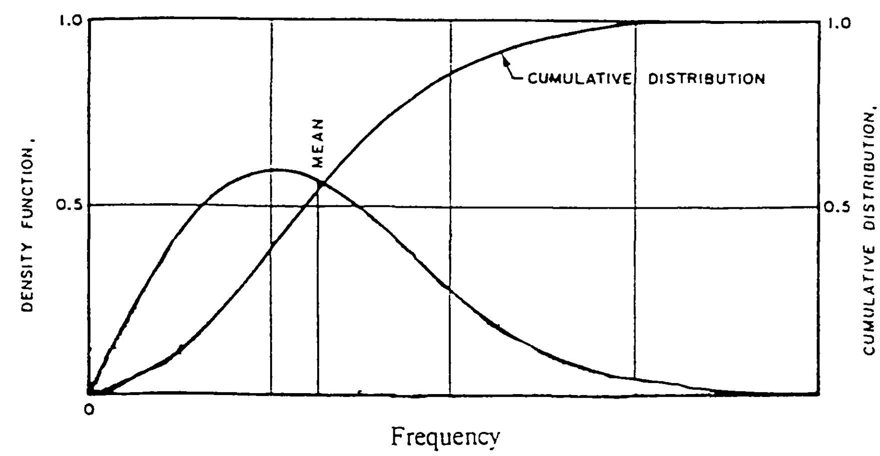


Fig. 2.10 Energy density spectrum:
The Rayleigh probability distribution and the related cumulative distribution curve (adapted from Chakrabarti 1987)

Sub-surface pressure gauges are widely used and have the advantages of being relatively cheap and less vulnerable to human interference. Pressure transducers, mounted on the sea bed or below the water surface, respond to changes in pressure due to the overlying water column. The pressure exerted by the passing wave attenuates with depth, and the degree of this attenuation varies with wave height and frequency (CERC 1976; Driver 1980; Hardisty 1989). This is a problem in an environment with a fluctuating water level, such as a lake or rising tide, but can be overcome with the deployment of a second transducer within a stilling well which enables continuous recording of the water depth and the calculation of appropriate correction factors. Earle and Bishop (1984) note that with increasing depth, the pressure attenuation for higher frequency waves is greater than for lower frequencies, and they provide pressure attenuation factors for different frequencies. However, there is a loss of resolution of wave form with transducers when they have to be designed to cope with considerable water level fluctuations. This problem is particularly acute in lakes where water level fluctuations can be two orders of magnitude greater than the wave heights of interest. Transducers also underestimate wave heights in the wave breaking zone by as much as 30% (Van Dorn 1978). Similar problems also apply to acoustic instruments. Mason (1985) used a pressure transducer to record waves off the Holderness coast, UK, but no correction factors were used on these records. A weakness of most wave recorders is that they do not record wave direction. Hardisty (1986) describes a low cost, directional wave recorder, using pressure transducers.

There are a number of methods which record waves at the surface. For long-term records automation of the observational method using calibrated staffs positioned in the surf zone (Ingle 1966) is required. Effective recording can be obtained from wave staffs based on capacitance, resistance or inductance. All consist of parallel wires immersed in water and are generally used in laboratory work. Liu and Katsaros (1982) compared results from thin wire gauges (resistance) with laser records, and found that staffs have a high degree of accuracy, but that different wire thicknesses produce different results. These methods have the significant advantage over sub-surface methods that they record the actual form of the waves at the surface and do not rely on empirical or theoretical corrections. Wave staffs are less suitable for high energy environments because of errors introduced by spray and the force of the waves. Wave force was measured successfully by a dynamometer, which operates by the compression of a spring induced by wave force, deployed at Benten-jima, Usujira, near Hakodate, Japan (Fuji 1988). Jetvic *et. al.* (1985) describe capacitance wave sensors for use on the Danube, but they were not field tested.

Offshore wave rider buoys record wave form from the heave of the buoy measured by an accelerometer in the buoy which produces an analogue voltage transmitted on a radio frequency (Earle and Bishop, 1984). Such a system is expensive but effective. However, on a lake, buoys are vulnerable to human interference and at the Loch Lomond site, radio interference from other users was expected. Error estimates for buoys vary from 3% (Driver 1980) to 5% (Earle and Bishop 1984). The sensitivity of these devices to small high frequency waves is unknown, but the technique is thought to be less suitable due to the known lag in the response of the accelerometer to small waves. Alrasoul (1986) successfully used two wave rider buoys at Loch Earn, Scotland, to monitor the lake wave climate, but few wave records were given. Examples of significant wave height ranged from 0.08-0.57 m with higher occurring more frequently in the Winter months.

Remote recording devices can be deployed above the water surface to measure waves. Aerial photographs, laser and radar imaging from aircraft show good resolution of wave crests and troughs, allowing wave length, period and direction to be measured. Stilwell and Pilon (1974) describe how single images can be Fourier analysed to produce directional wave spectra. Satellite based systems provide similar information with an error of 15%. Systems include GEOS-3, Geodynamics Experimental Ocean Satellite-3 and SEASAT with a synthetic aperture radar (SAR) (Earle and Bishop 1985). However, only short wave records can easily be collected, depending on the over-pass times of the remote sensing platform. The use of fixed position video-recording offers a solution to this, but has had limited application as yet. At Loch Lomond no wave recordings have been made.

2.3.3 Water level changes

In lakes, water level changes are generally associated with changes in catchment hydrological input or output, wind stress, storms or human regulation. On the marine coast, water tidal variation results in water level changes which vary the level at which waves can operate. On longer temporal scales, marine and lacustrine water level changes (at various scales) can also be associated with tectonic, eustatic and isostatic variation (e.g. Vail *et. al.* 1977; Lowe and Walker 1984; French 1993). Water level rise is usually associated with shore retreat, and the theoretical relationship of these variables underpins the development of much research. Bruun (1962) relates the concept of the equilibrium beach profile to rising sea level and shore erosion. It begins with the premise that an equilibrium profile is maintained with an optimium water depth in the nearshore zone. As the sea level rises, deposition must take place in the nearshore to re-establish the water depth. After a specific rise in sea level, the equilibrium beach profile occurring at SL1 (initial) is re-established in the same form at SL2. In the process, the profile extends further onshore (i.e. it is recessional). This erosion continues until the nearshore sediment bed is elevated by an offshore moving sediment volume, sufficient to re-establish a new nearshore depth equal to that existing under SL1. Thus the rise in nearshore bed elevation equals the rise in sea level. The rate of shoreline recession can be determined by the volume of sediment required to raise the nearshore bed to the required height (Fig. 2.11). A number of modifications have been made to the so-called Bruun Rule (e.g. Dubois 1975, 1992; Dean 1977, 1991; Bodge 1992). In modifying the Bruun Rule, Dubois (1992) tried to take account of bar and trough forms rather than the simple concave shore profile used by Bruun. In barrier island systems, Dubois proposes transgression of the shoreface, but without the depositional ramp assumed by Bruun. This work suggests that a fundamental assumption in Bruun's work may be false, that rising water level may not be linked to sediment transfer to the nearshore (the ramp).

The original assumptions of the Bruun Rule are (after Orford 1987): 1). initial and re-establishment profiles are in net equilibrium; 2). longshore sediment transport is absent or inputs and outputs balance one another; 3). eroded sediment carried to the nearshore does not go beyond a certain point, the 'closure depth'. The Bruun Rule (with modification), is important for interpreting coastal responses to water level rise. On a lake beach, if the Bruun Rule applies, rising water levels would be expected to cause shore recession, nearshore deposition and a re-established beach equilibrium.

Leatherman (1989) models shoreline response to sea level rise on sedimentary coasts and identifies the following reasons for shore erosion in response to sea level rise:

1). waves get closer to the shore before dissipating their energy by breaking;

2). deeper water decreases wave refraction and thus increases the capacity for long shore transport; and

3). with a higher water level, the wave and current erosion processes act further up the beach profile, causing readjustment of that profile.

Significant water level changes can result from wind tides (on-shore winds) and storm surges (surges associated with cyclonic activity). Davis and Fox (1972) note water level changes of several cm over a 48 hour period. With intense offshore winds, the opposite effect occurs and water levels are lowered. A further cause of water level variation in lakes is seiche action. This is where wind stress causes water to 'pile up' at the down-wind end of the lake. When the wind drops, the water surface oscillates at a constant frequency, the seiche period, but with decreasing

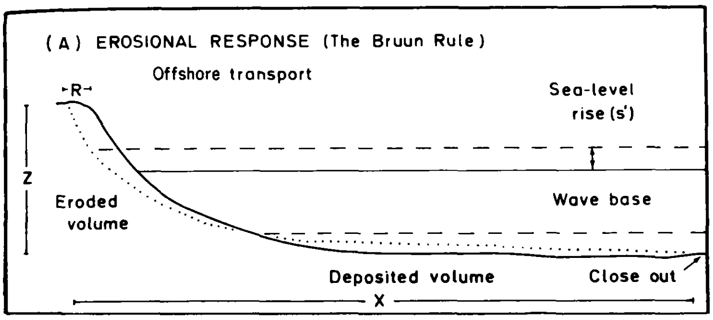


Fig. 2.11 The Bruun Rule (Bruun 1962; 1983)
R (shoreline erosion) = x . sea level rise (s') / profile depth (z)

amplitude. Carter (1988) reports that many lakes resonate at a number of seiche frequencies. On the shore, a seiche can cause considerable increases in water levels e.g 0.2 m at Lough Neagh, N. Ireland over 35-40 minutes. Carter describes associations with extending transverse bars 2-3 m with the rapid pulsed increase in water level.

At Loch Lomond, evidence of water level fluctuation is documented by Water Board records and Poodle (1979) suggests seiches may occur. Murphy *et. al.* (1995) describe vegetation degradation on the foreshores attributed to high water levels, sediment removal by waves and flooding. Field examples of lake shore retreat elsewhere associated with water level variation include Hands (1979) and Thompson and Baedke (1995), both working at Lake Michigan, US. Hands correlates long term increases in water levels with shore retreat on the mid-eastern shore and successfully applies the Bruun Rule. He identifies a time-lag of 'probably' 2 years between water level rise and shore response. Periods of water level fall in-between periods of increasing levels are associated with shore progradation giving an overall reduction in recession rates. Hands concludes that the mean water level is the principal factor for establishing a potential erosion rate for a given shore type. Davidson-Arnott (1989) in contrast suggests that coastal erosion and storm wave damage is independent of water level fluctuation in the long term. He examines the relationships between the forces acting on the shore and sediment available within a coastal system, relating shore response to local beach sediment budgets at lake Erie which seem to be independent of water level fluctuation. Beach response to water level change and to variation in sediment supply emerge as significant variables for investigation on lake beaches.

On the macro-temporal scale, shore displacement resulting from sea level rise during the Holocene as a result of glacial or isostatic activity is well documented (e.g. Price 1983; Comber 1993 Svensson 1991).

2.3.4 Beach variability and shore erosion

The beach is the accumulation of material (sand and shingle) along the coast (Monkhouse and Small 1978). The beach and/or cliff acts as a buffer to wave energy and reacts to change in process conditions. These may be traced through changes in beach morphology and sediment characteristics and transport over different spatial and temporal scales.

Beach response to changes in process conditions is reflected in two dimensions:-beach plan (overall alongshore shape) and beach profile (transects of beach morphology perpendicular to the waters edge). Profile forms are broadly determined by wave steepness and sediment size (Goudie *et. al.* 1994). Beach morphological change can be at the micro-scale of individual particle movement or a major readjustment in profile shape. Temporal variations in morphodynamics can be from less than a second as a wave breaks and transports sediment to hundreds or thousands of years as a shoreline form adjusts.

Studies of beach plan were often purely descriptive, classifying the coast into morphological types (e.g. Steers 1964; Davies 1972). Dolan (1971) developed coastal classifications further by linking shoreline form with processes at different timescales. He showed relationships with rhythmic topography such as cusps and crescentic beach forms and time. Davies (1980) recognised a relationship between beach form and wave crest orientation. He used the term *drift alignment* beaches to describe the oblique alignment of open beaches. The term *swash alignment* was applied to pocket beaches where sediment remained within the headlands. Beach width is important in coastal protection, where the sediment covers a sufficiently wide area to prevent waves reaching the back beach or shore platform, then it provides good protection (King 1972). An analytical model relating beach width (and therefore plan) to rates of change of sediment transport was developed by Komar (1973). May and Tanner (1973) constructed a predictive model of beach plan shape using the long-shore gradient of wave power which affects sediment transport and beach plan. This shows wave energy to be concentrated at headlands and dispersed in the adjacent bay, a finding applicable to Loch Lomond macro-scale morphology of bay and headland sequences.

The theoretical background to beach profile development is the idea that there is a beach equilibrium form for a given set of water and sediment conditions. Inman and Bagnold (1963) proposed that there is a position on the beach where net sediment transport equals zero i.e. inputs equal outputs. This leads to the assumption that the equilibrium concept can be equated with balance between the force from the internal friction between individual sediment particles and the force of gravity working tangentially on the sediment over the beach slope. Essentially the beach has an ideal state or 'equilibrium' to which it will return. This concept underpins much of coastal geomorphology, although Pilkey *et. al.* (1993) criticise the validity of the concept, particularly as used in coastal engineering, as assumptions associated with the equilibrium profile fail to be met in the real world (e.g. underlying geology does not play a role in determining profile shape; bi-directional movement of shoreface sediment does not occur; sediment is not lost beyond a closure depth; the equation is universally applied).

Measurement of erosion and deposition on the beach profile has provided the starting point for much coastal work, usually focusing on net surface change rather than vertical exchange and sorting of sediment. There is the general assumption that beaches behaves as units. Ingle (1966) identifies three causes of sediment movement inside the breakpoint on sand beaches which affect the profile. These are: 1) the force of the waves moving sediment offshore; 2) longshore currents transporting sediment alongshore; and 3) an increase in beach slope. Recent approaches include recognition of beach morphodynamic states closely linking process with form (Short 1979; Wright *et al.* 1979; Wright and Short 1983) shown in Fig. 2.12. The model shows the dissipative and reflective extremes with intermediate beach states. It recognises how antecedent conditions of a beach influence future stages of development. Dissipative (storm) beaches occur where incident waves break and lose much of their energy before reaching the beach face, where there is a wide surf zone. Reflective (swell) beaches are characterised by steep profiles where a large proportion of wave energy is reflected from the foreshore or front berm.

Changes in the shore zone are often recognised because of shore recession which has provided the impetus for much research. Shore erosion occurs in response to: 1) a rise in water levels; 2) a change in the wave climate; 3) a change in sediment supply; or 4) a combination of these (e.g. CERC 1977; Clayton 1980). CERC (1977, 1984) provide a comprehensive list of the causes of shore erosion: Table 2.1. Most of these could affect lake beaches, with waves, water level rise, and sediment supply being of particular significance (e.g. Hands 1979; Davidson-Arnott 1979).

In some environments, a significant contributor to beach sediments is material from cliff erosion. Cliff erosion has been related to rock hardness; structural weakness; coastline configuration; solubility of the cliff, cliff height; nature of wave attack; corrasion; attrition; corrosion by hydraulic action (King 1972); water table fluctuations; pressure change; human interference; freeze-thaw action; vegetational degradation followed by substrate erosion; wave action and from mass movement (slumping, landslips etc.) activated by seepage of water through the substrate (Shepard and Grant 1947; McGreal 1979; Sunamara 1983). The ability of the cliff to withstand pressures acting on it depends on composition or 'strength' in terms of cohesive, compressive and tensile properties (Carter 1988). Wave action has a dual role in both eroding cliffs and in the development of cliffs in unconsolidated materials. Cambers (1976) describes attrition of glacial diamicts in cliffs in North Norfolk and the removal of sediment by wave action during storm surges and Sunamara (1983) the development of cliff notches and their role in erosion. Overall, unconsolidated cliff retreat is primarily due to slope processes such as mass movement,

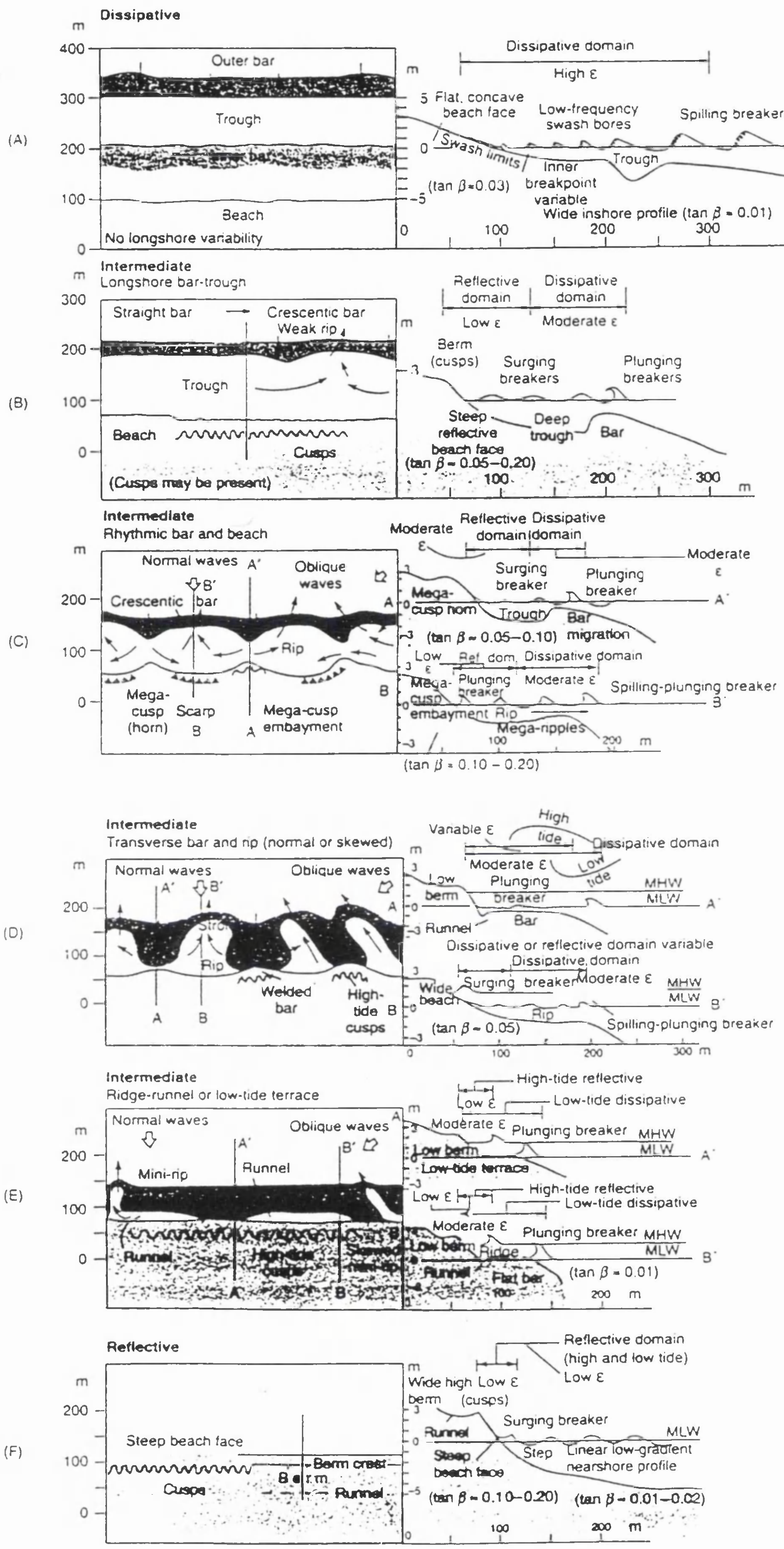


Fig. 2.12 Six morphodynamic beach states (after Wright and Short 1983)

The model was developed from field data at Narrabeen Beach, NSW, Australia (sand, micro-tidal, medium energy beach). It is useful for understanding relationships between process conditions and beach morphology. ε = surf scaling parameter (a relationship between wave height and beach gradient); β = beach gradient.

Table 2.1 Causes of Shore Erosion

Physical causes of shore erosion

1. Water level rise due to direct flooding, and resulting in beach profile adjustments to the higher level.
2. The combination of long and short waves because of a short sea.
3. Variability of sediment supply to the littoral zone.
4. Storm waves.
5. Wave and surge overwash depositing material shoreward of the beach.
6. Deflation.
7. Sediment transportation.
8. Beach sorting.

Human causes of shore erosion

1. Land subsidence because of removal of subsurface resources.
2. Interruption of material in transport, because of the presence of artificial structures for example.
3. Reduction of sediment supply to the littoral zone.
4. A concentration of wave energy on beaches, e.g. because of the presence of sea walls.
5. An increase in water level variation, e.g. by harbour dredging or the dredging of navigational channels.
6. Where there is a change in natural coastal protection e.g. the levelling of dunes or beach ridges.
7. The removal of beach material.

(Adapted from CERC 1977, 1984).

sometimes as a result of catchment land-use change, and wave action are related to highly erodable soil types.

An important model of cohesive shoreline evolution was developed by Davidson-Arnott (1989) based on work by Sunamara (1983) and Davidson-Arnott (1986), (Fig. 2.13). The model constitutes two sub-systems, one affecting cliff toe and upper beach, the other, the lower beach and the nearshore zone. Sub-aerial processes which operate on the cliff face (slumping, sheetwash etc.) have little affect on the toe erosion and dynamic equilibrium that develops (other than delivering sediment). The erosion rate of each sub-system is a balance between processes which cause erosion and those which resist or reduce erosion. At Loch Lomond causes of cliff erosion have been attributed to recent water level rises (e.g. Scott-Park 1979) wave action at high water levels (e.g. Tivy 1979; Dickinson and Pender 1990) but no quantitative analysis of erosion rates linked to water level rise has been made.

2.3.5. Coarse clastic beaches

As most Loch Lomond beaches are coarse clastic beaches, they are distinctive from sand or mixed sand and gravel beaches (e.g. Kirk 1989; Dingler 1981) in terms of response to waves, profile characteristics, sediment transport and evolution. The term coarse clastic beach is often applied in the literature to beaches comprising gravel, cobble or boulder sediment sizes. Such beaches are most common in high latitudes with sediment supplies of glacial diamicts. In the UK, coarse clastic beaches are primarily a result of onshore sediment forcing (of all sediment sizes) during rising relative sea levels of the Holocene maximum (Pethick 1984). These sediment supplies may no longer be available. Coarse clastic beaches formed in this way can exhibit morphological and sedimentological trends which are no longer active features but reflect former wave climates (e.g. Chesil Beach, Dorset; Carr and Blackley 1972). In the UK, and especially on the southern coasts, the gravel size fraction dominates the beaches. Most coarse clastic beaches contain a sand fraction matrix infill, and many a sand fringing low tide terrace (Orford 1987). Others are of biogenic origin such as an eroded reef (Bluck 1967; Matthews 1983), and in many lakes including Loch Lomond, leaf litter is the predominant biogenic contributor to sediments.

Coarse clastic beaches tend to be steeper than sand beaches, a function of sediment size, and therefore exhibit reflective characteristics. They are dominated by plunging breakers, have a limited or absent surf zone and strong longshore sediment transport in the swash zone. In shorelines with headland bay formation, gravel beaches and bi-directional sediment transport are

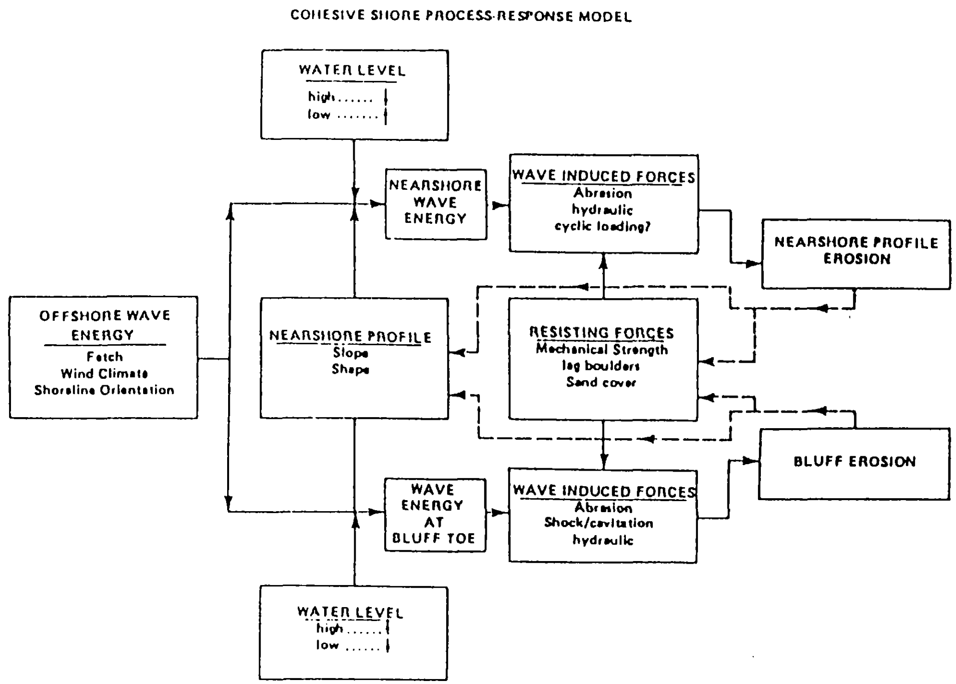


Fig. 2.13 Conceptual process-response model of a cohesive coast system. Note the feedback loops from nearshore and bluff erosion which act to modify the nearshore profile (after Davidson-Arnott 1989).

common. Orford and Carter (1984) observe that steep coarse clastic beaches encourage onshore sediment movement and crest build-up. There is often a 'rolling onshore' of the beach, especially in storms where sediment overtops the back berm. Altitudes of gravel ridges are associated with storm activity rather than actual water level. Profile development is often characterised by steps or ridges. A ridge invariably occurs just seaward of the breaker line. Sequences of shingle ridges often exist parallel with the water's edge, with younger ridges seawards of older ridges. Recurving at the distal ends of shingle ridges is common and has been associated with tidal eddies (Steers 1926), and enhanced by wave refraction (King 1972).

Sedimentological studies on coarse clastic beaches have largely been based on principles of size, sorting and shape (Krumbein 1941; Sneed and Folk 1958). Bluck (1967) and Orford (1975) identified distinctive sedimentology with cross-profile sorting, with disks occurring on the upper beach and rollers and spheres on the lower and some imbricate packing. Sediment characteristics can affect beach packing, beach steepness, wave run-up, and sediment transport.

Kirk (1975,1980) highlights distinctive characteristics in mixed sand-gravel beaches in New Zealand. Examination of these sand and gravel beaches shows the distinctiveness of bi-modal grain size distributions reflected in morphological characteristics. Whilst grain size provided a primary control on foreshore slope, sorting was important in determining actual slope. The best sorted sediments were associated with the steepest gradients, while zones of poor sorting tended to form plateaux. This is of particular significance in the examination of mixed sand-gravel beaches at Loch Lomond.

Davis (1972) describes development, modification and migration of ridges on lake beaches which is faster than in tidal environments where water level variation slows change, thus highlighting the different process scales in a lake environment. Normann (1964) investigated shore morphology and sedimentology of Lake Vattern, Sweden. He identified 4 zones of beach type on a mixed sand and gravel beach at Sandudden Ness across the profile. The foreshore sediments were well sorted sands, the surf zone had poorly sorted mixed sediments, the steeper slopes were silt-rich, the offshore zone was characterised by suspended load sediments. This work points to a close relationship between morphology and sedimentology. In the UK, Tivy (1980) classifies Scottish lake beaches (gravel or sand and gravel) as Line beaches (a more or less unbroken stretch of linear beach, Arc beaches (ones generally widest at the centre) and Fan beaches (one generally widest at the centre with an abrupt change of shoreline alignment towards the loch), but there is no critique of process-morphology and morphology-sedimentology relationships highlighting areas for further research.

2.3.6 Sediment transport

Waves, currents, river inflows and wind provide the main processes energies transporting sediment in the coastal zone. Sediment entrainment and transport is discussed in relation to delivery to the beach and transfer through the beach system. The coastal theoretical work is almost entirely devoted to sand transport although a number of studies have documented coarse clastic sediment transport in the field. This section briefly introduces the concepts of fluvial and beach sediment transport and field examples at a variety of scales. Fluvial theory is important for addressing the issue of sediment delivery and the coastal sediment transport theory underpins the variability of lake beaches.

Bedload in gravel dominated streams can be defined as sediment which moves by rolling, sliding or saltation, and is arbitarily defined as sediment > 2 mm in diameter (Richards 1982; Gomez 1991; Goudie 1994). The resistance or fluid force required to move a particle, shear stress τ, was defined for uniform flow in a wide channel by du Boys (1879) as:

$$\tau = \rho g h S \qquad (2.7)$$

where ρ is the density of water (kg m^{-3}) , g is acceleration due to gravity(ms^{-2}), h is mean depth (m) and S is slope.

With reference to the entrainment of a particle of size D_i, Shields (1936) defined a dimensionless shear stress as:

$$\tau^* = \frac{hS}{(S_s-1)\, D_i} \qquad (2.8)$$

where, τ^* is the ratio of forces acting to move a particle of diameter D_i and the forces keeping it at rest. (S_s-1) is the submerged sediment weight related to density $\left(= \frac{\rho s - \rho w}{\rho w} \right)$. Shields described the point at which sediment begins to move (incipient motion) as a critical dimensionless shear stress τ^*_c. For fully turbulent flows and uniform sediment size, Shields suggested a constant value of $\tau_c^* \approx 0.06$, implying that the stress required to move a particle is linearly proportional to it's diameter. The graph expressing Shields' parameter shows that the ratio drops with increasing grain size until $D_i \cong 0.1$ cm, then it rises to become constant at grain sizes greater than 0.6 cm. Shields concluded that incipient motion did not occur at critical shear stress values below 0.06. Other authors have shown the scatter inherent in Shields' diagram (e.g. Yalin and Karahan 1979).

Sediment grains *en masse* do not behave as individuals but exhibit bulk properties depending on mean grain size. Although mean grain size is often used, recent work (e.g. Limerinos 1970) suggests that sorting is critical and if a single grain size is used, a coarse percentile such as D_{84} is better. Sediment entrainment and transport depends on other variables including relative as well as absolute sediment size, packing, sorting and shape. Beach composition therefore has a significant effect on beach mobility and the development of morphological features.

Thoeretical and empirical research on detailed aspects of fluvial sediment transport is covered by a variety of authors. For example, Fenton and Abbott (1977) examined the effect of protrusion on critical stress for entrainment, and several authors have considered the formation of a coarse surface layer in response to gravel mobility (e.g. Parker and Klingeman 1982; Andrews and Parker 1987; Dietrich *et. al.* 1989). These serve to highlight the complexity of coarse clastic sediment transport processes. In the coastal literature, the relationship between entrainment velocities, current strength and slope has also been explored (e.g. Miller *et. al.* 1977).

On the coast, as waves are essentially periodic and unable to sustain steady flow, so are the modes of sediment transport. Normally the depth at which waves can entrain bottom sediments is determined by wave base calculations, typically half the wave height for sand transport (CERC 1984). The lake environment can be divided into wave dominated and deep water sedimentary systems, and here the focus is on the wave dominated system, within which shore-normal (perpendicular to the shore) and alongshore processes operate. A number of approaches to sediment transport have been adopted. Various field experiments tracing the movement of small samples of beach material (e.g. Kidson *et. al.* 1958; Kidson and Carr 1961; Mason 1985) have dominated the research. These experiments identify direction and rates of transport for various sediment sizes. Hardisty (1991) used passive acoustic sensors to demonstrate that gravel sediment attenuates with different frequencies of flow. Caldwell (1981, 1983) suggested that there is a direct relationship between clast size transport and wave dimension. There is however, debate over the classic view that larger clasts require more energy to move them and so are less mobile. Mason and Hansom (1989) state that fines within the sand and gravel move offshore leaving the coarse fraction onshore where energy is high. In sand and gravel mixtures, the sand is nearly always more mobile, unless it is buried. In poorly sorted gravels the relationship between size and mobility is more complex, and closer to 'equal mobility'. This means that the relationship between critical shear stress required to entrain a particle increases only slightly, if at all with increased grain diameter (Parker *et. al.* 1992; Andrews 1983; Ashworth and Ferguson 1989). A number of authors suggest that that larger clasts can travel further and faster than smaller ones and that selective entrainment occurs (e.g. Ashworth and Ferguson 1989; Werritty 1992). Once entrainment has occurred and particles are moving, within the surf and swash zones, sediment sorting occurs. Under the asymmetry of shoaling waves, differential sediment transport occurs, favouring onshore migration of larger particles and offshore movement of finer ones. This is offset to some extent by gravity, whereby downslope (offshore) transport occurs (Miller 1976). Thus sediment sorting takes place.

Equations for transport of individual grains developed by Inman and Bagnold (1963), provided the basis for much further work and modification (e.g. Allen 1970; Komar 1971, 1976; Tanner 1971; Komar 1976; Leeder 1982). One of the most widely used sediment transport equations is that of Komar and Inman (1970) which predicts potential sediment transport alongshore but it applies to sand (1mm) sediment transport so is of limited value on gravel beaches.

$$I_L = 0.77\,ECn\ \sin\alpha\,\cos\alpha \qquad (2.9)$$

where, I_L = potential alongshore sediment transport ($J^{-1}\,m^{-1}\,s^{-1}$); ECn = wave power (eq. 2.3); α = angle of breaking waves to the shore. This is used primarily for computing alongshore sediment transport after wave refraction.

Larger scale patterns of sediment transport in terms of cell circulation were recognised by Shepherd *et. al.* (1941) and developed by Shepherd and Inman (1950). The cell system involves slow onshore mass transport which is transformed into alongshore currents landward of the breaker zone. Rip currents, running offshore, are fed by these alongshore currents, thus transporting sediment within a 'cell'. Bowen and Inman (1966) identified cell circulation patterns at Point Arguello, California (Fig. 2.14). Various theories of cell circulation have been developed which identify sediment transport circulation patterns (e.g. May and Tanner 1973). On a coast with bay headland sequences (as at Loch Lomond) the headlands can act as physical barriers to sediment circulation. These ideas are developed with the concept of the sediment budget.

2.4 The concept of a sediment budget

Sediment budgets have been studied at a variety of temporal and spatial scales and resolutions (e.g. Mason 1985; de Ruig and Louisse 1991). A sediment budget or 'coastal cell' is an attempt

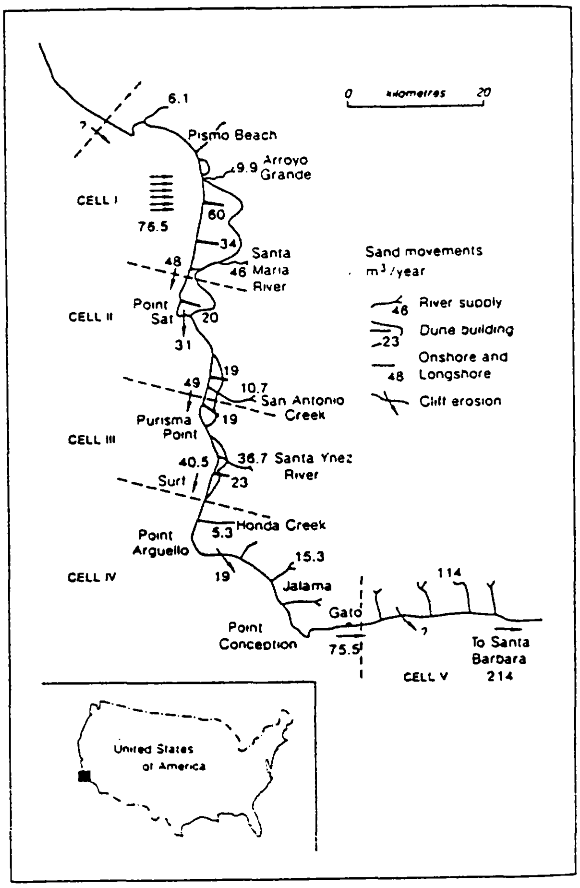


Fig. 2.14 A littoral sediment budget on the California Coast north of Santa Barbara. Cells delimiting sediment transfer are shown with estimates of sand volumes moved. (after Bowen and Inman 1966).

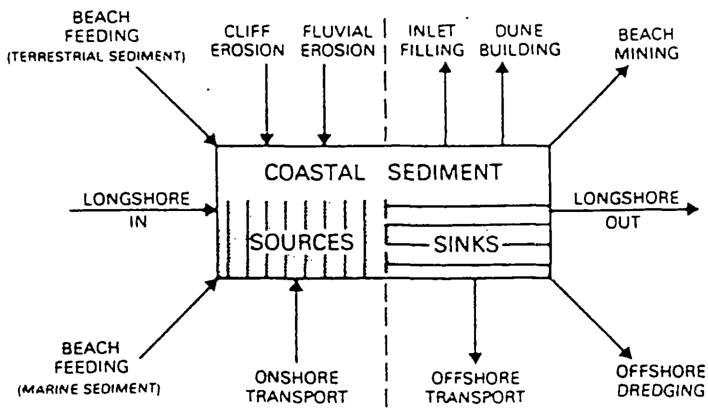


Fig. 2.15 Detailed components of a sediment budget showing sediment inputs, outputs and storage. (after Hansom 1988).

to compartmentalise the shore zone into process units. For each unit the sediment inputs, transfers, sources and sinks are computed and the linkages between cells are assessed. It formalises the examination of sediment transfer within the coastal system. Sediment is delivered to the coastal 'cell' usually by rivers, cliffs, onshore or alongshore sediment transport. It can be stored in the beach, in deltas or lost offshore or transported alongshore. A sediment budget primarily quantifies sediment gains and losses within a coastal cell (Bowen and Inman 1966; Davies 1972) as shown in Fig. 2.15.

Setting boundaries for the sediment budget can be difficult (Davidson-Arnott and Amin 1985). This is related to identifying sediment sources and sinks, and sediment transfers through the system. The primary unit of the sediment budget is the 'littoral drift cell'. Davidson-Arnott (1979) defines the upper drift boundary as where there is a reversal in sediment transport direction, and the lower boundary where sediment accumulates. The limit of sediment transport by waves can define the landward and offshore boundaries (Davies 1974; Tanner 1974). Although geomorphologically sound, field definition is difficult. Lowry and Carter (1982) define two types of budget boundary, fixed and free. Fixed boundaries are morphological (e.g. river mouths or headlands), which inhibit littoral drift and affect the pattern of wave refraction. Free boundaries e.g. limits of current deposition, are more difficult to locate as their positions are not permanently fixed. They result from changes in the wave climate and sediment movement from adjacent cells.

Schuisky and Schwartz (1983) give a general form of the beach sediment budget equation representing gains and losses:

Δ S = inputs-outputs

Sediment budget =

$$\Sigma\left(A + d + Q + O_t + E + K_g + I\right) - \Sigma\left(O_s + O_{ds} + E_a + K_{gl} + T_g + T_t + K_{red}\right) \qquad (2.10)$$

where the sources of sediment are:

A =sediment eroded from cliffs; d = sediment eroded from platforms; Q = fluvial sediment volume; O_t = biogenous material; E_a= aeolian material; K_{gl} = sediment ice rafted into the coastal zone; I = the contribution of volcanic eruptions.

and where the sediment sinks are:

O_s = sediment deposited in formation of coastal features (e.g. beaches, berms, bars); O_{ds} = suspended material carried out from the shore; K_{gl}= sediment ice rafted away from the shore; T_g

sediment loss into submarine canyons; T_t =sediment removal via tidal currents; K_{red} = loss due to disintegration by abrasion.
For Scottish lakes contributions of volcanic eruptions, ice rafting, tidal currents would be excluded. To date there are no sediment budget calculations for Loch Lomond.

Pierce (1976) gives a comprehensive critique of sediment budget approaches to shore zone variation. In the short-term the approach identifies the processes for which data are lacking, including biogenic data. Previous estimates of processes can be quantified and changes in conditions whether natural or anthropogenic, can be pinpointed and management plans structured. It emphasises an approach to shore zone change which considers natural processes. The quality of the resulting budget depends on the quality of the data used. Typically Σ Inputs and Σ Outputs are both very big numbers. ΔS is small relatively and therefore is subject to large uncertainty, even if the percentage errors in the Σ Inputs and Σ Outputs are small. Often, composites of survey information, no fluvial measurements for sediment delivery and very short time periods are used, giving less than satisfactory budgets. Kondolf and Matthews (1991) have calculated imbalances in some published sediment budgets, where the components have been quantified (or estimated) and found net errors ranging from 1% to over 100% for the total sediment export. Where the components of a budget are subtracted from a total of 100%, incorporated in the budget are the net errors in the measured components.

Shuisky and Schwartz (1983) emphasise the importance of mechanical sorting processes in sediment budget analysis. The physical qualities of sediment can change erosion and transportation, so for example not all eroded cliff material will become beach material. The transfer of sediment through the beach system is poorly understood and frequently ignored.

Two approaches to sediment budget analysis are described by Shuisky and Schwartz (1983), the Structural and the Systemic. The Structural approach considers the coast as a lithodynamic system, a complex of stable connections. No account of sediment sorting is taken and repeated profile measurements are used to quantify volumetric change. The Systemic approach is an open lithodynamic system and involves grain-size and sorting analysis, the latter giving more detail of sediment transfer. The structural approach is the most commonly used.

Numerous authors have calculated sediment budgets to assess marine shore zone change, especially at erosional shorelines, or have evaluated components comprising a sediment budget (e.g. Vincent 1979; Leatherman 1989; Allen 1980; Bokuniewicz and Ellsworth 1986; Davidson-

Arnott 1989; De Ruig and Louisse 1991). Overall, few papers give estimates of uncertainty in the budget figures, and the amount of in-situ field measured data is remarkably small. This highlights yet again the paucity of field data in coastal studies and especially lake coastal environments including Loch Lomond.

2.5 Shore zone variability at Loch Lomond

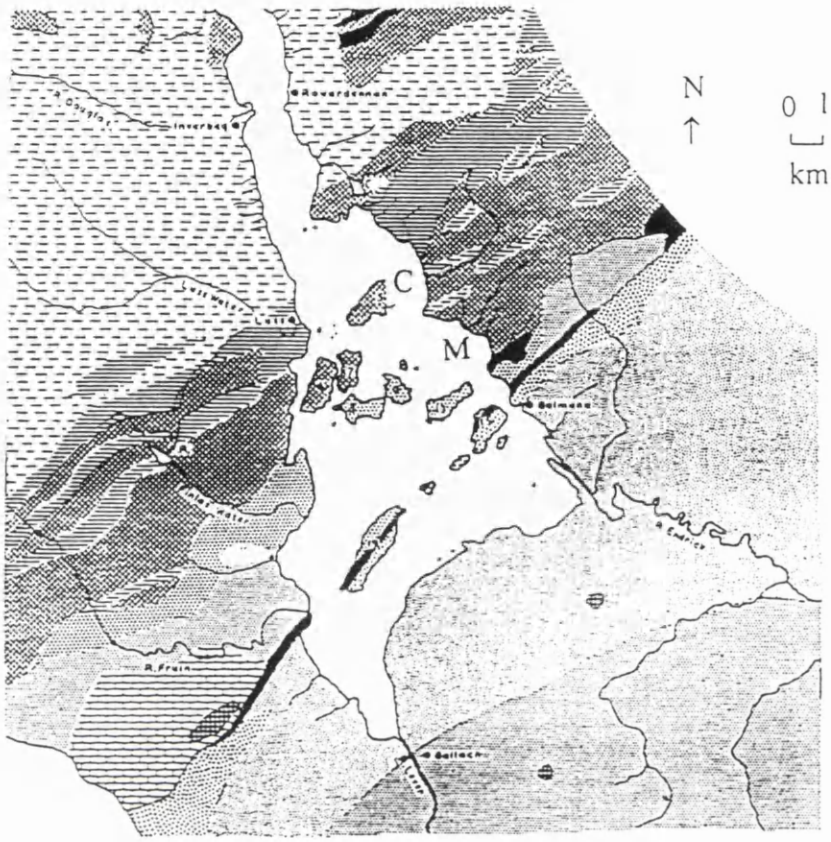
In this section the geological controls on present-day shoreline morphology, short-term and longer term trends in coastal variability are described and some of the areas requiring further research highlighted.

2.5.1 Geological controls on shoreline morphology

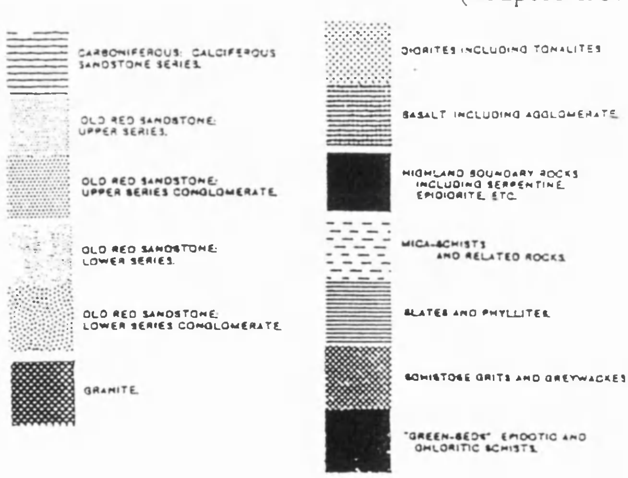
The regional geology is complex (Fig. 2.16) due to regional metamorphism and the proximity of the Highland Boundary Fault (MacDonald 1994) which is within 1 km of Milarrochy Bay. The coastal belt on this section of eastern shore has a narrow plain behind which the shore rises steeply to altitudes of over 570 m. The Loch Lomond Southern Highland rocks on the eastern shore are composed of Ben Ledi Grits and Leny Grits. The coastline consists of a series of headlands and bays with gravel or gravel/sand beaches. The headlands are of Dalradian age (Precambrian and Cambrian), comprising schists, greywackes and phyllites (1:50000 Geological Map of Scotland, Ben Lomond, sheet 38W). The whole area is overlain by glacigenic sediments (Rose 1981) and on some beaches these form low-level cliffs. In particular the headland bay sequences of much of the shoreline exert a macro-scale control on beach mobility.

2.5.2 Short-term shore zone change

Whilst there has been little quantitative investigation of shore zone variation, the issue of shore erosion is a common theme (e.g. CCS 1979; Tivy 1980; Dickinson and Pender 1991; Alexander 1991; Pierce 1996). Few of these have included quantitative data but most point to increased water levels, visitor pressure and vegetation degradation being key factors in shore erosion. Smith (1979) attributes shore degradation to wave action as well as anthropogenic factors (e.g. walking and boat launching). He estimated significant wave heights ranging from 0.19 m in the north, to 0.37 m at Rowardennan to 0.32 m SW of Balmaha. The significance of wave activity at high water levels was recognised by Dickinson and Pender (1991) and Pender *et.al.* (1993) in assessing the impact of the 1990 floods at Loch Lomond. High water levels, onshore winds causing wave activity with maximum effect on the shore. Within the Loch Lomond catchment, mean annual precipitation has increased by more than 30% from 1969-1988 (Curran and Poodle 1991). Lake water levels are variable and are increasing over time and flooding is a problem



(adapted from Slack, 1957)



C = Cashel M = Milarrochy

Fig. 2.16 Regional geology of southern Loch Lomond
Note the geological complexity in the Highland Boundary fault area

(Curran and Poodle 1991; Dickinson and Pender 1991). These factors all contribute to shore variability.

2.5.3 Long-term shore zone change

Indications of long term shore zone change at Loch Lomond are provided by the Quaternary history of the area. Several former glaciations and interstadials have moulded the landscape prior to the last Devensian ice sheet, but of particular significance are the events during and after the waning of this ice sheet. The 'Loch Lomond Stadial' (circa 10500-16000 BP) involved ice sheets at Rannoch Moor and ice complexes in the Highlands feeding valley glaciers to the Loch Lomond area. These glaciers had a significant effect on the present day geomorphology. The nature of the Quaternary environment has been established from a variety of morphological, lithological and biological evidence supported by various dating methods. The Quaternary history provides evidence of shoreline change and water level fluctuation, marine incursions and variable sediment supply associated with glacial deposition and sedimentation rates.

During the Loch Lomond Stadial, glaciers readvanced into Gareloch, Loch Lomond, the western Forth valley and the Teith valley. The largest ice stream of these was approximately 50 km long and occupied the Loch Lomond basin producing a 20 km wide piedmont lobe (Fig. 2.17). Sissons (1976) suggests the Loch Lomond glacier was 600 m thick, 25-30 km back from the ice limit. The total volume of the Loch Lomond glacier was in excess of 80 km^3 and it lay in a trough indented from previous glaciations thus further moulding the Loch basin and shore zone.

At the time of the Loch Lomond glacier, ice dammed lakes existed in the Blane, Endrick and Fruin valleys (Rose *et. al.* 1988). The evidence is from borehole lake bottom deposits 12 m thick in both valleys, from a deltaic accumulation of sands and gravels near Drymen, and shoreline beaches developed on the flanks of drumlins in the Endrick valley. During the Loch Lomond Stadial the Blane and Endrick valleys are thought to have been linked for at least some of the time (Price 1983).

The key exposure sites in the Loch Lomond area are Croftamie, Rhu Point, Gartness and Aucheneck (Fig. 2.17). The Gartness sites at south Loch Lomond of Portnellan (NS 404873) Ross priory (NS 413876) and Claddochside (NS 427878), 7 and 4.5 km from the field sites, are of particular interest. These are the type sites for the Loch Lomond Stadial, and show exposures of Clyde Beds (Claddochside) and shore platform and cliff at Portnellan and Ross Priory at altitudes of between 12 and 13 m OD (Dickson et. al. 1978; Rose, 1980). The Clyde beds are

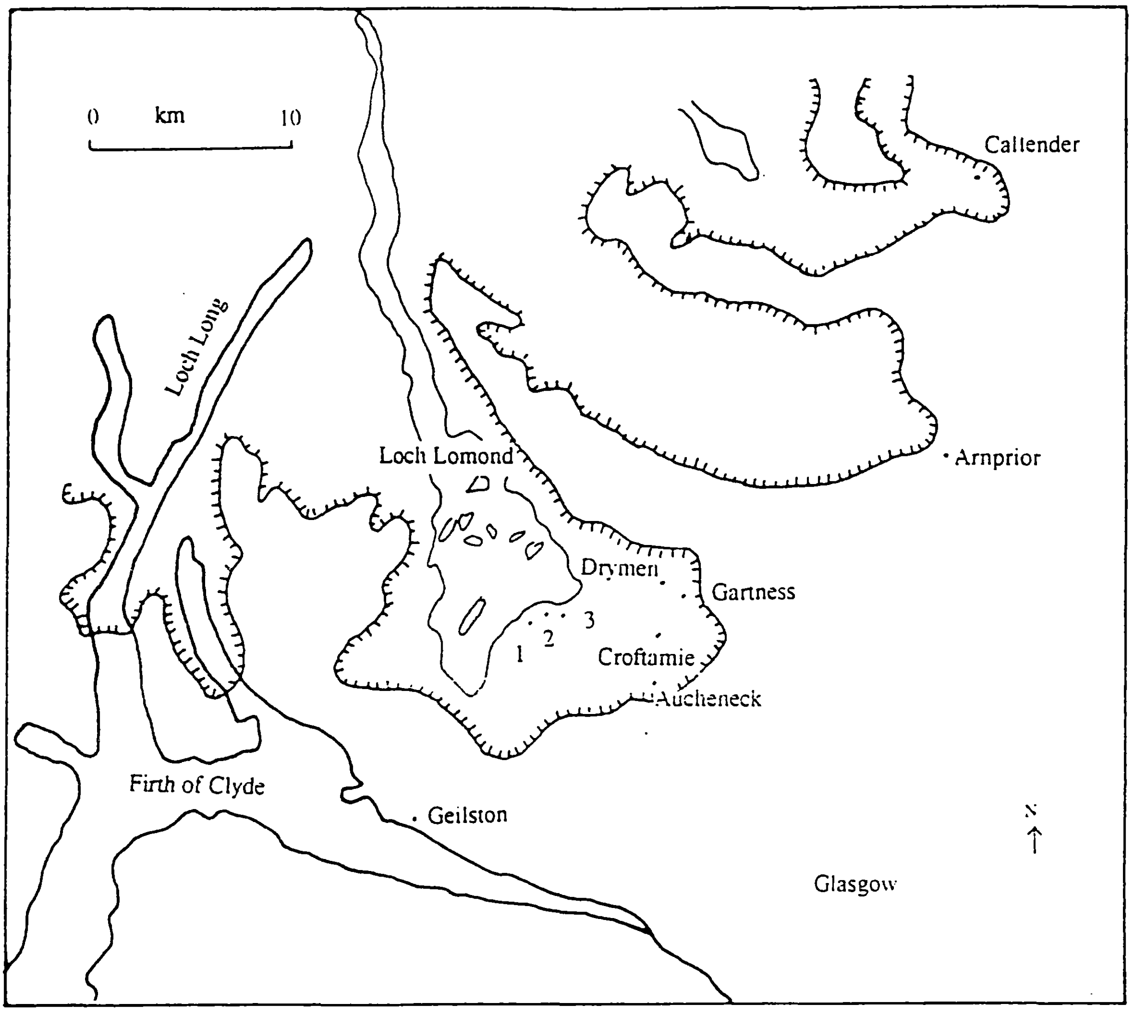


Fig. 2.17 Loch Lomond Stadial glacier margins in the Loch Lomond area (after Gordon and Sutherland 1993).

Loch Lomond Stadial glacier margins

1 Portnellan

2 Ross Priory

3 Claddochside

dated at 11 700 BP ± 170 yrs. (Jardine 1980). Dickson *et. al.* (1978) trace these shorelines through the Vale of Leven, linking them with the marine shoreline of the Clyde estuary. During this period, sea levels varied. The Loch Lomond Stadial is dated by various evidence, at Loch Lomond, the till deposits at Rhu and Ross Priory. Marine encroachment of (some of) Loch Lomond is suggested by the Clyde Beds (Rose 1990). The Flandrian marine transgression (c. 8400-5000 BP) is associated with the raised shorelines, including Ross Priory (at +13 m, +12 and +9 m) when Loch Lomond became a sea loch (Jardine 1980). Whilst a variety of shoreline altitudes have been suggested in the literature, there have been no attempts to reconstruct sea/loch level histories in this area.

2.6 Summary

This review of the literature draws on a wide range of sources which provide the background for this study of gravel beach variation. A systems approach to investigation is important to identify inter-linking components of the coastal system and the controls they exert on beach change at varied temporal and spatial scales. This review has identified components of coastal system. The wave climate, currents and water level variation have been identified as significant processes affecting beach variation. Shore responses to process changes have been discussed: beach morphological and sedimentological change, sediment transport, shore recession and progradation. Examples of different approaches to research and the theoretical basis of previous research have been presented. Of particular value is sediment budget calculation which enables linkages between significant variables in the coastal system to be quantified at various resolutions. Overall the paucity of field data, particularly for low energy gravel beach changes is striking. With reference to the aims of this research, the review identifies in particular a lack of published low energy wave data, gravel beach variation (except barrier beach data), gravel sediment transport on beaches, sediment routing and storage through beach systems, lake beach morphological trends, and detailed real-time sediment budgets and controls on beach behaviour. At Loch Lomond, apart from the Holocene data, coastal geomorphological investigation has been limited although variability has been identified (e.g. Tivy 1979; Dickinson and Pender 1991). At such an important national and international site, investigation is long overdue on the response of gravel beaches to wave conditions. Whilst Loch Lomond provides an interesting and environmentally significant site in its own right, it is hoped that the findings will be important for documenting low energy gravel beach behaviour and for improving the understanding of lake coastal environments.

2.7 The approach of this research

The review summarises much of the present knowledge of gravel beach behaviour and coastal dyanamics and has identified areas where further research and clarification is required. Within the remit of this research, the following aims are investigated:

1) The relative energies of small lacustrine wave climates are poorly documented. Since wave processes are fundamental in beach development, examination of the heights and frequencies of lake waves and the role of water level variation as the control for this wave activity is important. In recording and specifying the lake wave climate, better understanding of coastal zone dynamics and in particular low energy gravel beach variation should be attained.

2) Variation in gravel beach types at differing energy scales and sediment supply ratios provide an area for further research. In general coarse clastic sediment transport on beaches remains poorly understood and further research is needed into the interaction of fluvial sediment delivery, beach storage and sediment transfer and loss. Within the scope of this research is the monitoring of shore zone variability in order to quantify as far as possible the scale of spatial and temporal change. The aim is to determine the nature and variability of the shore zone.

3) The review highlights many of the inter-linking relationships between nearshore and shore variables. Attempts to better understand low-energy, sediment-poor gravel beach behaviour and the links at various scales between different variables will be made in the collection of field data. The aim is to identify relationships between nearshore and shore processes.

4) As sediment budgets provide both a conceptual and practical approach to coastal research, and there is an overall lack of detailed coastal field-data, calculating component parts of a budget is seen as a valuable framework for research. Therefore the aim is to calculate a beach sediment budget for one year.

Chapter 3 METHODS

Introduction

The research approach and data collection including field and laboratory procedures, analytical techniques and the modelling and use of secondary data are described in this chapter. The Methodology gives the theoretical framework and subsequent sections describe the fieldwork and laboratory research programme of data collection under the broad headings of the nearshore and shore zones, and the sediment budget.

3.1 The approach

3.1.1 Methodology

This study investigates lake waves and gravel beach variation within a low energy lake environment. The focus is to establish the nature of the processes and forms and the relationships between them (section 1.2) and to obtain the following outcomes:

1) to obtain and analyse wave records at Loch Lomond;

2) to obtain an estimate of shoreline recession;

3) to determine the scale of beach morphological and sedimentological variation;

4) to calculate an annual sediment budget; and

5) to better understand the processes and mechanics of geomorphological change within the coastal zone.

Due to the dearth of lake shoreline data, this research was predominantly field based, focusing on temporal and spatial variability of the coastal zone. Observable phenomena which have been identified as significant from the literature and field observation, have been selected for measurement/observation and integrated with available secondary data. Various authors (e.g. Pender *et. al.* 1993; Dickinson 1994) acknowledge a changing environmental pattern with shoreline recession, degradation and flooding at Loch Lomond.

As the theoretical base for lacustrine geomorphology is poorly developed to date, theory from marine coastal work, oceanography and fluvial studies is adopted (described in chapter 2), and it makes an important contribution to the methodological approach. Some distinctive characteristics of the lacustrine environment have a bearing on the design and development of the research project. Inevitably compromises have to be made to match data requirements to logistics.

The framework in which the research was designed is that of a 'systems approach' whereby various phenomena are identified and their interaction examined. This is particularly important in the shore and nearshore zone as variables exhibit a high degree of inter-dependence. For example, waves are wind and fetch dependent, beaches respond to wave action and water level. The way in which individual phenomena operate is of particular interest in understanding the broader scale operation of the shoreline. Investigating process studies plays a highly significant role in the way in which the research was conducted, and the temporal and spatial scales at which phenomena were measured.

The field site is of international, national and local importance as the largest British freshwater lake, yet little is known of wave climates and lake beach variability at this scale. The aim is to improve on this imperfectly understood relationship between water level, waves and beaches, sediment delivery and the fluvial system/beach interface in the lacustrine environment. Knowledge of lakes and lake processes is a growing area of research, where a multi-disciplinary approach is helpful and this study offers a geomorphological perspective.

A systematic approach in which various significant phenomena of coastal zone dynamics and linkages are identified is a suitable framework for this research. Empirical research is needed on the mechanics and 'strength' of such linkage as well as the identification of significant phenomena. For example it is known that wave action is the direct cause of shore erosion, but the wave climate is not known. By measuring the processes (e.g. the wave form), the strength of the 'link' may be determined. Many studies fail to differentiate between tentative assumptions of linkage between phenomena and clear evidence of 'cause and effect' linkage. Although it would seem logical to draw together certain relationships between natural phenomena, particularly as many links are well established in the literature, some caution needs to be exercised. Simultaneous real-time field data collection is an important component of the approach as published information on geomorphological systems is limited. Field data are invaluable in validating computer models and for addressing the geomorphological processes taking place.

As with any research programme, once the aims have been established, and the lines of enquiry identified, the methods of data collection need to be designed to satisfy the aims under appropriate temporal and spatial scales. The spatial limits of the research and the field sites selected for detailed study are described in sections 3.1.3, 4.1 and 5.1. The data collected were subjected to temporal, spatial and scale filters which are described in this chapter. Davidson (1978) (in Goudie *et al.* 1990) lists the main sources of error encountered in physical geography which are:-

sampling error, observer error (including operator variance), instrument error, environmental error (where the conditions under which research takes place may influence the results), and the nature of the observed phenomenon (where the actual method of measurement influences the results). Where appropriate, instrumental error is noted.

3.1.2 Research Programme

The methods of data collection were designed so that the most appropriate and accurate results could be obtained within the limitations of time, available field support and logistical constraints. During the course of the study, some techniques were revised as a result of field trials. The research involved field and laboratory work between October 1992 and April 1995. The core research presented herein focuses on measurements taken during 1994, the year used for the sediment budget. Details of temporal and spatial scales of sampling rates are described within each methods section.

3.1.3 Selection of fieldsites

In order to investigate shore zone variability within the timescale of the research, a sampling framework was needed. Detailed measurement of the whole shore zone was not possible, given the temporal, financial and personnel constraints. Chapter 2 has highlighted the lack of detailed lake coastal zone research both at Loch Lomond and of lakes of this scale, so focusing on one or two representative sites was seen as essential. Preliminary reconnaissance of the coastal zone took place in September-November, 1992. Suitable sites were identified as: 1) those free from artificial structures or shore protection attempts; 2) those where accessibility was relatively easy; 3) and those where permission for research access could be obtained. The main 'honeypot' sites were avoided because of human interference. Secondary research revealed several areas identified as having a 'variable' shoreline undergoing morphological and recessional change. Given the research timetable, it was seen as desirable to record variable areas, firstly to quantify the 'popular perceptions', secondly to identify operating processes and improve the understanding of variability. Less variable areas may need much longer research timescales.

The reconnaissance revealed that most of the western shore of Loch Lomond was affected by artificial structures such as rip-rap and walls. The beaches on the western shore were limited in extent and very easily accessible to visitors. The north-eastern shores were predominantly cliffed and difficult to access, some of the southern shores are marshes and others have till cliffs and gravel beaches, as do the south eastern shores. On balance, it was decided that the most suitable research sites were the accessible beaches on the south-eastern shore north of Balmaha. Two beaches were chosen for detailed study. Milarrochy was selected as it had been identified as undergoing shore erosion (e.g. Alexander 1991). Reconnaissance showed it exhibited a number of characteristics common to most Loch shore beaches, namely clearly defined hard rock headlands and gravel/sand beaches, within well vegetated backshores. A disadvantage of this site was the number of visitors. The second site at Cashel was chosen because part of the site exhibited a well developed beach although the other part was erosional and it was enclosed by headlands and thus clearly defined. The purpose of monitoring two beaches was to identify similarities and differences in operational processes, to gain as much information as possible on lake beach variability, and to provide a better baseline of information from two sites.

3.2.1 Investigation of the nearshore zone

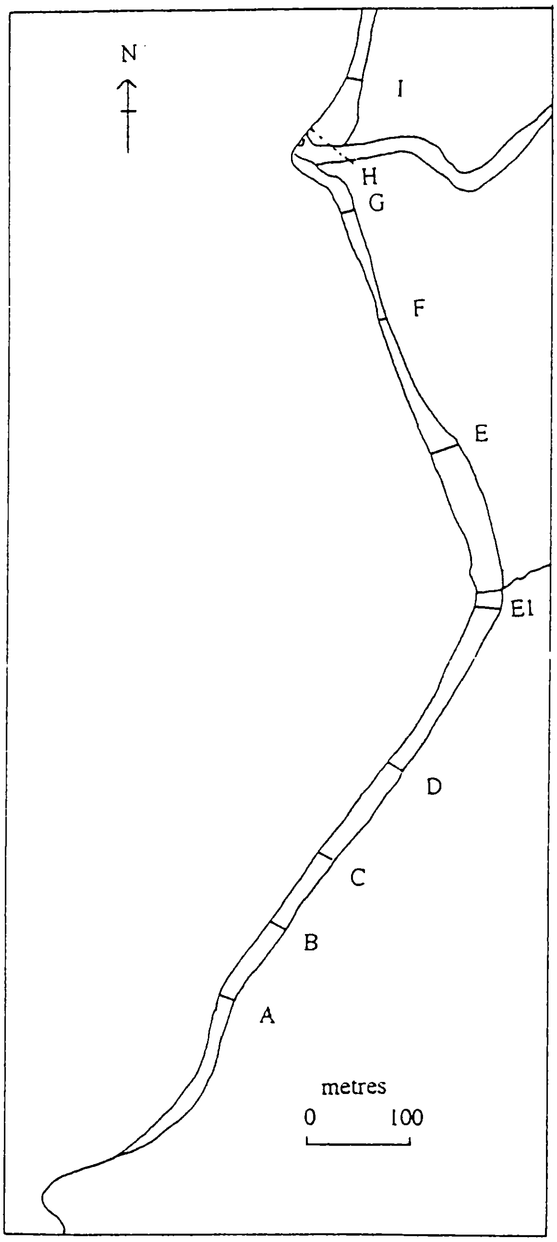
The first part of the investigation entailed the collection of baseline information from which variability could be established. The underwater geomorphology investigations are described, followed by wind and wave recording, water level monitoring and lake processes.

3.2.2 Bathymetric characteristics

The nature of the nearshore bathymetry affects wave behaviour and thus shore zone behaviour. The 1861 Admiralty chart, provides the basis for the bathymetric information for Loch Lomond. As detailed bathymetrical information was required for Milarrochy and Cashel bays, a bathymetric survey was designed to survey the nearshore region to just beyond the headland boundaries.

The survey strategy was to link the regularly surveyed beach profiles (Fig. 3.1, section 3.3.2.2) to the offshore and into very deep water (Figs. 3.2, 3.3). Water depths between the survey lines were interpolated. Cross bay (shore parallel) checks were made to ensure survey accuracy. The bathymetric survey was set up from the temporary bench marks established on the shore. A shore-based Total Station (Leica T1010) was used to monitor boat location via tracking to a reflective prism being mounted on the transom. On each profile, at the correct bearing, two marker buoys visible from offshore were positioned on the beach to allow the boat to line up. At each profile, the echo-sounding survey was taken from offshore towards the beach, using the profile marker buoys as bearing targets. In calm conditions, using the slowest engine speed, the echo-sounding boat and survey was run to within 0.5m depth at the shore. The Cashel Bay survey was carried out on 2/7/94 and Milarrochy on 23/5/94.

Cashel



Milarrochy

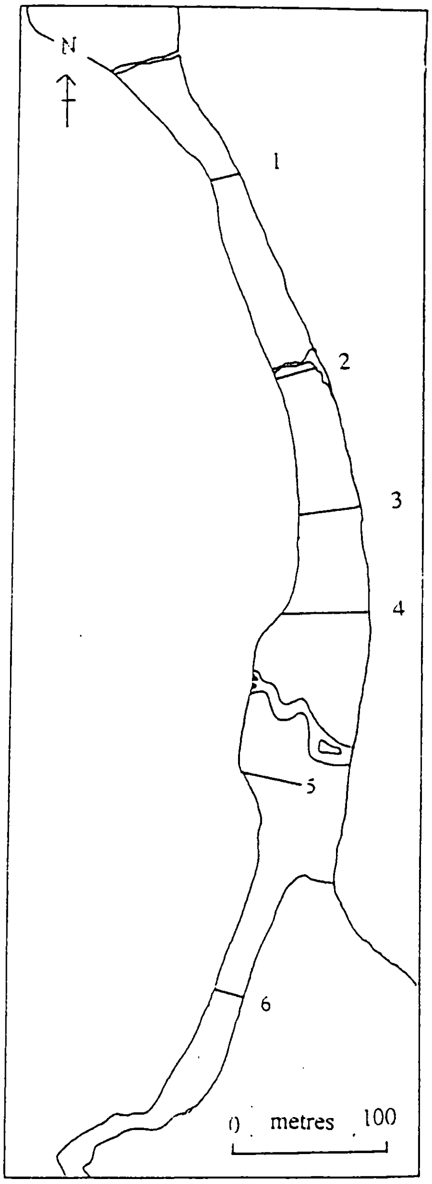


Fig. 3.1 Profile locations at Cashel and Milarrochy beaches.
Profiles were used for morphological and sedimentological surveys and extended offshore.

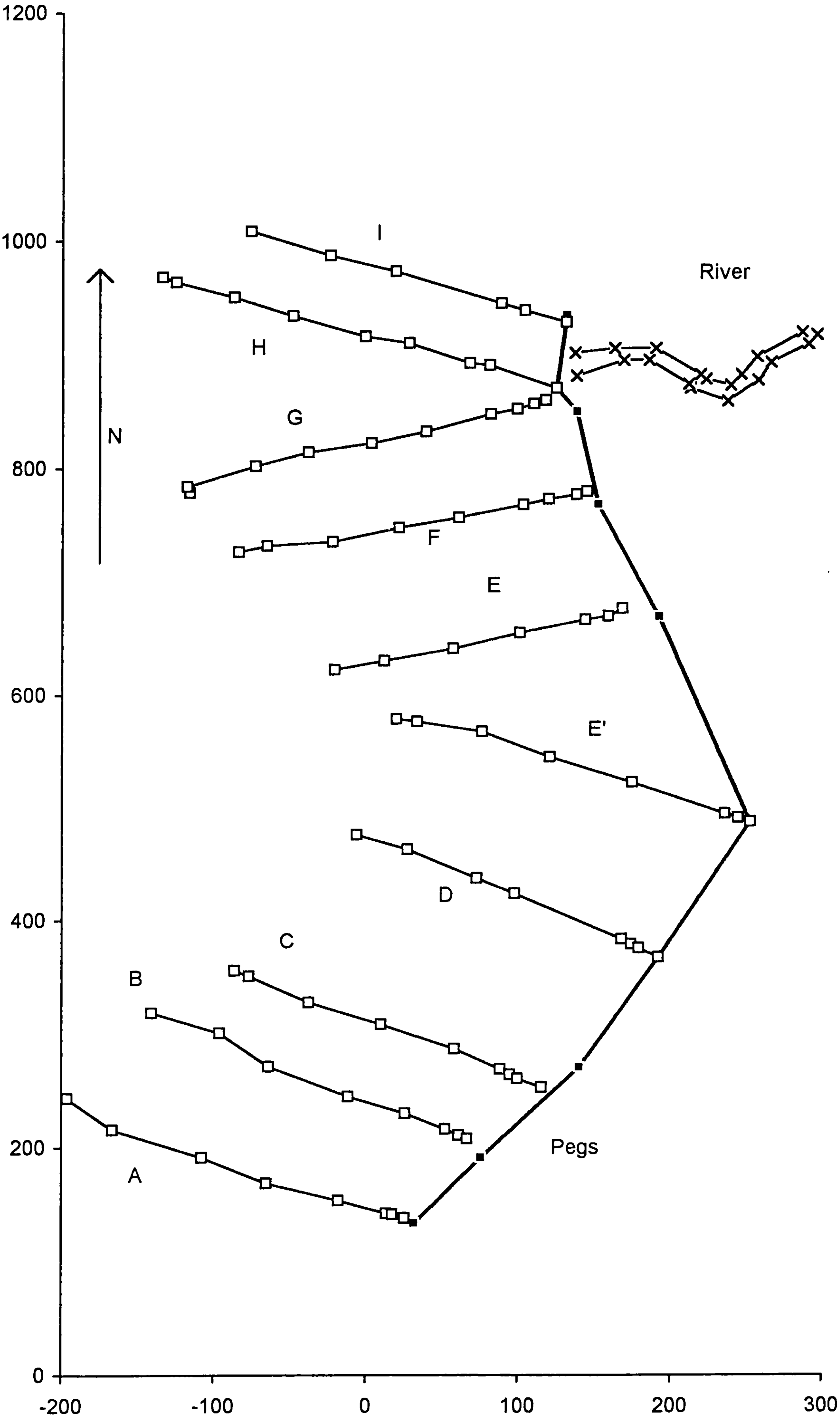


Fig. 3.2 Nearshore bathymetric survey route: Cashel
Note axes denote local survey grid.

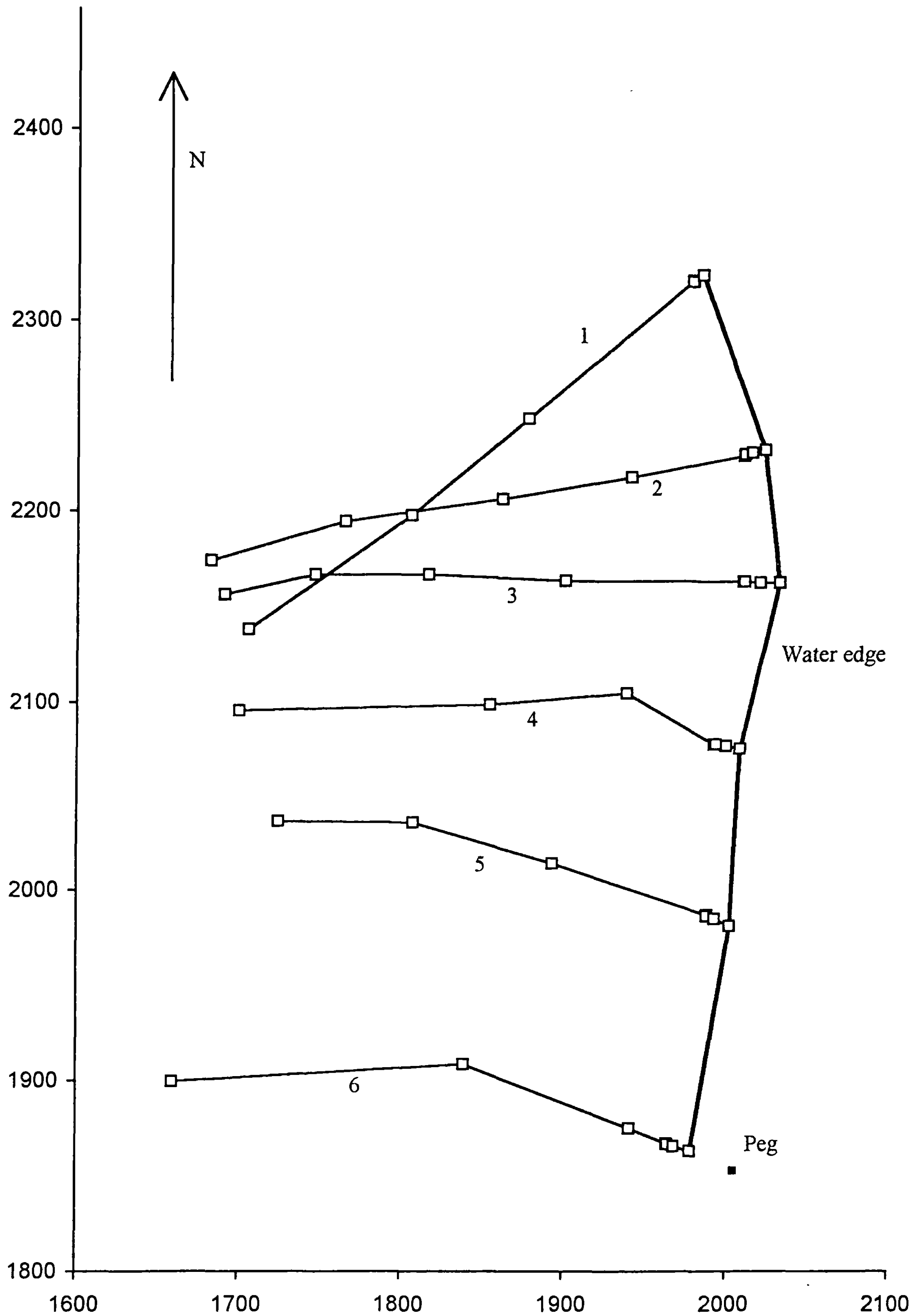


Fig. 3.3 Nearshore bathymetric survey route: Milarrochy
Note axes denote local survey grid.

The survey used an inflatable flat-bottomed dinghy, most suitable for shallow water work, with an echo sounder (Fuso 1000) mounted aboard. The echo-sounder transducer was positioned along the beam, away from the hull minimising bubbles and turbulence. A paper trace was obtained for each profile run. The depth range of the sensor was adjusted according to water depth to gain maximum sensitivity and accuracy was to 1cm in shallow water and 10cm in deep water. Prior to field use, the echo sounding equipment was tested and calibrated in a laboratory wave tank, and also at Loch Lomond using a jetty, where tank reflection signals were absent.

Large scale (1:1000) maps of the two bays were compiled using the co-ordinates collected from the boat tracking integrated with the echo-sounding traces to give a high degree of bathymetric detail. These were eventually reduced in size and are shown in Section 4.1.2. The bathymetry was contoured at 5 m intervals in deep water until the area adjacent to the shore which was contoured at 1 m intervals in order to show the nearshore gradient close to the beaches.

3.2.3 Wind and wave recording

A review of the literature (section 2.4.1) shows that waves are significant processes in the coastal zone. In view of the dearth of lake wave information (including Loch Lomond) wave recording was seen as a priority research area. The purpose of wave recording was to attempt to define the wave climate in the sample year of 1994 (i.e. to describe the types and magnitude of waves generated in the Loch and to establish their likely impact on the shore zone). This would assist in the estimation of sediment transport. Winds were recorded as a surrogate for wave direction.

3.2.3.1 Wind recording (for wave direction).

Most lake waves are wind driven, with the exception of seiches. At Loch Lomond the location is mountainous, local winds are highly variable so in-situ recording was seen as advantageous. The aim was to record wind directions and velocities that could be correlated with wave recordings. At the time of the research, no wind recording stations within the Loch Lomond basin were reliably operational. Correlation of wind direction with wave direction is a largely neglected area of research, although such correlation is frequently an unstated assumption. This study also assumes this relationship, although with a higher degree of confidence than many marine environments because of the importance of wind in a fetch limited environment.

The field sites had been selected on the eastern shore of the Loch (section 3.1.3), so ideally wave recording within the vicinity of the study beaches were required. As the eastern shoreline of Loch Lomond is largely forested, open sites available for a meteorological station were limited. A wind and wave recording station was established at Grid. Ref. NS 40409278 (OS 1:50000, sheet 56), where wave recorders could be located with maximum efficiency and minimum interference. The anemometer and wind vane were secured to a pole above the wave recorders, giving the advantage of in-situ wind recording.

The wind recording station comprised a three cup switching anemometer, a wind vane (Vector) cabling and data logger (Eltek 8 bit). The anemometer was positioned 5 m above the jetty (6 m above the water surface at installation). The system was chosen for robustness and sensitivity to the range of wind speeds. It was accepted that wind velocities from the east may be reduced because of the trees, but these are unimportant to beach processes. Wind speeds were recorded hourly, on the hour, taking a mean reading of a one minute record. The calibration is linear with 1.001 revolutions per m s^{-1}. Wind velocity, to an accurate to +/- 1 m s^{-1}, over a temperature range of -30 -+65^{0}C. Wind direction was measured by a wind vane connected to the data logger. Instantaneous error when there is a sudden change of wind direction can be up to 10^{0}. Observations of wind and wave correlation made at intervals during the research period suggested a good correlation. However, during the recording periods, the data logger proved to be unreliable and so incomplete records were obtained. Wind results for wave directions are given in section 4.2.

3.2.3.2 Wave recording

The theoretical development of wave characteristics has been discussed in Chapter 2. It is from this well established theory that the characteristics for measurement are determined, namely wave height, period and velocity. There are a variety of methods for wave recording (section 2.4.2). The primary aim of wave recording was to determine the nature of the nearshore wave climate (aim 1) and to provide data for the understanding and interpretation of nearshore processes and forms (aim 3).

Wave recorder design and testing

Wave recording at Loch Lomond required an instrument to meet various criteria: (a) to have sufficiently high resolution to detect small, high frequency waves; (b) to be able to record over a 2m range in mean water level; (c) to be robust in gale force winds (40 m s^{-1}) and persistent large waves; (d) to be low cost, require infrequent maintenance, and be compatible with readily available data logging and transfer equipment; and (e) to be as inconspicuous as possible because of likely human interference.

Prior to field deployment of the wave recorder, experimental trials with different instruments, were carried out in the University Wave Tank (72 m long x 5 mm wide x 2.5 m deep). This facility allowed instrumental testing, comparison and calibration. Trials of a wave recording pressure transducer were run with various wave staff recorders. Sinusoidal waves were used in the wave tank tests, as these idealised waves are used most commonly for design applications. Since transducers react to the behaviour of the water column above them, rather than to the waves themselves, their wave records are suppressed and errors are introduced which are not removed completely by correction terms.

The scale of Loch Lomond in terms of fetch length, affects wave properties and therefore the recording technique selected. Large lakes, such as the Great Lakes of the USA and Canada, operate hydrodynamically as small oceans where relatively large waves can develop. Smaller lakes, limited primarily by fetch and in the case of Loch Lomond with winds influenced by mountain topography and a distinct micro-climate, have different wave characteristics. The maximum wave height at Loch Lomond (peak to trough) is estimated as 2 m (Pender *et. al.* 1993) although no previous wave records have been made. Water levels fluctuate by approximately 2 m throughout the year, in response to seasonally varying precipitation inputs, causing unique problems for wave measurement.

After various field and tank experimental trials, a suitable wave recorder was developed from existing knowledge of thin wire wave gauges deployed in wave tanks. A prototype wave probe was developed, built, tested and calibrated in the University Wave Tank, prior to field deployment. The wave probe, consists of two units, the field data collection unit (Unit 1) and the data processing unit (Unit 2). Unit 1 comprised the probe, cabling, amplifier, filter and 8-bit data logger (Fig. 3.4). The use of an 8-bit logger limited resolution, although this could be improved by using a 12-bit one. The data were downloaded onto a laptop PC at weekly intervals and then transferred to a workstation for analysis. The data logger records wave data as a voltage prior to calibration at the last stage of Unit 1 of the system. At this stage wave data can be checked from graphical displays and basic statistics (times, dates, mean water levels, maximum and minimum wave heights), although analysis is carried out after data transfer and calibration (Unit 2).

The probe consists of two parallel stainless steel wires of 3 mm diameter, mounted on a polyurethane painted wooden block. The unit was weighted and secured to a jetty with industrial strength cable ties. Cabling connections were sealed and routed to a secure logging site 90m away. The wave probe was immersed to mid point in water and works by applying an AC

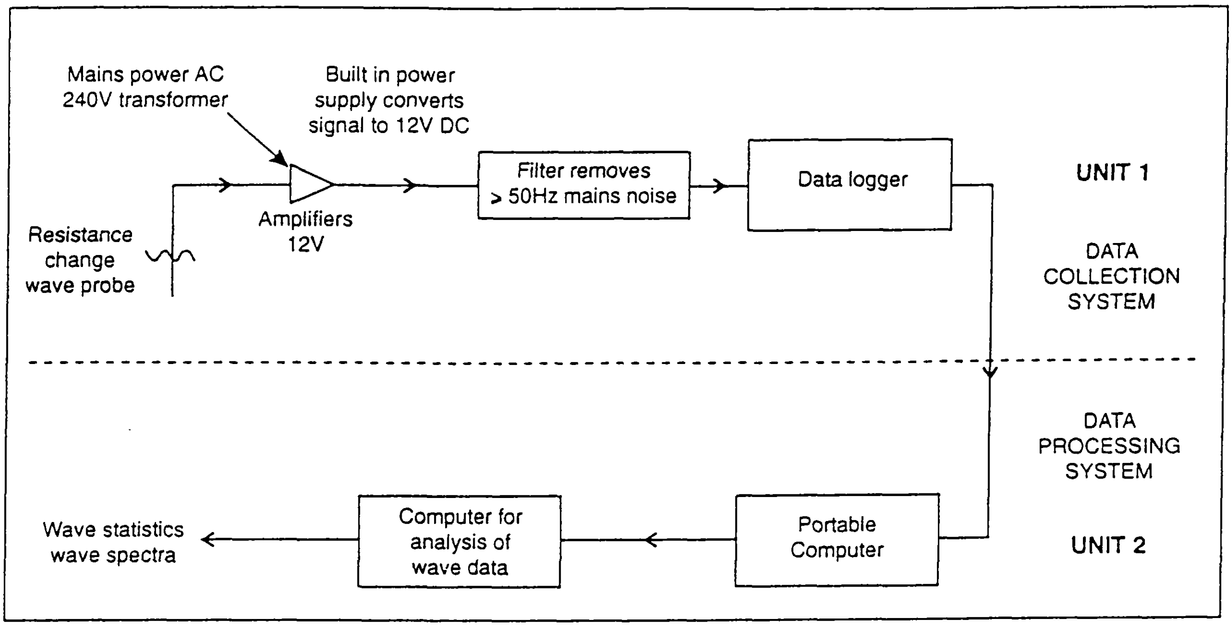


Fig. 3.4 Schematic diagram of Loch Lomond wave recording system

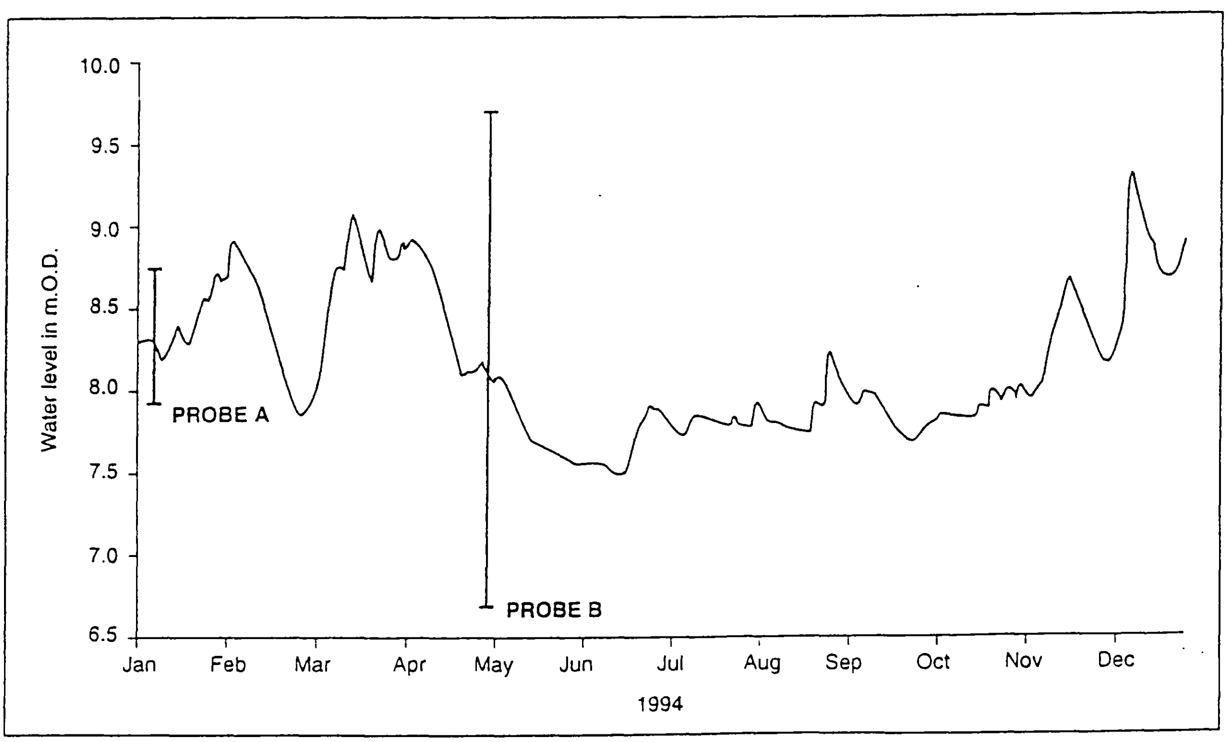


Fig. 3.5 Wave probes A and B deployed sequentially in Loch Lomond.
Probe A obtained higher resolution records. Probe B recorded waves over a greater water level range.

voltage across the wires. Conduction through the water completes the circuit. The water level between the wires controls the length of the wire through which the current passes, and thus its' resistance. The voltage developed as the current passes through a resistor installed in series within the circuit is fed to a difference amplifier from which a DC output voltage is measured. This voltage is directly proportional to the height of the water at the probe (i.e. wave height). The output from the amplifier is fed through a low pass filter which removes any noise at ≥ 50Hz allowing a clean signal to be fed to the data logger. The resolution of the recorded changes in water level depends on resolutions of both the probe and the data logger. To avoid the common problem of electroplating of probes after a period of immersion in water, which can cause undetected offset voltages and suggest spurious water level change, the probe was driven by an AC voltage at a frequency of 5kHz.

Calibrations were carried out in the wave tank and then at the field-site, by immersing the probe at 0.2m increments in water and recording the output voltage at each depth of immersion. The resultant calibration curve is used in the data processing stage. For wave recording, a suitable deep water, open, exposed site was needed to determine nearshore wave conditions. Although few shore areas at Loch Lomond are free from public access and interference with equipment, a suitable site was chosen at Blair (GR 40409278) between Milarochy and Cashel where the maximum fetch is 7.5 km. The nearshore is relatively steep, with maximum depths in the bays reaching 45m within 250m of the shore. The particular advantage of the site was a private deep water jetty available for mounting wind and wave recording instruments and a mains power supply. This allowed high quality data collection in the vicinity of the field sites.

Field deployment

Two wave probes were deployed sequentially in Loch Lomond, in water depths varying from 3 to 5.5m. There is no precedent set for lake wave recording and, given the constraints of logger battery life and volumes of data generated, a recording frequency was adopted of 5 minute runs of wave conditions every 6 hours. From January 1994, a prototype 0.75m probe (Probe A) sampling at 0.1 sec (10Hz) was used to obtain high resolution records showing the small scale detail of wave shapes. This probe was flooded during much of February 1994, on account of prolonged precipitation and increased Loch levels and a second probe, Probe B, which was 3.0m long with a sampling rate of 0.2 sec (5Hz) (the maximum possible with the electronic system) was deployed in May 1994 (Fig. 3.5). Compared to open coast sampling rates (typically 0.16Hz) the above sampling rates are very high. Resolution for Probe A was 2mm and for probe B 15mm. Probe A provided important information on the detail of wave shape over a limited range of water levels, whereas Probe B provided a robust wave recording system which could cope with marked water level fluctuations but which still provided a good degree of detail. Consistently reliable wave records were obtained. It should be noted that there was no clear way of differentiating between wind-waves and any boat generated waves. However, at some time periods boat wake would be unlikely (e.g. 0000hrs, 0600hrs), and over a 5 minute period, boat wake would be inconsistent and stand out on the graphical wave records.

The data logger records wave data as a voltage prior to calibration at the last stage of Unit 1 of the system. At this stage wave data are transferred to a lap-top computer in the field and checked from graphical displays and basic statistics (times, dates, mean water levels, maximum and minimum wave heights). Further analysis is carried out after data transfer and calibration (Unit 2). A chart recorder, instead of a logger, was used to record some of the early wave records. This method produced good quality records but analysis had to be by hand, recorder paper and inks are expensive, and the paper tend to be affected by the damp environment.

3.2.3.4 Wave Analysis

In the laboratory, the data processing system (unit 2) comprises data transformation to *Lotus* format and delivery to a *DEC Alpha* computer workstation via an *Ethernet pathworks* connection. The analysis chosen uses the Tucker-Draper (TDM) wave classification and analysis method (Hardisty 1989) and spectral analysis programs which are described below.

The first part of the analysis used the following standard wave parameters: 1) Crest period (T_C), the mean interval between successive wave crests. The crest is defined as the point where the water level is momentarily constant, falling to either side; 2) Zero crossing period (T_Z), the mean interval between successive occurrences on a wave trace where the surface water level crosses the mean level in an upwards direction; 3) Significant wave height (H_S), the wave height exceeded by one third of the waves; 4) Maximum wave height (H_{max} or H_l) the most probable value of the height of the highest wave; and, 5) Spectral width parameter (ε), a measure of the statistical distribution of waves within the wave spectrum. The TDM is important as it reduces vast quantities of data into a useful descriptive/analytical summary which describes wave conditions and allows for inter-site comparison, and so providing data to satisfy aim 1 of the research.

The second part of the analysis involved spectral analysis of the wave time series using a Fast Fourier Transform (FFT) for rapid analysis of large data sets. Essentially this involves converting data from the time to the frequency domain and determining the energy distribution of waves on a frequency basis. Use of this technique showed the significance of the frequency components of the Loch Lomond wave climate (aim 1). Spectral analysis is also useful as an analytical tool, for predictive purposes and for inter-site comparison.

Naturally occurring waves do not have the regular and precise properties of regular sinusoidal waves. In order to describe the variance of the wave surface, wave spectra give the distribution of wave variance as a function of frequency. The wave climate can be defined in terms of energy, the total energy being the sum of the energies of all waves (statistically this is proportional to the sum of the squares of the heights of all the waves), a measure of which is obtained by the area under the energy density spectrum. Spectra can be described using the spectral width parameter (ε) which ranges between 0 and 1, where values closest to zero represent a regular monochromatic sea or sinusoidal, regular waves and higher values represent more mixed distributions of different wave heights and periods, closer to a fully developed sea (Tucker 1963; Draper, 1967; Hardisty 1986). When ε is low the distribution of wave energy is Gaussian, and as ε increases the distributions tend toward Rayleigh distributions (Carter 1988). The value of ε was estimated using the approximation $\varepsilon^2 = 1-(T_c/T_z)^2$, this approximation avoiding problems in estimating the higher moments of the energy spectrum (Chakrabarti 1987).

A spectral analysis program was written which utilised NAG sub-routines (NAG 1990) and a Fast Fourier Transform (FFT), although commercial wave analysis programs are available. These routines provide a number of options, enabling the most appropriate analysis to be used for the data collected. Introductions to this type of analysis are given by Diggle (1990), Bloomfield (1978), Jenkins and Watts (1968), Carlson (1992) and Press *et. al.* (1992).

Spectral analysis was performed on each of the 5 minute wave records after calibration. A mean water level (0) was derived from the wave data from the highest and lowest water surface elevations. Trend corrections (for example for a rising tide) were not needed. As the data were filtered to remove electronic noise at the collection point, no further filtering was applied. Two problems of harmonics and leakage sometimes occur in spectral analysis. Spectrum leakage can result when a truncated signal is used (Carlson 1992), where Fourier frequencies are placed in the wrong frequency class (this is usually only a problem when short runs of data are used and the frequency classes have to be quite crude). Harmonics arise as a by-product of the spectral analysis technique sometimes showing up as multiple peaks in the final spectrum (Carlson 1992) but filtering can eliminate these. Leakage is not very important if the aim of the technique is the overall spectrum shape, as here; leakage error may be less than the statistical uncertainty (Earle and Bishop 1984).

The NAG routines also allow tapering, which determines how the first and last parts of a wave train are terminated (i.e. continued to the mean water level). This option is of little importance when long wave records are considered in which the start and end of the series are close to the mean value (Yuen and Fraser 1979). No smoothing was applied to the data as the recording interval used was small relative to the celerity of the waves (i.e. each wave was described by several recorded points). In most cases the spectral analysis results lay within 95% confidence limits. The output from this analysis was in the form of an energy spectrum for each wave record which clearly shows the frequency distributions of the recorded waves and summarises the energy of the 'sea'. These spectra are important in defining the Loch Lomond wave climate (aim 1).

Overall the wave recording was very successful and a large, high quality data set was obtained. The accuracy of the wave probe remained stable throughout the recording period which included extreme weather conditions (wind speeds up to 45 m sec^{-1}), periods of snow, 2 m fluctuations in water level). Apart from weekly downloading of data, no regular maintenance was required although weed was removed from the probe on two occasions. The high resolution of the small probe (A) was effective in determining the characteristics of very small waves under relatively calm conditions. The larger probe (B) was more effective for all wave conditions with the fluctuating water levels. Of a total of 767 wave records, 20 were discarded because of electrical faults (power surges, logger problems and thunderstorm damage to the amplifier). Further logger malfunctioning was the cause of further gaps in the annual record, for some of which on-site wind records are available. The results of the wave recording are presented in section 4.2, and the full record of the TDM results is in Appendix C.

3.2.3.4 Wave refraction

Waves are the principal source of energy affecting the shore, and the way they refract at the shore results in energy divergence or convergence. This determines beach sediment readjustment, potential longshore sediment transport and therefore beach morphodynamics. By modelling refraction trends and calculating refraction coefficients (a measure of the wave energy at the shore), potential longshore sediment movement can be estimated (equation 2.10). Understanding rates of sediment transport helps to explain beach variability and relationships between process and form which assists the construction of a sediment budget by showing potential boundaries of sediment transport. The primary aim of wave refraction modelling was to identify areas of high and low wave energy (and thus erosion) and to produce sediment transport rates for different offshore conditions.

During 1994 records of wave directions, frequencies and heights were recorded. From these potential sediment transport rates were calculated using a graphical wave refraction modelling technique, appropriate for wind waves (King 1972; CERC 1984) as described in section 2.3.1.

Initially the aim was to use all the wave data to calculate significant wave seasonal trends for medium and high energy waves in terms of refraction. Using the percentages of wind and wave directions, the wave energy from each direction reaching the shore could then be calculated. From these results, cells of sediment transport could be defined and potential net sediment transport quantified. However, after data collection and refraction trials, the method had to be modified to accommodate the nature of the results obtained. Analysis of the wave results, showed waves which fell at the extremes of the refraction calculation capabilities. Thus much less detailed modelling was possible, and a different set of priorities was established for this technique.

Most of the wave heights recorded were too small for refraction modelling, the usual method of taking either mean or modal significant wave heights and calculating frequencies of occurrence and a total net transport rate was inappropriate. For this reason, only selected diagrams were prepared. Primarily these showed incident wave direction and refraction for sample waves and from these to calculate the magnitude of potential longshore sediment transport. These results were used to aid definition of sediment transport parameters for the sediment budget. The technique and results proved to be more important for what they did not show, rather than for what they did.

As medium energy waves occurred more frequently than high energy waves, the best reflection of Loch Lomond refraction conditions was to use examples of medium energy waves for the modelling. Medium energy waves were so defined by taking the range of all wave classes and selecting the most frequently occurring class from the middle of that range and refraction diagrams were produced for the principal approach directions of NW, W and SW waves (refer to section 4.1.1) at Cashel and Milarrochy. A further refraction diagram using a rarely occurring high energy wave with SW approach direction (the maximum fetch) at Milarrochy was produced to illustrate the magnitude of refraction and therefore potential transport rates with a larger wave.

The graphical refraction modelling used was the wind-wave method outlined by CERC (1984). The effect of refraction is best illustrated by orthogonals or wave rays. These are lines drawn perpendicular to the wave crest which show the direction of the incoming wave.

The following assumptions for wave refraction modelling apply (after CERC 1984 p2-62):

1. wave energy between orthogonals is constant i.e. no wave energy flows laterally between wave crests;
2. the direction of wave advance (represented by orthogonals), is perpendicular to the wave crest;
3. changes in bathymetry are gradual;
4. incident waves have a constant period, are long crested, small amplitude and monochromatic;
5. the wave velocity at any point is dependant only on water depth;
6. effects from currents, winds, reflected energy from beaches and headlands and bathymetry are negligible.

A large scale chart of nearshore bathymetry for Cashel and Milarrochy was prepared (section 3.2.3). For each example, using the selected wave height and frequency, the deep water wave length (L_0) was calculated from the equation:

$$L_0 = gT^2/2\pi \tag{3.1}$$

where g = acceleration due to gravity ; T = wave period in seconds.

$$\text{or } L_0 = 1.56T^2 \tag{3.2}$$

and refracted into the nearshore using the orthogonal method (CERC 1984).

The resultant angle of the wave crest and the shoreline (α) was measured. This procedure was repeated for each orthogonal.

Using the equation 2.6 (P_L = ECn sin α cos α), the potential energy values or longshore power values for each beach were calculated. Thus longshore energy variation could be seen. These values could then be used to calculate potential sediment transport longshore, discussed in section 2.4 (eq. 2.10).

The results from the wave refraction are presented in section 4.3 with examples of wave refraction diagrams. These contribute to the understanding of sediment transport patterns at Milarrochy and Cashel.

3.2.4 Water level recording

Varying water levels are identified as significant factors in coastal zone change in the literature (section 2.3.3), so they were recorded at Loch Lomond. Primarily, the water level data shows the changing margins of the nearshore zone (i.e. it delimits the sub-aerial and sub-aqueous beach and can help to quantify 'flooding'); it also provides the baseline for wave activity and sediment transport. Water level is a factor which affects the extent and operation of other shore/nearshore processes.

Loch level data was obtained from a secondary source, the Clyde River Purification Board for 1994, (now SEPA). Daily recordings of water level in metres OD are made at Ross Priory, 3 km SW from Milarrochy. Although water levels could be calculated from the wave records, because of the complicated calibration required for waves and further calculations required to determine water level, the secondary source of data was used since water level was measured directly.

Mean daily water levels were recorded for 1994. Whilst there are many options for data presentation and analysis, the most helpful ways of illustrating the water level variation for 1994, in line with the aims of the research were to show mean monthly Loch level variation, cumulative percentage time at particular water levels, and variation within one month. The issue of beach submergence and 'flooding' was also considered, the results are presented in section 4.2.

3.2.5 Currents and lake circulation

Littoral currents include flows of water both parallel (longshore currents) and perpendicular to the shore (shore normal currents). The processes behind these are complex and include wave approach both normal and oblique, edge waves, tides (on the open coast), wave diffraction and wind action. Temperature gradients within layers of water can be set up causing currents to form within the lake. The existence of longshore and shore normal currents is recognised and accounted for in the wave refraction results and they are discussed in relation to these and sediment transport and budget dynamics in sections 4.3, 4.5, 5.3, 5.4 and 6.1.3 and 6.3.

Water circulation within lakes is affected by geostrophic forces, temperature differentials and streams entering the lake. Hakanson (1982) recognises circulation above and below wave base which is usually taken as:

$$d/L = 0.5 \tag{3.3}$$

Seiche action is discussed in section 2.3.3. Different thermal regimes within Loch Lomond are identified by Slack (1957) and Murphy *et al.* (1994). Whilst these affect fine sediment transport and circulation, their overall significance with regard to the aims of this research are limited, and so no experiments were designed to measure water circulation. However, they are important processes affecting sediment and vegetation within the lake context and so deserve brief mention here.

3.2.6 Nearshore sedimentology

The purpose of the nearshore sediment sampling programme was to determine the nature of the nearshore sediments, information which helped to define the shore zone (aim 2). Such a survey also yielded information on sediment movement onshore/offshore and alongshore, and thus assisted with understanding and compilation of the sediment budgets (aims 3 and 4). As the only sedimentological Loch Lomond data available was from deep water cores (e.g. Slack 1957; McKenzie 1978), a field programme was designed for sampling of bottom sediments at Cashel and Milarrochy bays.

Field procedure

There are a number of sediment sampling methods appropriate for this kind of work, most use some form of grab or divers to collect sediment. From a dive taken in December 1992, the existence of a steep nearshore slope and trench was identified at Milarrochy as well as a crude determination of the bottom sediment types. Preliminary trial attempts at sediment sampling were tried, but the visibility and surface tracking of positions were problematic. Thus sampling by boat using a grab, was seen as a preferable option.

An Ekman grab was used for the sampling in preference to the van Veen grab (as used at Lake Vattern, Sweden by Norrman 1964). This latter type can jam when collecting coarse sediment causing fines to leak from the grab jaws. A similar type, the Petersson grab is also criticised for leaking (Dyer 1979). The Shipek and Ekman grabs recommended for gravel sampling (Dyer 1979) are good alternatives. The Ekman grab has two spring controlled clam-like buckets, and a sampling area of 20 x 25 cm. Although the sampling area is relatively small, for the purposes of this analysis, this provided more than sufficient sample sizes. The grab when lowered onto the lake bed is activated, scooping the sediment and shutting when a weight is dropped down the taught cable. It was appropriate for most sediment sizes fractions and as it was not too heavy, could be used without mechanical assistance.

The sediment survey used the basic grid of the pre-existing beach profiles and echo-sounding extended them offshore to beyond the headlands of the bays into very deep water (Fig. 3.1-3.3).

In addition, a number of intermediate points were sampled, particularly at the stream exits and around the headlands so the extent of coarse sediment movement could be ascertained. The survey was carried out on 7/9/94 in calm conditions.

As in the bathymetric survey (section 3.2.2), shore markers, visible from offshore were positioned on the bearing of each profile. A shore-based Total Station was used to monitor boat location, a tracking reflective prism being mounted in the boat. Two-way radios were used to report sample numbers and depths from the boat to the shore based field-assistant. A boat mounted echo-sounder, which gave actual water depths was used to monitor depth. At each profile, samples were taken from the bottom sediments. Samples were taken at intervals approximately along the lines of the profiles at Milarrochy and Cashel. Stream exits were sampled extensively and the extent of coarse sediments noted. On the survey day lake bottom visibility was high, intermediate sediments were noted where visible, particularly close to the shore. The sediments from the grab were transferred into sample bags marked with location number and depth. Further samples were taken in intermediate positions, basic sediment type noted (e.g. gravel, sand etc.), but these were not bagged. They provided a field check for later interpolation on the maps. In total 43 samples were collected. At some locations an anchor was used to hold the boat position while a sample was taken. The samples were then taken back to the laboratory for analysis.

Laboratory analysis

The method chosen was hydrometry which could be done in the Department laboratory, and was suitable for the sediment samples collected. After field collection all samples were examined wet (and later dry colour coded) using Munsell Colour Charts for preliminary sediment description. Any vegetation was removed and approximate compositional percentage determined. Samples were transferred to crucibles and dried in a drying cabinet over several days at 45^{0} C, thus avoiding decomposition of clay rich materials. Some samples had to be disaggregated using a pestle and mortar before sieving and hydrometer analysis. 50 g of each sample was used for this method which was carried out according to standard procedures (eg. Allen 1981), using settling cylinders, sediment solutions of 40 g/l of sodium hexametaphosphate and hydrometers. Five experiments were run concurrently with staggered start times, each taking three days. This was repeated for all the fine samples.

After the hydrometry, cumulative frequency curves were drawn and the standard calculations were performed to determine particle sizes of the samples and the sediment density for the analysis calculations; the results are found in section 4.5. Bearing in mind the aims of the research, the most useful presentation of the results was in the form of isoline maps of mean particle size. These were drawn at a large scale for accuracy (1:1000), and later reduced. The findings of the survey, describing trends of sediment size variation in the two bays and the maps are presented in section 4.5.

3.3 Investigating the shore zone

This section describes the methods used to identify contemporary shore zone characteristics and evidence for historical change. The shore zone is described in sections 2.1 and 2.2 as the interface between water, land and air, a zone characterised by change. To establish the nature of shore zone variability, a critical analysis of secondary data was made and contemporary characteristics were documented and monitored. This section describes the investigations of map and air-photo evidence, contemporary beach geomorphology, beach morphological change, sediment supply and sedimentology.

3.3.1 Historical evidence for shore zone change

Maps

Maps and air-photographs were examined to determine previous shoreline change, trends of change and to place contemporary shoreline change within a longer perspective. A selection of maps was used to make measurements of coastal recession and progradation.

Ordnance Survey maps are available for the field area at scales of 1:10,000, 1:10560 1:50000 and 1:25000. From these, composite maps of the field sites were drawn to a uniform scale, using the OS surveys of 1860, 1861 and 1975. As the early maps were drawn on a County basis with different meridians and with the Loch Lomond coast as the boundary, the total error after photocopying reductions is estimated to be 10%. From the composite maps, measurements of shoreline position were taken under magnification at intervals, to an accuracy of ≤ 0.5 mm or 12.5 m on the ground. The composite maps show shoreline change (section 5.2.1). A further map from the Forestry Commission showed dated shoreline positions of the northern section of Cashel which allowed retreat rates to be measured. The findings from the map analysis are in section 5.1.2.

Aerial photographs

Aerial photograph analysis is generally a useful tool in assessing shore zone change, as photographs, have a date and time, allowing precise shore positions to be determined. If wind or wave records are available very detailed analyses of shore characteristics are possible.

Unfortunately few aerial photographs of the field sites were available. Vertical photographs taken in 1946, 1948, 1988, 1971 and 1993 were analysed. These were largely black and white, and of relatively small scale (1:24000). The photographs were of poor quality, being blurred, over exposed in places, with some tilt, and a lot of shadow, particularly from the trees at Cashel. Defining the exact shore position (water level) was consequently very difficult. In addition, a number of the photographs has the shoreline very close to the edge, where distortion is at a maximum. Shoreline (water level) positions were traced for Milarrochy and Cashel from each photograph and error established. The main findings from these analyses are reported in section 5.2.3. As the area is heavily wooded, the use of most air photographs for determining shoreline features is limited.

3.3.2 The Contemporary shore zone

Geology

As the underlying geology provides the structural framework for the contemporary shore zone and determines macro-scale form, a very brief analysis of the geology was included in the investigation. Geological maps, literature and geological field reconnaissance provide fundamental information for identifying sediment type and sources of eroded sediment and interpreting contemporary processes and change. This section aims to give an overview of the underlying geology of the two field sites as background to understanding present day processes.

The geological map of Scotland, Ben Lomond (1: 50,000) was analysed and the solid geology described. No drift maps are available for the area, although some of the literature refers to glacial till overlying the area. Field samples of cliff material were taken from profile 6 at Milarrochy and profile E at Cashel and sieved to determine particle size using the method described in section 3.4.4.1.

3.3.2.2 Beach morphology

Geomorphological maps are invaluable for their record of landforms. Such maps also provide detailed information on the spatial variability of processes and comparison of successive geomorphological maps of the same site can show temporal variation. No geomorphological maps existed for either field site and so geomorphological maps were drawn for Cashel and Milarrochy Bays at a scale of 1:1000. No OS maps are available at this scale so Cashel and Milarrochy were surveyed using a Total station (Leica T1010). A series of temporary bench-marks (TBMs) were set up at both sites with closure errors of +0.07 m at Cashel and +0.04 at Milarrochy. The position of trees and large bushes and vegetated areas was recorded since some geomorphological features on lake beaches are vegetation controlled. The records of tree positions have been found to be useful in quantifying vegetational degradation from both human and natural causes as well as providing useful reference points in the field. From the TBMs, levels and surveying tapes were used to plot detailed features on the base maps. The geomophological maps are found at the back of this volume.

Beach profiling

Beaches can be described morphologically in terms of profile and their plan shape or shoreline configuration. Measuring profile change is recognised as a suitable method for establishing beach variability (section 2.3.4). The profile data was collected to record beach morphology at any point in time and temporal change and for estimating volumetric beach change for the sediment budget calculations. In order to establish the nature of beach variation, a method which allowed for repeatability of surveys was required. This allows a record of beach conditions at any point in time to be determined and therefore temporal change to be quantified. Thus a stratified survey system was set up to monitor beach change. The disadvantage of this method is that the fixed positions may capture an anomaly leading to incorrect generalised conclusions, although this can be avoided with careful observation of morphological change between profiles.

There are no standard procedures for the spatial positioning of profiles. Examples in the literature (where distances were given) showed Davidson-Arnott and Amin (1983) used 70 stations 200 m apart at SW Lake Ontario. Buckler (1988) used 1 mile intervals from maps at Lake Michigan; 5 survey positions were used on the 9 km long Waihi beach, Australia, by Harray and Healy (1978); Mason (1985) at Holderness used variable distances averaging 500 m apart. Temporal sampling rates vary from daily surveys on the marine coast (Harray and Healy 1978) to map surveying intervals which can be decades (Buckler 1988).

At Loch Lomond, the total number of profiles was chosen so that all surveying could be completed in daylight on one day. Profile locations were chosen to represent morphological characteristics of the adjacent beach area, and where a TBM could be set up with good back markers, averaging 90 m apart at Cashel and 87 m at Milarrochy (Fig. 3.1). At each survey, profiles were surveyed from the TBM on a consistent bearing (perpendicular to the waters' edge) into the Loch to a water depth of between 0.5 and 1.0m (which could be done without a boat). Profiles were surveyed at monthly intervals from January 1994 to January 1995. From this information, cross beach variation could be determined along each profile, and inter-profile beach change interpolated from these measurements. The profiles also showed alongshore beach variation over time. The profiles were numbered 1-6 at Milarrochy and A-I at Cashel to avoid confusion. An extra profile was inserted at Cashel E1, at a later point. Figure 3.1 shows the profile locations on each beach. To establish a greater resolution of profile change, profiles were surveyed on alternate days for two weeks at two periods during the research (July/August 1993 and February 1995).

To show lake beach form and variation, profile co-ordinates for each profile were calculated and plotted. In order to show beach morphological change, profiles from the 1994 measurements were superimposed. From these results a classification of macro-form profile type was derived (section 5.3).

Volumetric beach change from survey to survey was calculated by superimposing profiles. These results showed both net change and total sediment moved between surveys, as well as spatial variation in profiles (section 5.3). To calculate beach volumetric change between surveys a FORTRAN program (*Beachpro*) was written. From the graphical output, erosional and depositional areas could be determined and between survey change calculated using a 2cm resolution along the length of each profile. As surveyed profile lengths varied on account of differing water levels, fixed lengths of profile beyond the surveying lengths were used. Thus surveys were interpolated in the nearshore region to this fixed length enabling comparison of same length profiles. These fixed lengths or closure-depths were determined from the offshore sedimentological surveys, defined as the nearshore beach limits, reported in Chapter 4. As profile change is measured by volume, details of bulk beach density adopted herein are given in Appendix A.

Small scale processes and forms

Whilst the beach profiling monitored overall beach morphological change, field observations showed a number of small scale forms on both study beaches. From these indications of depositional and transport processes were gained. Throughout the fieldwork period, dimensions of beach surface features were measured and recorded when they were observed. This informal but regular monitoring system identified drift directions, patterns of sediment fining and deposition and degree of beach variability and provided important input to an overall understanding of the beach system, particularly that of beach morphological variation and sediment transport thresholds. Examples of the findings are presented in section 5.3.

Sediment transport

Sediment routing through the river/beach system is generally poorly understood, but sediment transport is a key link in determining coastal zone operation. Detailed direct measurement of coarse clastic sediment transport is difficult to determine. In the literature various methods have been used to record sediment transport routing most involving some kind of tracing of materials (section 2.3.6). Entrainment and deposition points are known (between fixed time intervals), but routing between these points is not necessarily known. The purpose of the sediment transport experiments was to gain an estimate of the magnitude of onshore/offshore and alongshore sediment movement. This helps to define transport rates, spatial extent of sediment and sediment budget boundaries and relationships between nearshore and shore processes (aims 2, 3 and 4).

Given the dearth of coastal zone sediment transport data, especially on lake beaches, rather than use mathematical models, field observations were seen as the best option for sediment transport estimates. Tracer particles are useful for identifying sediment transfer, indicating direction and rate of sediment movement. The surveying (section 3.3.2.2) can be used to characterise sediment storage, from which generalised patterns of change and mobility can be derived.

Although a variety of techniques are available, the simplest method of using hand painted tracers was seen as the best method. Magnetic tracers were not used because of the natural magnetism in the field area and the potential for human removal. Radioactive tracers were deemed unacceptable because Loch Lomond is a reservoir. Radio tracers were explored as a possibility, but the cost proved prohibitive. Painted tracers (with different colours) are cheap, convenient and allow several experiments to operate simultaneously, large scale preparation is possible and hydraulic properties are unaffected. Pilot experiments in February 1993 with 200 painted indigenous pebbles taken from the lower beaches, showed the tracers could be clearly identified, traced, and deposition points noted. From these data a sampling frame for the experiments was determined. The aim was to release tracers at a known injection point and sample periodically using a grid surrounding the injection point (the lagrangrian or space integration method; Goudie 1990). This method allows for estimates of the mean velocity of particle movement over a given time period. It also enables spatial concentration of tracers to be established and isolines of tracer concentrations to be constructed, which are important considerations for sediment transport rates (Goudie 1990).

Clasts were extracted from the foreshore at two points at each of the two beaches (Cashel at Profile D and Profile E; Milarrochy at Profile 6 and Profile 3). Tracers were later released at the waters' edge at these points. Two sediment samples from each beach were painted red and the other yellow. The pebbles were then measured, (a, b and c axes) and numbered.

At the injection points, the four sets of 100 tracers were released using domestic detergent to facilitate release into the water body. The injection position was recorded and provided the basis of the recovery grid. The recovery grid system for plotting tracer recovery, comprised m^2 grids set up around the injection point in all directions, using tapes laid on the beach surface (refer to Fig. 3.7). The recovered particles were allocated to the appropriate grids and any trends noted. The experiments ran from 2/2/94-8/2/94, with grid monitoring on alternate days following the tracer release (as appropriate for the weather conditions). After 8/2/94 no further tracers were found. It should be noted that the temporal scale at which results were recorded may have affected the results. Wind and wave conditions can change considerably even within the course of one day, as can tracer position. As these tracer experiments represent a very small sample of total beach sediment, any conclusions need to be drawn with care. The results obtained from these experiments are presented in section 4.5.2.1

3.3.3 Sediment Supply

Sediment supply estimates were determined for shore zone variability definition, relationships between nearshore and shore processes and forms and the sediment budget calculations. As discussed in the previous chapter, beaches are supplied with sediment from rivers, cliffs, and from sediment delivered from alongshore and from offshore. This section considers fluvial and cliff derived sediment. During the offshore bathymetry and sediment investigations and from the wave results (sections 4.1, 4.2 and 4.5) evidence emerged that suggests that offshore coarse sediment (≥ 2 mm) supply may be limited, although this is difficult to measure. Alongshore sediment supply was to be calculated from the wave refraction modelling and the results are discussed in section 4.4. Here, the methods used to estimate sediment supply from rivers and from cliffs to the beaches are described.

3.3.3.1 Fluvial sediment supply

Fluvial sediment supply to the beach is significant as numerous transient depositional features occur in the stream/beach interface. Cashel beach is fed by two streams, and Milarrochy by three, and all are steep mountain streams. Understanding sediment supply requires an understanding of complex fluvial sediment transport processes, suspended sediment and bedload

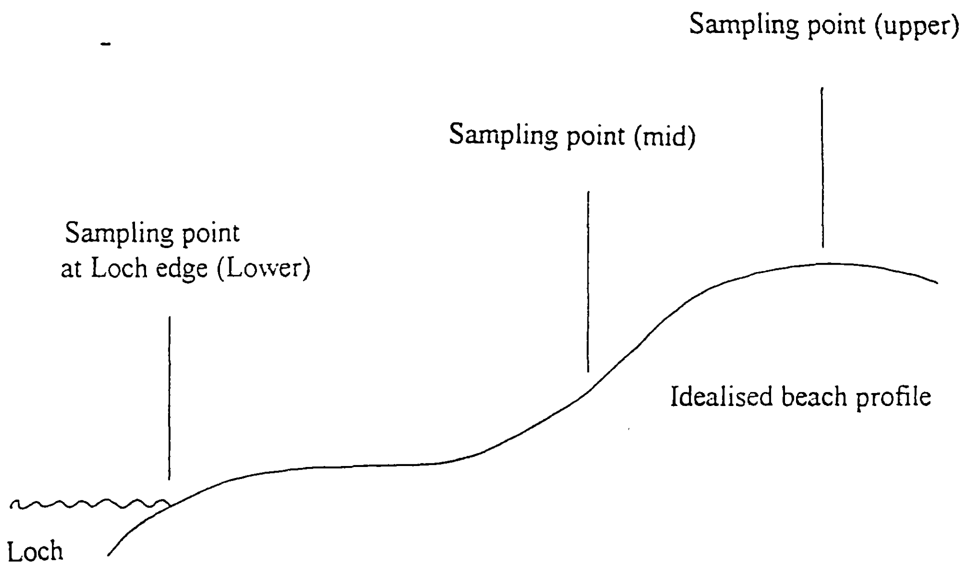


Fig. 3.6 Sediment sampling points for extractive sediment sampling and vertical photographs.

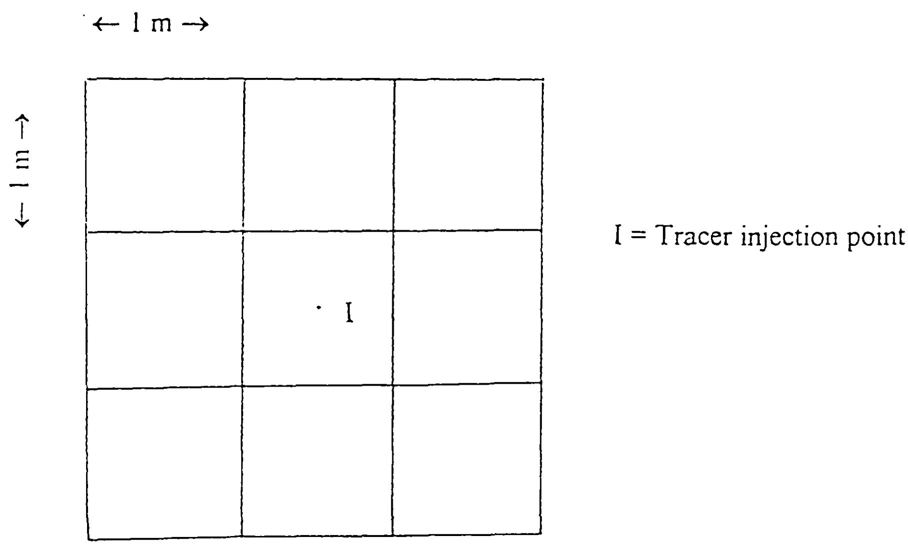


Fig. 3.7 Tracer experiment monitoring grid.
The grid is based on metre squares which can be extended outward from injection point as required.

transportation. For practical reasons this research focuses on bedload (section 2.3.6). Bedload is defined as 'fluid transported sediment which moves along or in close proximity to the bed of the flow' (Goudie *et al.* 1994). The particles which constitute the bedload are generally heavier and move by rolling, sliding, or saltation. Bedload usually constitutes less than 10% of the total sediment transport, although in mountain streams, as in the field area, higher percentages have been suggested (Harvey 1991; McManus 1993).

Long-term bedload discharge (and therefore sediment delivery) can be estimated using traps, (e.g. Richards 1982), tracers (Hassan *et al.* 1984) empirical equations and modelling and morphological methods (Gomez and Church 1989; McManus 1993; Lane *et. al.* 1996). Traps and tracers were not used because of the high degree of human interference on the sites and their time and labour consuming nature. As there is no local sediment delivery data, estimates of magnitudes of bedload were made using published equations and basic hydraulic data. The method entailed the calculation of sediment delivery from records of maximum stage, flow reconstruction and estimating sediment transport under these conditions in each stream feeding Cashel and Milarrochy.

Calculation of sediment delivery by this method uses fluvial sediment transport theory described in section 2.3.6. Bedload transport can be approximated using empirical rating curves. These assume full capacity loads controlled by flow hydraulics (Richards 1982). Many bedload rating equations take the general form:

$$Q_b = a\,(Q-Q_c)^{b} \qquad (3.4)$$

where Q = discharge (m^3/sec); a, b, = empirical constants (b>1.5); Q_c = threshold value for onset of transport. Many different methods can be used to estimate bedload transportation often providing a wide range of results. Theoretical equations can rarely accommodate all the variables of a field site without becoming extremely complicated. Often the theoretical equations are used outside the conditions under which they were calibrated and tested. When used carefully, the estimates obtained are of value when as here, the aim was to use a low cost technique to estimate fluvial sediment delivery to the beach.

The method chosen to calculate fluvial sediment delivery involved three steps. The field measurement stage gauge was deployed and maximum stage readings were taken, then hydraulic conditions were reconstructed and bedload transport and delivery estimated. These estimates were then used in the sediment budget calculations described in section 5.7. A further estimate of sediment delivery from Cashel Burn the largest stream at Cashel was also provided, derived from volumes of sediment removed from Cashel Burn every 8-9 years giving a calibration for the theoretical estimates of sediment delivery (Watson *pers comm.* 1993).

Field procedure

Stage gauges were built and deployed on each of the five streams feeding the two sites, between April 1994 and April 1995. These were positioned just upstream of the beach. Each stage gauge comprised two plastic pipes, one inside the other. The outside pipe was drilled with a series of holes to allow inflow and outflow of water and this was painted with water resistant paint for camouflage. The inner pipe was painted with water soluble ink, which washed off to the level of the water thus measuring maximum stage. The ink was re-painted after every reading. Maximum stage was recorded for each month (the same temporal sampling frame adopted for beach profile measurement) and accuracy was estimated to +/-1cm. This means that even if a series of high discharge periods took place during the sampling period, only the maximum stage was recorded. There were 4 instances of vandalism/gauge removal during the study period, but the loss was discovered quickly and minimal data were lost.

At each of the stage gauge sites, a series of cross sections were measured both up and downstream of the site, on the reaches adjacent to the beach. This enabled the calculation of cross sectional areas, wetted perimeter and channel slope. Water depth across each profile was taken at 0.5 m intervals. The water surface slope was surveyed over 40m. At each cross- section a random sample of 100 bed particles was measured, using a template divided into half-phi sizes (Wolman 1954). This gave sediment size and bed roughness information to be used for estimating sediment entrainment and mobility in varying conditions of stream discharge.

Analytical procedure

In gravel-bed rivers the most widely used flow reconstruction method is that of critical tractive stress (e.g. Church 1978; Maizels 1983; Hoey 1989). From the stage measurements, the technique estimates flow depth and hence discharge from the grain size of the bed material, thus enabling estimation of sediment delivery. The technique uses Shield's entrainment parameter (eq. 2.9, section 2.5), which assumes the largest particles present in a deposit representing the largest entrained by the flow and that all are derived from the bed. Shield's entrainment parameter is appropriate as there is a recognised relationship between the volume (or weight) of the largest particle and velocity (Rubey 1938).

To convert flow depth to velocity and discharge, a measure of roughness is required. There are a number of roughness equations which are similar and about which there is debate in the literature (Maizels 1983; Hoey 1989). Any one would be of use for this analysis so the equation of Limerinos (1970) is used after Hoey (1989). In this, Manning's Roughness coefficient is estimated from:

$$n = 0.113\, R^{1/6} / [1.16 + \log (R/d_{84})] \tag{3.5}$$

$$u = R^{2/3} . S^{1/2} / n \tag{3.6}$$

where n = Manning's Roughness Coefficient (s $m^{-1/3}$); u = mean flow velocity (m s^{-1}); S = channel slope; d_{84} = particle size diameter with 84% finer (mm) ; R = hydraulic radius (m).

The analytical technique used two programmes. The first FORTRAN programme used the bed particle sizes (Wolman counts), the cross sectional data, the angle of slope, the base of the stage gauge height in m OD and the stage (flow) measurements. From this summaries of hydraulic radius, mean depth (across section), mean velocity and discharge were calculated at each water surface elevation in m OD. From this friction velocities (m/s) were calculated for each stream for each month at peak stage, using the following equation:

$$u^* = \sqrt{g . R . S} \tag{3.7}$$

where u* = friction velocity; g = acceleration due to gravity (9.81).

The friction velocity is a measure of the flow stress estimated using the roughness equation (Limerinos 1970), the mean water slope and the grain size data.

The second programme *ACRONYM 1* (Parker 1990) is based on gravel bedload > 2mm measured at Oak creek, Oregon. This was used to estimate, volume transport rates per unit width of stream, and therefore sediment delivered. For each stream, the programme used the friction velocities for each peak stage recorded, the grain size data and submerged specific gravity (for quartz: 2.65-1). Shields' stress for the measured surface bedload (Wolman counts) was derived and volume transport rate in m^3 m^{-1} s^{-1} per unit width estimated.

The results of this technique are presented in section 5.4.1.1 where monthly peak stage and sediment delivery estimates for each stream are shown with catchment sizes, stream slopes, channel widths and bedload particle size.

Two significant problems arise with recording only peak stage over a series of fixed time periods. The first is that there is no record of the frequency of high flows. Secondly, nor is there a record of the duration of flows during that period. In order to overcome this, the duration and frequency of high flow events, were assessed by comparison with stage readings taken from the River Falloch, located in the north of the Loch Lomond catchment (Chapter 1), giving a form of calibration to the field area results. The Falloch is the nearest mountainous gauged station and stage readings are taken every 15 minutes. Direct correlation between the Falloch and the 5 field site streams has not been previously attempted but such a comparison is not unreasonable as the streams have mountainous catchments draining into the same Loch, north of the Highland Boundary Fault. The Falloch catchment is 28 km north of Cashel and 80.3 km^2 in size. The results of this are given in section 5.4 and from these comparisons, the duration and frequency of peak flows was developed, giving the best estimates for the sediment delivery section of the sediment budget.

From these results total sediment delivery for 1994 was calculated. As no data was available for January to April 1994, a surrogate data set was collected from January to April 1995 and substituted in the 1994 sediment budget. The use of the stream discharge estimates for the sediment budget is shown in section 5.5.

3.3.3.2 Cliff sediment supply

The second source of sediment to the beach was from the cliffs. These are predominantly fine sediments (< 2mm) with occasional clasts within the fine matrix. Both Cashel and Milarrochy have small cliffs as shown on the geomorphological maps in the back pocket. Section 2.3.4 describes how cliffs are subject to a variety of processes which can cause erosion and reports have suggested the Loch Lomond cliffs are erosional (section 2.5).

In view of the aims of the research, namely to establish shore zone variability and to calculate a sediment budget for the field sites, cliff monitoring was carried out. The level of monitoring involved measuring linear distances from marker pegs to the cliff top at the time of the monthly beach surveys. Eight survey points were used at Milarrochy and three at Cashel. Cliff foot measurements were obtained at monthly intervals when profiles 6 at Milarrochy and F at Cashel were monitored. In addition, after cliff-falls, volumes of sediment on the beach were measured. Observations of apparent processes were recorded over the study period. Mean recessional rates were calculated and used as input sediment delivery figures in the sediment budget calculations (section 5.7).

For the sediment budget, an estimate of the degree of mobility of cliff sediment was needed. This was partly revealed by beach profile surveys where beach elevation at the cliff foot increased. However, cliff face sediment samples were collected and particle size analysed using hydrometry (described in section 3.2.6). An estimation of percentage fine matrix and clasts was determined at Cashel and Milarrochy. At profiles E at Cashel and 6 at Milarrochy, using tapes, a 1 metre wide section of cliff was used to calculate proportions of fine: coarse sediment. Whilst the proportion changes depending on recent recession and clast inclusion at any one time, this method gave a crude indication of composition and potential supply to the beach.

3.4. Beach Sedimentology

Sedimentological analysis of beach material is important for an understanding of sediment provenance, delivery, composition, beach characteristics and conditions under which sediment transport and deposition take place. Sediments can be analysed in terms of lithology, size, shape texture, sorting and mobility. Various methods were used to investigate these variables on the two beaches, including standard sedimentological methods.

As little is known about lake beach sediments, a comprehensive sampling and analysis strategy was devised which included standard sedimentological methods as well a non-extractive photographic record of surface sediments at sampling points.

3.4.1 Particle size analysis

Standard particle size analysis was used to analyse the spatial characteristics of the beach sediments at a fixed point in time. A systematic stratified sampling procedure was adopted, using the existing profile positions. Samples were taken at each profile at both Cashel and Milarrochy from the upper beach, the beach face (mid beach) and the Loch edge (Fig. 3.6) in November 1994. At each sampling point, surface and subsurface samples were collected over a square metre. The top layer of sediment, determined by the depth of the largest particle in the sampling area provided the surface sample. The sub-surface samples were taken to a maximum depth of 0.2 m over the square metre at each sampling point. Theoretically the largest grain in the sample should be less than 0.1% of the total mass of the sample to estimate median size reliably (Gale and Hoare 1981). For very coarse material this is relaxed to 1% as in the case of this study.

Ninety-six samples were collected in total for this single analysis. In the Laboratory, samples were washed, dried and split where necessary. The large sample sizes for the coarsest sediment necessitated several splits being made (all of which were recorded). Particle size analysis was carried out by sieving using 0.5 phi interval sieves (with square holes), from -5.0 ϕ (32 mm) to 4.0 ϕ (0.063 mm) and a mechanical shaker for 15 minutes per sample (Appendix B gives a particle size classification). The coarsest beach sediment was measured using templates of sizes -3 ϕ (8 mm) to -8.5 ϕ (362 mm), and then weighed. For all samples, sediment mass and percentage mass per class size was recorded. Both sieving and templates measure 'nominal diameters', (Goudie *et al.* 1990) which are approximately equivalent to the b axis of a grain. From these data, phi median, mean, sorting and skewness of each sample was calculated, using a *Microsoft Excel* program (sieve0_5). The program also plotted cumulative size distributions from the sieving results, making for easy comparisons between samples and from which d50 and d84 were calculated. Examples of these together with the summary results of mean particle size, sorting and skewness are presented in section 5.5.

Details of the standard parameters and formulae (after Briggs 1977) used to describe the sediment are given here. In the program the values were derived from the cumulative percentage curves.
The *median* particle size is $\phi 50$ (d50, where d is the particle diameter). (3.8)
which is the 50th percentile of the distribution.

The *mean* particle size is $$\frac{\phi 16 + \phi 50 + \phi 84}{3} \qquad (3.9)$$

The *sorting* of the sample gives an estimate of the spread of the sample distribution akin to the standard deviation, estimated from the cumulative percentage/grain size curves. Poor sorting (a large standard deviation), indicates that little particle selection has taken place during transport or deposition and vice versa (Pethick 1984). The formula used to calculate sorting was :

$$\frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \qquad (3.10)$$

Table 3.1 overleaf shows the sorting parameters and interpretations which are used to describe the sediment (overleaf, after Briggs 1977).

The *skewness* of a sediment distribution is a good indicator of the history of a sample. The formula used to calculate skewness was:

$$\frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84\ \phi - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)} \qquad (3.11)$$

A positive skew on the phi scale indicates an excess of fines. This may be because fines have been added to the sample, or coarse grains may have been selectively removed (Pethick 1988). Table 3.2 summarizes the skewness values (after Briggs 1977).

Table 3.1 Particle Sorting

ϕ size	*interpretation*
0-0.25	very well sorted
0.25-0.5	well sorted
0.5-0.71	moderately well sorted
0.71-1.0	moderately sorted
1.0-2.0	poorly sorted
2.0-4.0	very poorly sorted
> 4.0	extremely poorly sorted.

Values for D84 and D16 were also calculated from the cumulative frequency graphs. D84 is the grain size diameter at the 84^{th} percentile. This means 84 % of the sample is finer than this value. These figures are valuable descriptors of the sediment sample and are useful for inter-site comparison.

Table 3.2 Particle Skewness

ϕ size	*interpretation*
-1.0 → -0.3	very negatively skewed
-0.3 → -0.1	negatively skewed
-0.1 → +0.1	symmetrical
+0.1 →+0.3	positively skewed
+0.3 → +1.0	very positively skewed

Further investigation of the sub-surface sediments was provided by stratigraphic beach sediment logs taken at Cashel and Milarrochy. The purpose was to identify the nature of sub-surface sediments, to see indicators of depth of beach disturbance under waves, and to identify any sorting trends with depth. Pits were dug to a depth of 1 m close to the upper beach, at Milarrochy adjacent to profile 2 with 2 m width and at Cashel at profile I for 80 m (x marks the pits on back pocket maps). Because of the difficulty of digging through coarse clastic beach sediments, only two pits were dug, by hand at Milarrochy and using a mechanical digger at Cashel. Statigraphic logs were drawn from both pits giving information of beach composition on a three dimensional basis. This information contributed to understanding of beach dynamics and was important for the sediment budget interpretation. The sub-surface stratigraphic profiles are presented in section 5.5.2.

The summary findings of all the particle size analysis for surface and sub-surface samples at Cashel and Milarrochy are given in section 5.5 and Appendix F. These data provide a comprehensive overview of the Cashel and Milarrochy beach sediments. Three statistics were used in the descriptive analysis, median grain size, sorting and skewness as these were seen as the most appropriate and meaningful descriptors of the beach sediment population in relation to the aims of the research. Alongshore and cross-beach trends were analysed, alongshore regression analysis performed, and the main characteristics highlighted.

3.4.2 Temporal and spatial sedimentological analysis

In order to monitor sedimentological variation both temporally and spatially, a less time-consuming method than sieving was required. A repeatable systematic point sampling strategy was used to identify the morphological and sedimentological changes that occurred simultaneously. Various photographic methods were investigated including that of Ibbeken and Schleyer (1986), who describe using photographs (vertical) as a method for grain size analysis of coarse unconsolidated bedding surfaces. This technique was modified to record surface beach sediment at Milarrochy and Cashel because it is fast, repeatable non-extractive and therefore does not interfere with the structure of the beach. It records imbrication and packing and provides a permanent record. Using the beach profile positions already set up, vertical image photographs were taken from a height of 1.3 m between January 1994 and April 1995 on the day following the beach profile surveys to allow for close correlation of morphology with sedimentology. A 35mm SLR camera with a 50mm lens was used, recording within each photograph a slate with profile name, location, date, and scale. Black and white 100 ASA film was used except in dark winter conditions when 400 ASA film was more appropriate, and though of poorer resolution, perfectly good for analytical work. The photographs were taken, at the Loch edge, (which was variable), at the foreshore/beach face and at the upper beach (Fig. 3.6).

This method of photographic sediment sampling provided a large data set and permanent record of beach conditions at the sampling points throughout 1994 and early 1995. The most effective way to present the findings was to classify the photographs into a series of sediment types which best described the surface sedimentology. Various groupings were tried (arithmetical and cumulative), but field recognition and laboratory visual analysis identified frequently re-occurring 'sedimentological types' (Fig. 3.8). The classification began qualitatively, on which a repeatable quantitative classification system was imposed. The system is explained below and is used because it best describes the variation of beach sedimentology.

The photographs were developed to give prints of 20 x 30 cm. Axes 30cm long were drawn on the photograph parallel and perpendicular to the waters' edge in a random position on each print. In this way, because of the orientation of the two axes, any trends are picked up. The number of grains along each axis in each print, were counted and recorded, and a general classification of sorting was developed. The number of clasts along each of the two random axes described above was recorded and an average taken. Where two or more sediment types were visible, sub-sections of axes were used (e.g. with two sediment types, one type would be measured over a half size axis (15 cm) and the other over the other 15cm, the two values being kept distinct). The numerical classification was in units of 10. Where between 1 and 10 clasts occurred on the 30 cm axis, the Type was designated Z; where between 11 and 20 clasts occurred the Type was designated Y; and 21-30 clasts for Type W. For the smaller sediment sizes, and less frequently occuring types, larger groups were used e.g. 31-60 for Type W, 61-80 for Type V, 81-100 for Type U. Type T comprised sand, Type S clays-silt and further Types were mixed. Where mixed sediment populations occur, two or more letters are used, the dominant type being named first.

The photographic record provides valuable information which can be linked with antecedent wave conditions. Any distortion associated with the angle of the beach face and camera position was obvious from the prints and only gave small error (> 1 mm at the corners), calibration being provided by vertical photographs of graph paper. Where a photograph coincided with a ridge or runnel or a sequence of these, uncertianty was estimated to be less than 1.5 mm in these areas. The packing of the beach affects the classification and where imbrication occurs and the clast b axis is hidden in the vertical plane, smaller clast sizes are estimated by the classification. Any such occurrence is recorded with the results presented in section 5.5. A full summary of the temporal and spatial sedimentological variability is reported in 5.6.1, where analysis and description of trends is given. Section 6.2. gives an interpretation of the sedimentological results.

3.4.4.3 Particle shape analysis

Particle shape was investigated to describe beach texture, to identify sediment provenance, spatial trends in shape and to help reconstruct palaeoenvironments. The sampling strategy used mid-beach surface point samples from Cashel profiles C, E1 and I and from Milarrochy profiles 1, 3 and 6 (Sample collection is recorded in section 3.4.4.1). In addition upper beach samples were

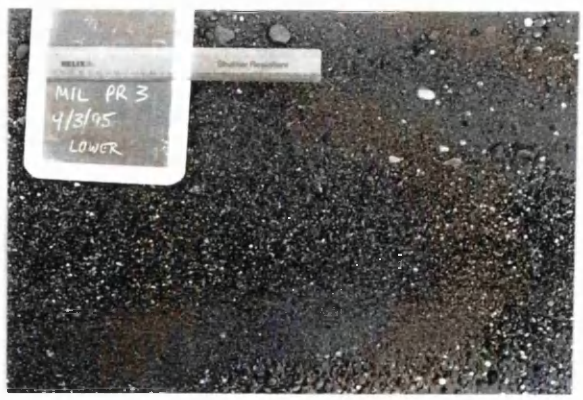
Type Z

Type Y

Type X

Type W

Type V



Type U

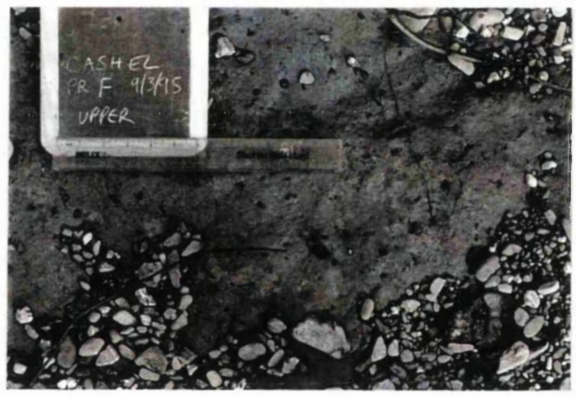
Fig. 3.8 Vertical photograph sediment classification (also overleaf)
See text for details

Type T

Mostly Type S

Mixed Types

e.g. Type ZT



e.g. Type SY

Fig. 3.8 Vertical photograph classification continued. (see previous page and text for details) taken from the back ridge at Cashel at profiles A and D, where monitoring had revealed a very stable system.

Particle shape analysis measures the three principle axes of a particle. Four descriptive categories were determined by Zingg (1935). These are *bladed*, where both axial ratios are less than 0.667; *tabular* or discoid, for which the b/a ratio is greater than 0.667; *equant* or spherical where the axial ratios are greater than 0.667; *prolate* or roller, where the c/b ratio is greater than 0.667. For this classification, the a, b and c axes of 50 particles from a selection of samples used in the sieving and template size analysis (section 3.4.1).

The second descriptor of particle shape used was roundness (Powers 1953; Fig. 3.10). This describes by roundness, the degree of particle abrasion which indicates palaeo-environmental conditions. For example, heavily rounded clasts are more likely to have been subject to high energy conditions such as wave action. From each sample 50 particles were classified.

The results from the particle shape analysis are presented in section 5.4.2. and the significant points highlighted. Appendices E and G show the Zingg plots and histograms of Powers' results. The information from these results is used in the interpretation of the beach sediment budget and coastal system (section 5.7 and chapter 6).

3.5 Sediment budget calculation

The method used for constructing sediment budgets at Cashel and Milarrochy is explained here, the results are presented in chapters 4 and 5 with the final budget construction described in section 5.5 at the end of the results.

The data collection was designed to enable quantification the 1994 sediment budget for both Cashel and Milarrochy. The main sediment budgets were calculated from the monthly beach surveys as explained in 3.3.2.2 using the sedimentologically defined closure depths. Volumetric change at each profile was quantified. To calculate net sediment change on areas of beach between profiles, total change at each profile was added to the total change at the adjacent profile and divided by two, giving the mean change. This therefore identified beach areas of net gain or net loss and showed the longshore pattern of erosion and accretion. A uniform width of 1 m of sediment was assumed for the volumetric calculations. These results indicate areas of sediment flux, stability and storage.

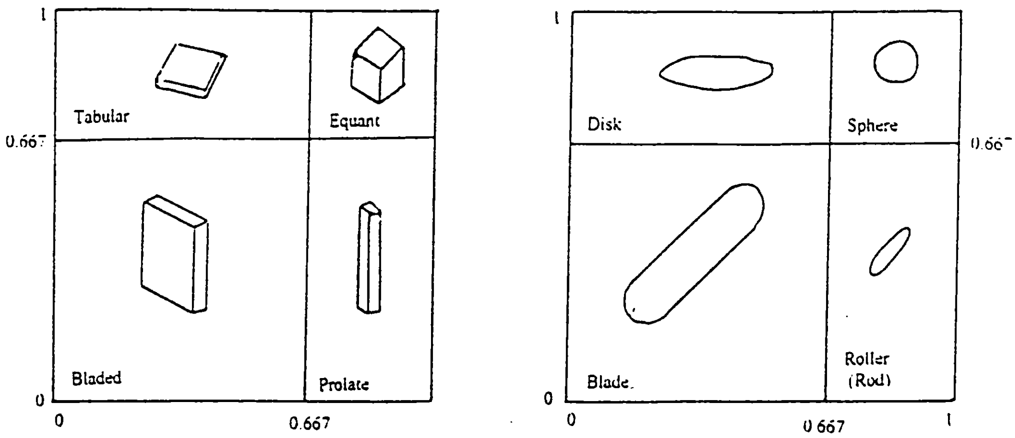


Fig. 3.9 Particle shape classification (after Zingg 1935)
The Zingg classification is a measure of all three principal axes of a particle. The long (a), intermediate (b), and the short (c) axes (defined at 90^0 to each other) are measured and plotted as a graph comparing the b/a axis ratio against the c/b axis ratio. The system divides particle shape into four categories: Bladed, Tabular, Prolate or Equant based on axial ratios being greater or less than 0.667.

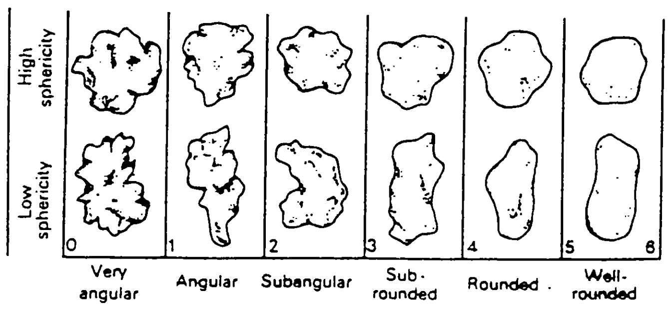


Fig. 3.10 Particle Roundness Index (after Powers 1953)

To identify the components within the sediment budget, investigations have been described in the preceding sections. Measurement include terrestrial sediment inputs from fluvial and cliff sources, sediment transport (by tracer experiments), wave refraction modelling and shore/nearshore sediment sampling indicating the extent of longshore and offshore sediment loss. Quantification of these components gives a better understanding of the operation of individual sediments. Areas of uncertainty in calculation include surveying error (estimated to be ± 2.5 cm), beach compaction, modelling of fluvial sediment delivery, assumed closure depths, and estimates of 'rollover volume' with landward movement of gravel. All of these uncertainties will be further discussed in the following chapters.

3. 6 Summary

This chapter has described the research approach and methods of data collection which include fieldwork, laboratory procedures, analytical and modelling techniques. The focus of the research and the routes via which the aims could be determined have been described. The research programme was broadly grouped into 3 sections: the nearshore environment, the shore environment and the integration of the coastal zone variables. The time-scales over which the data was collected have been explained along with the methods used for experiments in each of the coastal sub-systems. The following two chapters present the results from these investigations, Chapter 4 focusing on the nearshore environment and chapter 5 on the shore zone and integration of the coastal sub-systems.

Chapter 4 RESULTS: THE NEARSHORE ZONE

4.0 Introduction

The terrestrial and hydrological factors which affect the lake coastal zone, and the methodology and data collection have been presented in chapters 2 and 3. In this chapter, the results of the hydrodynamic processes affecting the shore zone and the physiographic conditions in which these processes operate are presented. These are:- the hydraulic factors of the nearshore zone (water level and waves), shoreline configuration, exposure, bathymetry and sedimentology (sediment characteristics, transport and delivery). These results combine to show the factors which influence beach variation and operation, and provide results for sediment budget calculations. The second part of the results, the shore zone geomorphology, sedimentology and beach variability, is presented in chapter 5, with the results from these two chapters discussed in chapter 6.

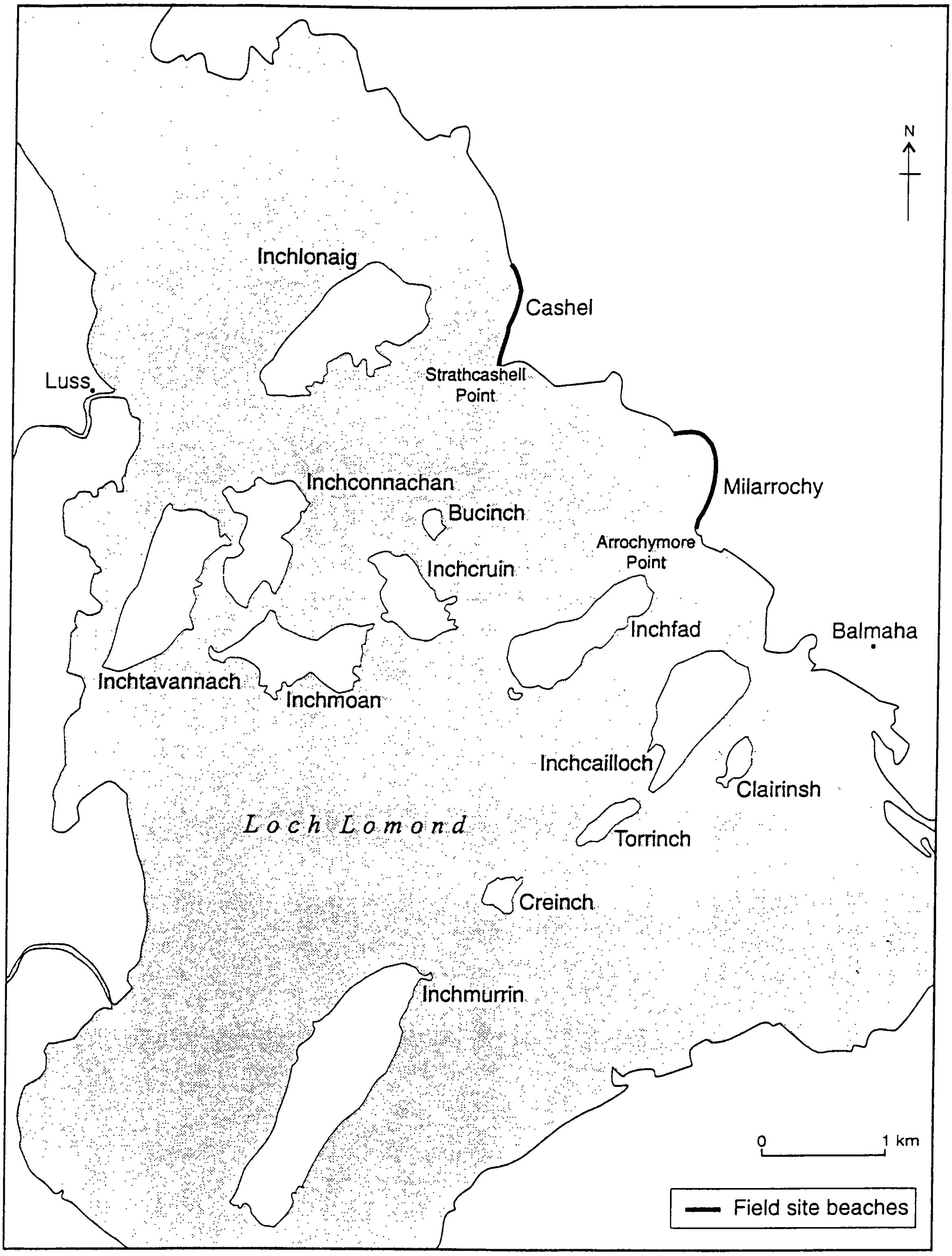
The nearshore zone is defined (section 2.2) as the lake zone adjacent to the coast, in which waves are transformed and most sediment movement occurs. It extends from the onshore limit of wave activity at the shore (at each water level), to the deep water of the offshore zone. For the purposes of these results, nearshore investigations extend to the offshore limit beyond the bay headlands and into the deep water of the Loch.

4.1 Characteristics of the nearshore zone

The characteristics of the nearshore zone and the processes acting within this zone (primarily waves) have a significant effect on the behaviour of the shore zone. In order to place the structure and physical context within which the processes operate, it is necessary to outline shoreline configuration, exposure, potential fetch and bathymetry for the sample sites at Cashel and Milarrochy.

4.1.1 Exposure of the shore

The south-eastern shore of the Loch where both beaches are located comprises bays and headlands which with nearshore bathymetry affect the way waves refract and modify the beach (Fig. 4.1). Numerous islands both afford shore protection from prevailing winds and waves but conversely contribute to funnelling of winds and water between islands so concentrating wave activity.



Source: Adapted from Ordnance Survey 1:50 000, Sheet 56.

Fig. 4.1 Shore configuration and field-site location:
Cashel and Milarrochy on the south-east shore of Loch Lomond.

Inchlonaig at Cashel, gives some protection to the shore from westerly winds and waves, particularly in the southern section of the beach.

The fetch (the length of water in the nearshore and offshore zones over which the wind blows causing waves to develop) is significant as it determines the potential wave size, given a specific wind velocity and duration from any one direction. Table 4.1 shows the fetch lengths from the major wind directions affecting the field sites and alongshore variability in exposure. (The profile positions referred to are shown on Fig. 3.4). Straight line fetches are used as they best represent wave heights in small lakes (CERC 1984).

Table 4.1 Maximum potential fetch affecting Cashel and Milarrochy

Wind direction	Maximum fetch length (km)	Comment
Cashel		
N	0.75	across bay only to Profile A
S	7.5	between islands: affects the bay north of Profile I
E	N/A	
W	6.4	island of Inchlonaig provides some protection, but profiles E-I are affected.
NW	5	affects delta area at profiles H and G
NE	N/A	
SW	3.5	affects all beach
SE	N/A	islands give protection
Milarrochy		
N	N/A	protected by headland
S	1.75	affects Profile 1, 2 and northern beach
E	N/A	
W	4.75	affects Profile 4
NW	3	affects profiles 5 and southern beach
NE	N/A	
SW	7.5	between islands affecting profiles 1 and 2
SE	N/A	

The effects of easterly winds are masked by the east shore location of the beaches and the presence of deciduous woodland 200 m from the water. Cashel beach is potentially vulnerable to north-westerly, westerly and south-westerly waves. These results show that the longest potential fetches are from the west and north-west at Cashel, the islands giving some protection. The longer fetch southerly waves are only likely to affect the shore to the north of Cashel unless wave refraction is significant. Southerly waves however may set up significant northerly alongshore drift. Northerly winds are relatively insignificant because of shore orientation.

Milarrochy beach is much more exposed and vulnerable to waves from the north-west, west and south-west. Milarrochy has the longest fetches from the west and south-west and more limited exposure to waves from the north-west. Like Cashel, northerly waves are relatively insignificant because of the shore configuration. The headlands provide protection from most southerly waves.

Locational similarities and differences can be identified. Neither site will be significantly affected by easterly or northerly winds and waves. Both sites are exposed from the west, north-west and south-west, Milarrochy having the longest fetch of 7.5 km from the south-west. The southern beach at Cashel is protected from long fetch wave development by the island Inchlonaig.

These fetches are very small, and highlight the distinctive fetch restricted conditions of the lake environment. If the dominant winds coincide with the longest fetches there is potential for maximum impact on the shore zone by nearshore processes (i.e. west and north-west at Cashel, and west and south-west at Milarrochy).

4.1.2 Nearshore bathymetry

Bathymetry of the nearshore is important to understand wave transformation in the nearshore as this affects sediment transport and beach changes. From the bathymetry, wave refraction patterns can be calculated and wave/shore interaction estimated. If the water is shallow in the nearshore, waves 'touch bottom' (section 2.4.1) some distance from the shore, refracting earlier and dissipating energy; conversely deep water in the nearshore means that waves almost reach the sub-aerial beach before refracting (depending on wave amplitude and frequency). This also means that higher energy waves break at the shore rather than further offshore, potentially causing greater transfer of energy to the beach. The main bathymetric features from secondary sources and from the bathymetric surveys are described here.

The Admiralty Survey of 1861 shows depth soundings in fathoms (Fig. 4.2). Much less detailed soundings were taken in 1910 (Murray and Pullar 1910), but there are no recent surveys. Significant beach development at Milarrochy is noted with relatively steep offshore shelving. Depths of up to 15 fathoms (27.4 m) are recorded within the bay. At Cashel bay depths of up to 24 fathoms (43.9 m) are recorded and deep water of up to 8 fathoms (14.6m) is found close to the shore.

The bathymetric field survey results (section 3.2.2) at Cashel and Milarrochy are presented as maps in Figs. 4.3 and 4.4. The letters denote profile positions (Fig. 3.4) which constituted the basis of the basis of the survey grid. The field survey suggests that water levels are higher (approximately 1.2 m) than the Admiralty survey 134 years ago.

The bathymetric contours at *Cashel* (Fig. 4.3) approximately follow the shoreline orientation. The immediate nearshore (closest to the sub-aerial beach) is characterised by a relatively steep incline and the water reaches a maximum depth of 45 m within 200 m of the shore. The steepest nearshore incline extends from profile A to the stream at E1 at the mouth of which a small delta was identified. Between this point where the beach orientation changes and Cashel Burn (profile H), the immediate nearshore has a shallower gradient. Immediately offshore of the Cashel Burn delta, there is an extremely steep incline. The nearshore is steeply inclined between this delta and the shore defences beyond profile I, the northerly limit of the study at this beach.

Of particular note is the steep nearshore bathymetric contouring, particularly between the 5 and 10 m contours). This pattern illustrates the existence of a steep offshore slope. The deepest section of the Cashel nearshore (45 m, 200 m from the shore) is to the north of Inchlonaig (island shown on Fig. 4.1). The stream exits show sedimentation and delta development affecting nearshore bathymetry. The Cashel Burn delta extends for 14.2 m beyond the waters' edge and the stream delta at profile E1 approximately 8 m.

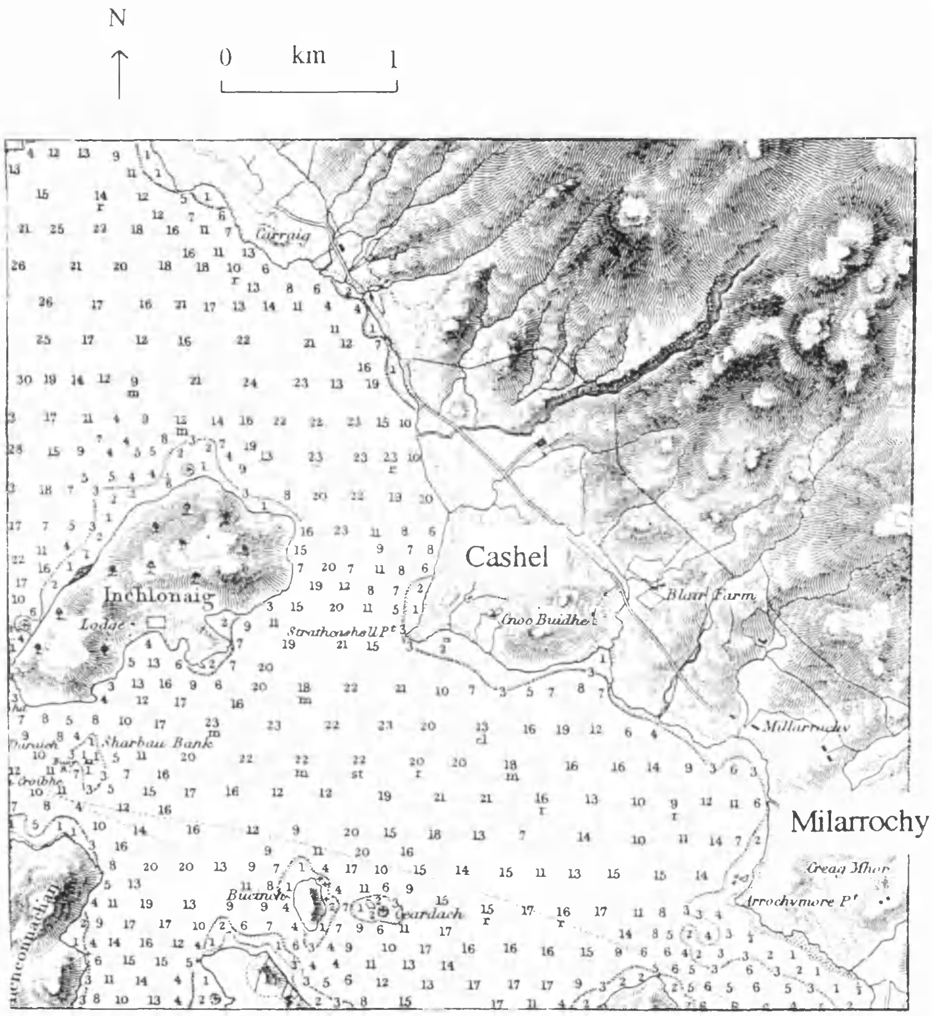


Fig. 4.2 Extract of Loch Lomond bathymetry at Cashel and Milarrochy (from Admiralty Survey 1861). Depths are in fathoms (1 fathom = 6 feet = 1.83m)

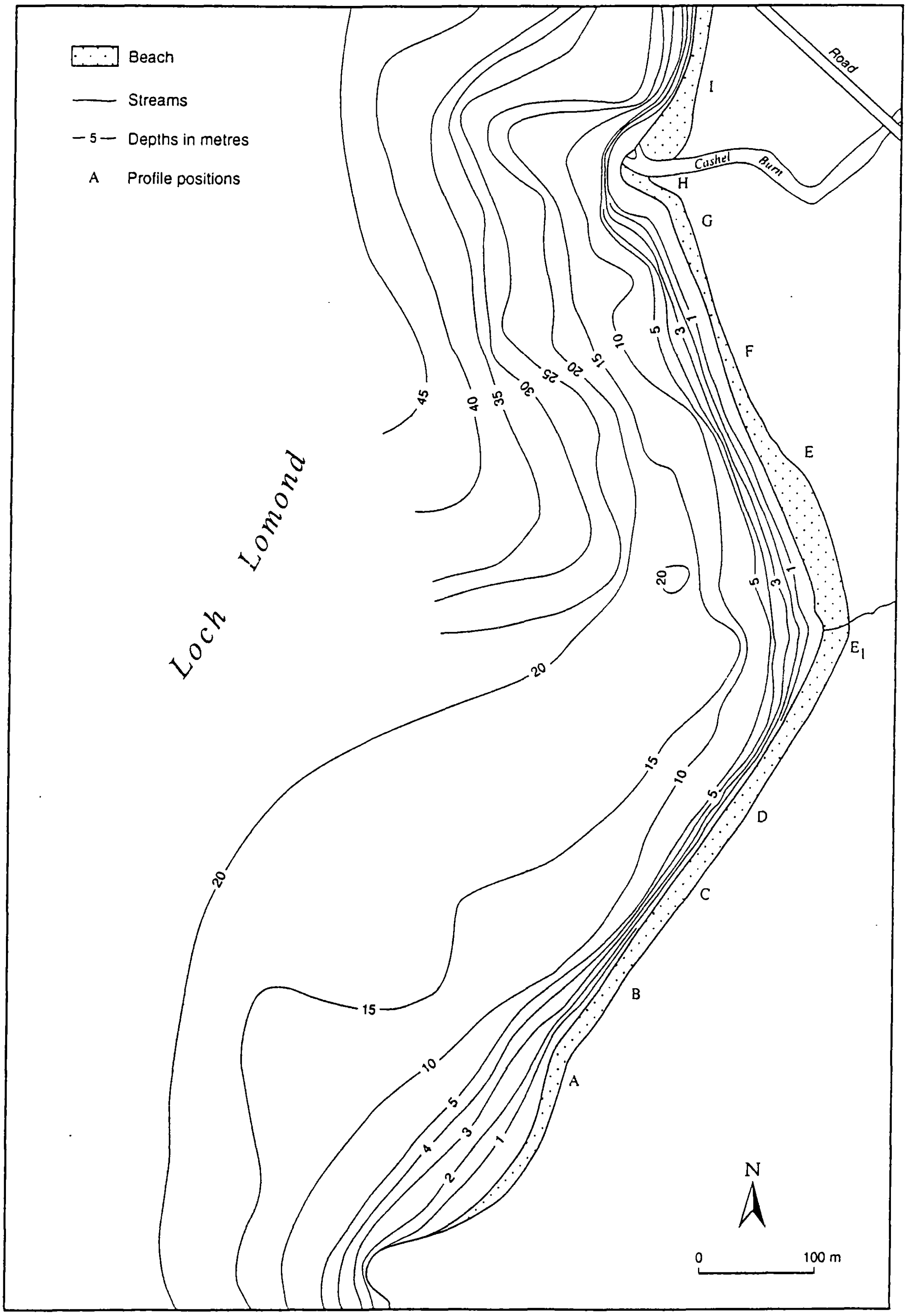


Fig. 4.3 Bathymetry at Cashel bay, Loch Lomond
Echo-soundings were taken on 2/7/94. Water level was 7.84 m OD at time of survey. The bathymetric contours stop at the limit of the survey.

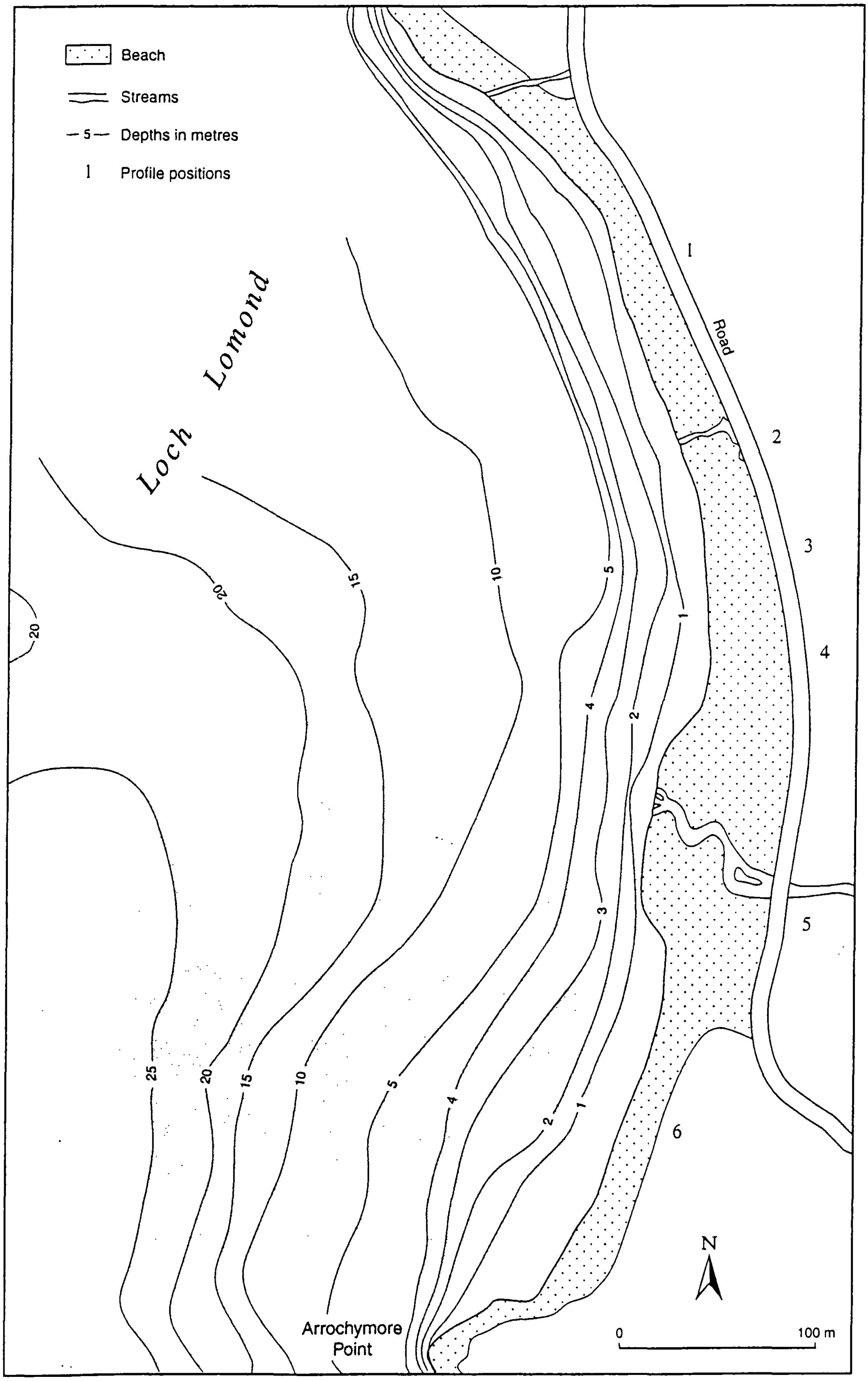


Fig. 4.4 Bathymetry at Milarrochy bay, Loch Lomond
Echo-soundings were taken on 23/5/94. Water level was 7.65 m OD at time of survey. The bathymetric contours stop at the limit of the survey.

The *Milarrochy* bathymetric survey (Fig. 4.4) showed generally shore parallel bathymetric contouring and with a relatively steep incline away from the waters' edge. The deepest water (25 m) is found offshore to the south of the bay, beyond the line of the headlands. As at Cashel, deep water occurs close to the shore. Two dives made in the area between profile 1 and the northern headland showed a bathymetric trough approximately 40 m distance offshore, beyond the 5 m depth contour (masked by the contouring at 5 m intervals, the echo-sounding traces confirmed the existence of the trough). Sedimentation resulting in shallower water at the stream exits was apparent, especially at the most southerly stream at Milarrochy (profile 5).

Overall the bathymetric surveys highlight a steep incline in the nearshore, nearshore deep water, and shore parallel contours. The nearshore zone is therefore characterised by deep water and incident waves are unlikely to be modified by shallow water bottom effects until very close to the shore. This means higher wave energies are likely to affect these beaches than those in locations where nearshore bathymetry is less steep.

4.2 Water Levels

Water level rise is associated with some of the most significant changes in shore morphodynamics both spatially and volumetrically (section 2.3.3). For this reason, water level recording was important, to establish the degree of fluctuation and assess the impact this has on the shore.

The range of water levels recorded since records began is from 6.752 m OD to 10.071 m OD (CRPB 1996 *pers. comm.*). When water levels are above 10 metres, as in January 1991 (Dickinson and Pender 1990) most of Milarrochy and the northern section of Cashel beaches are submerged. In 1994, the minimum level was 7.492 m OD and the maximum 9.254 m OD. With relatively low water levels in the summer months and high levels in the winter months (Fig. 4.6) a trend which is repeated in most years. These seasonal changes are related to precipitation patterns (Black 1995; Ventura 1995) and resultant stream input. Monthly averages conceal rapid changes in water level which vary from day to day by up to 0.2 m (Fig. 4.6).

The water level at the beaches is also affected by wave set-up where breaking waves cause a rise in the mean water level inshore of the breaker. Where wave heights are greatest, potential wave set-up is greatest, although the amount is proportional to beach slope, and the width of the surf

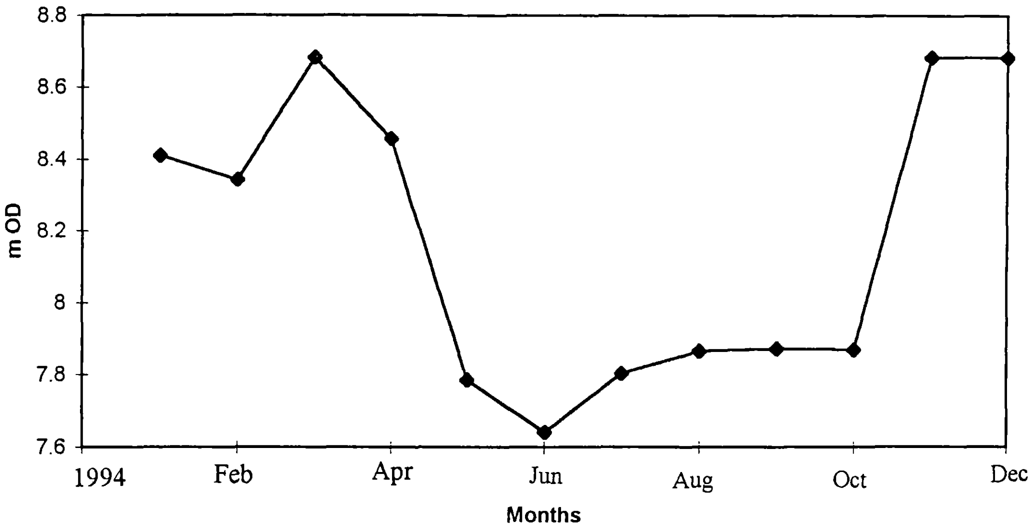


Fig. 4.5 Monthly mean water levels at Loch Lomond during 1994

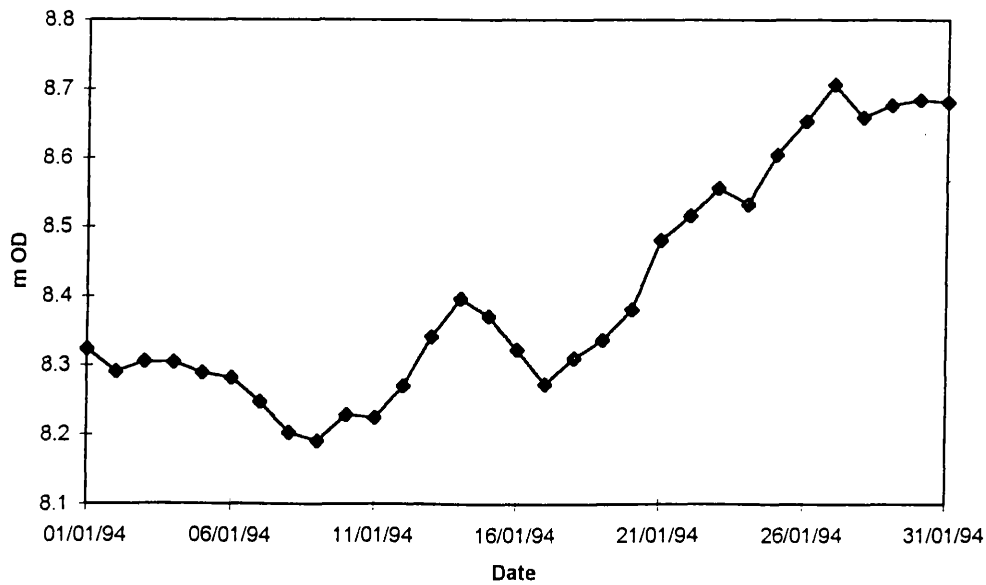


Fig. 4.6 Daily Loch levels at Loch Lomond during January 1994

zone (Longuet-Higgins 1983; Van Dorn 1978). Although breaking wave dynamics were not recorded here, the relevance is that wave activity increases the water level on the beaches (c.f. sec. 4.3), so transferring more wave energy shoreward (e.g. up to 0.8 m). Seiches, or short-term standing waves/oscillations are difficult to detect and no clear evidence for seiche activity was established during the course of this research (c.f. secs. 4.3 and 6.1.1). The water level provides the fundamental control for the effects of wave activity. If water levels are high, the upper beach, cliff foot and backshore vegetation are vulnerable to wave action.

4.3 Wave climate

The most significant processes controlling changes in the coastal zone are those associated with wave action (Davidson-Arnott and Pollard 1980). Quantification of wave energy at the lake shore (wave height, period, and direction of wave approach) is needed for understanding sediment transport and beach morphodynamics (e.g. King 1972; Pethick 1984). In this research, waves were recorded to define the Loch wave climate *per se*, (aim 1) and as part of the investigation of beach morphodynamic and sedimentary response to wave conditions (aims 2 and 3). Limited fetch at Loch Lomond prohibits the development of significant swell as occurs in the ocean, so wind waves predominate.

In this section, the wave records at Loch Lomond are presented, including a critique of the instrumentation, data resolution and record quality. The wave statistics derived from the wave record are then reported, using standard wave parameters described in Chapter 3: crest period, zero crossing period, maximum wave height, significant wave height and spectral width parameter, (the summary statistics for 1994 are in Appendix C). The wave spectral analysis and examples of the different types of spectra derived from the wave records are given, followed by wave direction and storminess results derived from the wind records. These results lead into the wave refraction modelling (section 4.4) as the relationship between wave conditions and shore behaviour is explored.

Data quality and resolution

A large data set was generated from the wave recording programme. As most of the results are presented as summary statistics of wave trends, this first section describes two examples illustrating data quality and resolution. Detailed examination of these records aids understanding and discussion of the wave records obtained. The wave probe recording technique (section 3.2.4) enabled high quality wave records to be obtained. The two wave probes (A and B) were deployed sequentially. The high resolution of the small probe (A) was effective in determining the characteristics of very small waves under relatively calm conditions (Fig. 4.7). When viewed over the 5 minute sampling period (Fig. 4.7a) the structure of the waves can be seen together with some evidence for a long period oscillation with a period of about 100 seconds. Of note are the occasional peaks and troughs up to 50% greater than the mean, which have been confirmed by field observation. The significant wave height of 0.038m and spectral width parameter of 0.51 indicate small, slightly irregular waves. Viewed over a smaller temporal scale of 60 seconds (Fig. 4.7b) further details of wave form become apparent. Double peaks are visible, a commonly observed feature of Loch Lomond waves. The larger waves visible in Fig. 4.7b are confirmed by repeated field observation to be characteristic of the Loch environment, with a series of smaller waves followed by single larger ones. Such detail, which is presented to illustrate the capabilities of the instrumentation, can be recorded only with probe A as there is a loss of resolution with the longer Probe B.

This lower resolution with probe B causes truncation of wave peaks and troughs (Fig. 4.8a, b). Despite the larger waves (H_S = 0.26m) many of the same features of wave shape and the superimposition of smaller waves upon larger ones, noted previously for small waves, remain detectable. Flat tops to the recorded waves occur when the peak has gone undetected and illustrate the limit to wave shape determination imposed by the sampling frequency and probe sensitivity. This occurs despite the very high sampling frequency and indicates high frequency waves. However, the overall patterns are retained in the results, and calculations of descriptive parameters remain reliable although subject to resolution dependent error. Probe B was re-calibrated several times in the field, and after a year's continuous use was found to be consistent. Further discussion of the technique is given by Pierce *et. al.* (submitted 1997).

Wave train analysis

Over 700 5-minute long wave records were recorded during 1994, most of these with probe B. representing one of the most comprehensive British lake wave climate data sets acquired. Selected examples of wave records are discussed here to show the *diversity* of record types, as not all the records can be presented. The aim of selecting the following examples is to illustrate detail of the

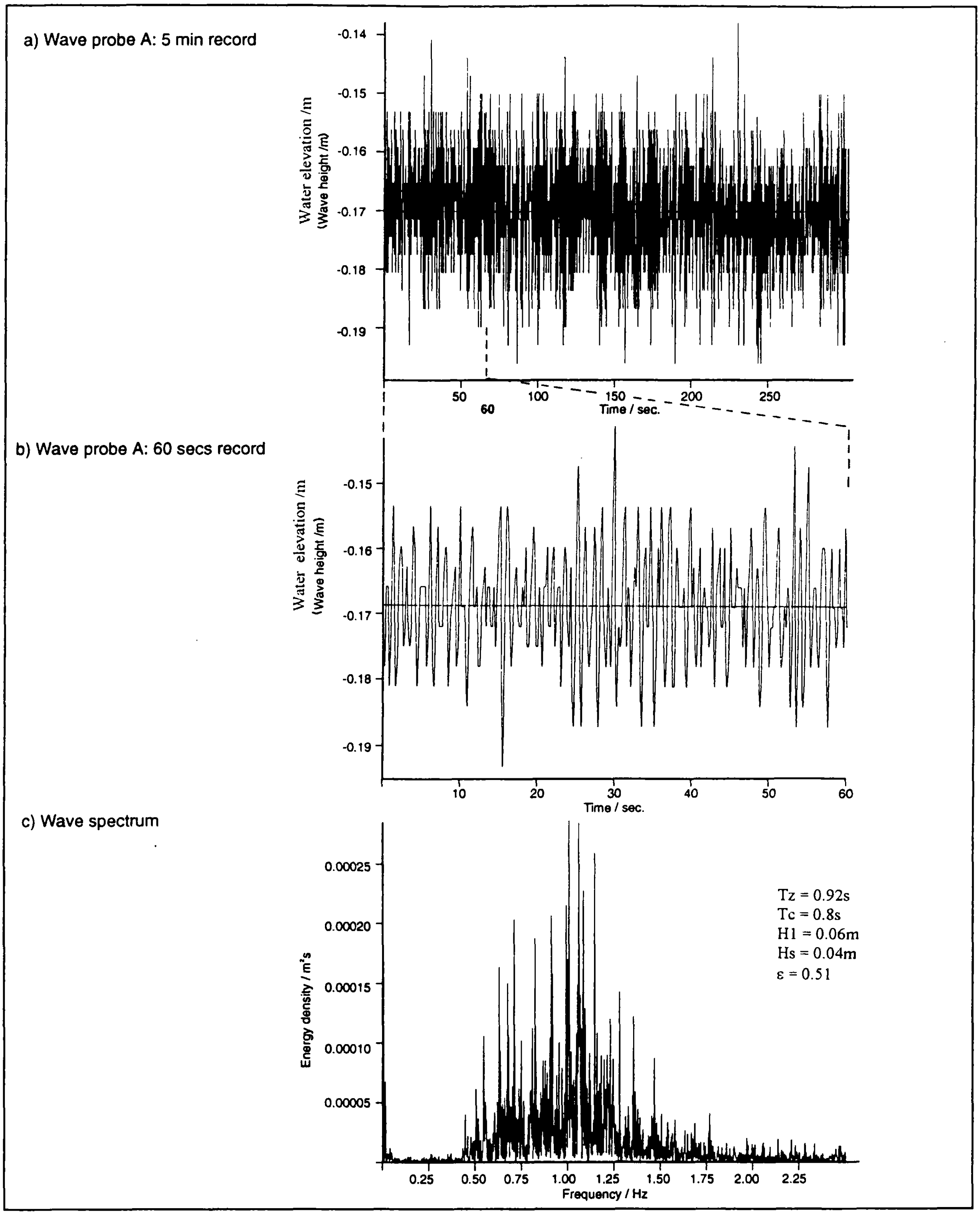


Fig. 4.7 Waves recorded on 25/2/94 at 1800hrs using Probe A

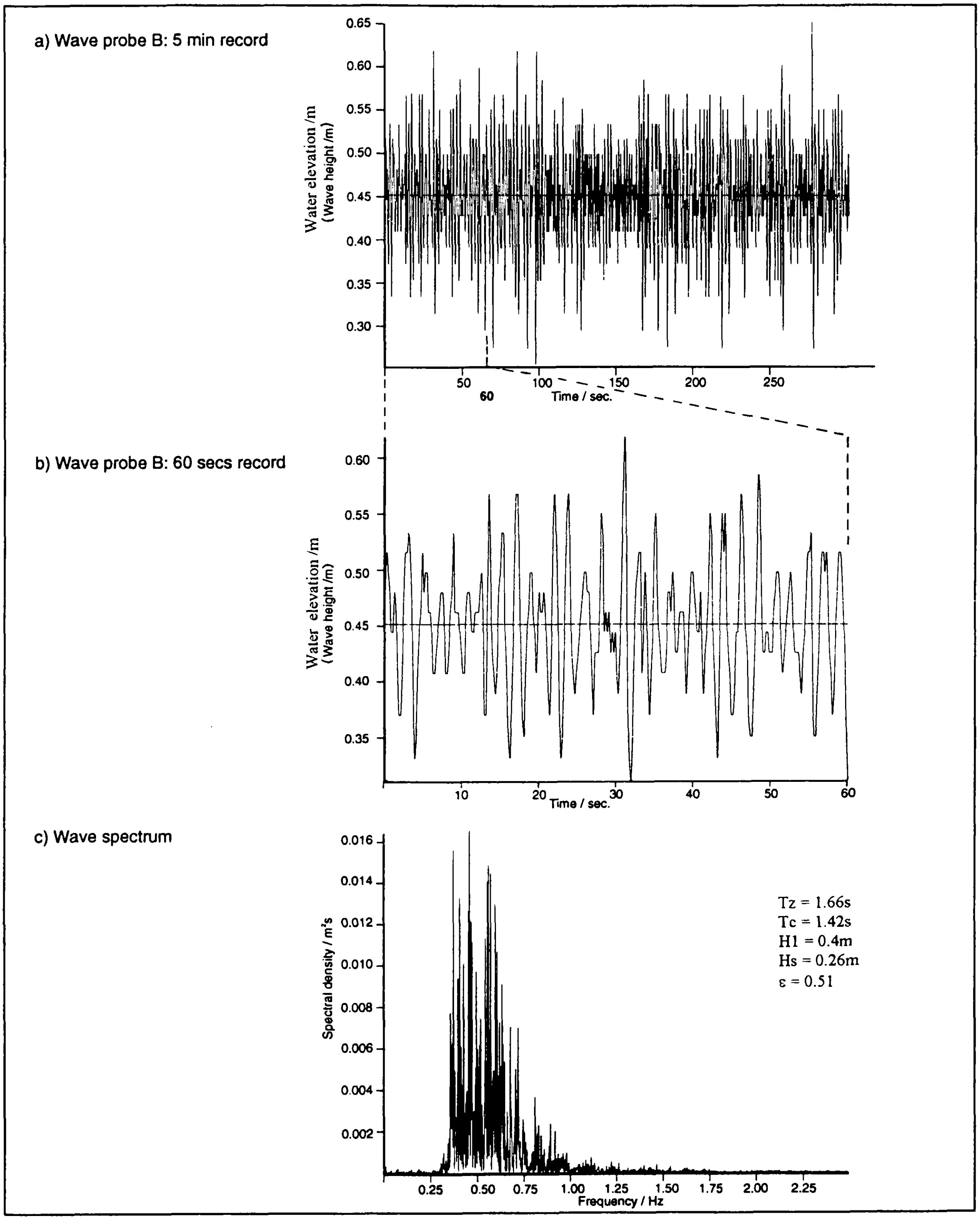


Fig. 4.8 Waves recorded on 7/12/94 at 1800hrs using Probe B.

types of wave record collected and to aid understanding and interpretation of the overall 1994 wave climate in the time domain. Some of the early records were recorded by chart recorder enabling immediate graphical representation of wave conditions. Statistical analysis of these was by hand. For the logger-recorded records computerised analysis was used. A mean water level is calculated for each 300 second record, and the variable position of this on the y axis of each record is a function of changing water levels. The wave record statistics, including maximum wave height and significant wave height are given on each figure. Details of the associated spectra are given in section 4.3.2 where the analysis of the wave conditions in the frequency domain is reported.

Examples

Fig. 4.9a shows <u>small waves</u> and a <u>record limited by probe resolution</u>, the trace appearing blocked at this scale. This record from 18/10/94 0000hrs, shows a recording limitation for detailed wave form (because of the ratio of relatively small wave heights to the calibration). However the record is of value for overall statistics which is the purpose of the recording. Mean significant wave height is 0.07 m and zero crossing period is 0.88 s, a high frequency wave. The largest wave in the record is 0.1 m high, and larger scale inspection (not shown here) confirms that these are genuine waves.

A <u>range of wave heights</u> is shown in Figs. 4.10a and 4.11a, which typify wave conditions at Loch Lomond, where larger waves are interspersed with smaller waves. Often a sequence of small waves is followed by a larger wave, a pattern which is often repeated. Graphical presentation of the wave train shows the wave sequence detail. Spectral width parameters of 0.5 and 0.49 indicate mixed wave patterns, as recorded here. Fig. 4.11a again shows a variety of wave heights. The wave train is particularly interesting as it appears to show part of a longer frequency oscillatory wave (approximately 200 s) imposed on the record. This was recorded when mean wind velocity was 6.4 m s^{-1} from a westerly direction. Antecedent conditions were a series of westerly and south-westerly winds, with 4-7 km fetches. This could be interpreted variously as a larger swell wave, only part of which is shown or an indication of seiche activity with waves having a long frequency . The record is too short to draw any firm conclusions on the occurrence of seiches.

Fig. 4.9a

FILE : oct24003 EXTRACT OF WAVETRAIN, FROM 18-Oct-94 00:00:00 TO 18-Oct-94 00:04:60

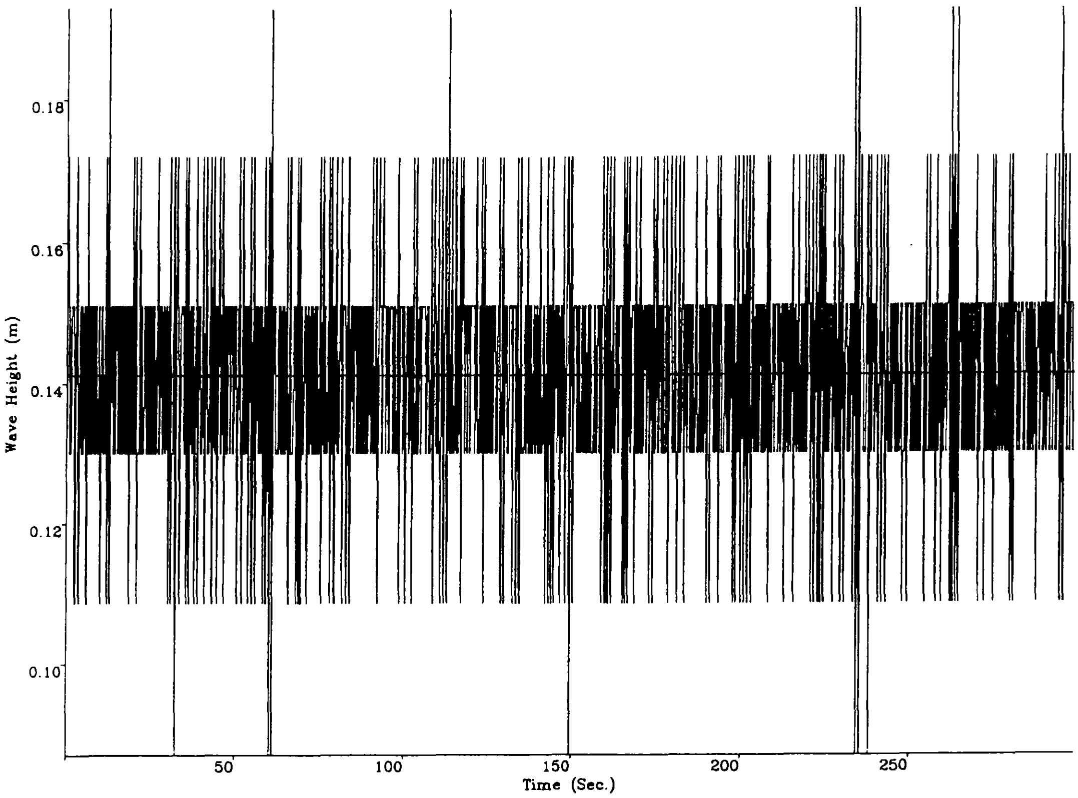


Fig. 4.9b

FILE : oct24003 SPECTRUM OF WAVETRAIN, FROM 18-Oct-94 00:00:00 TO 18-Oct-94 00:04:60

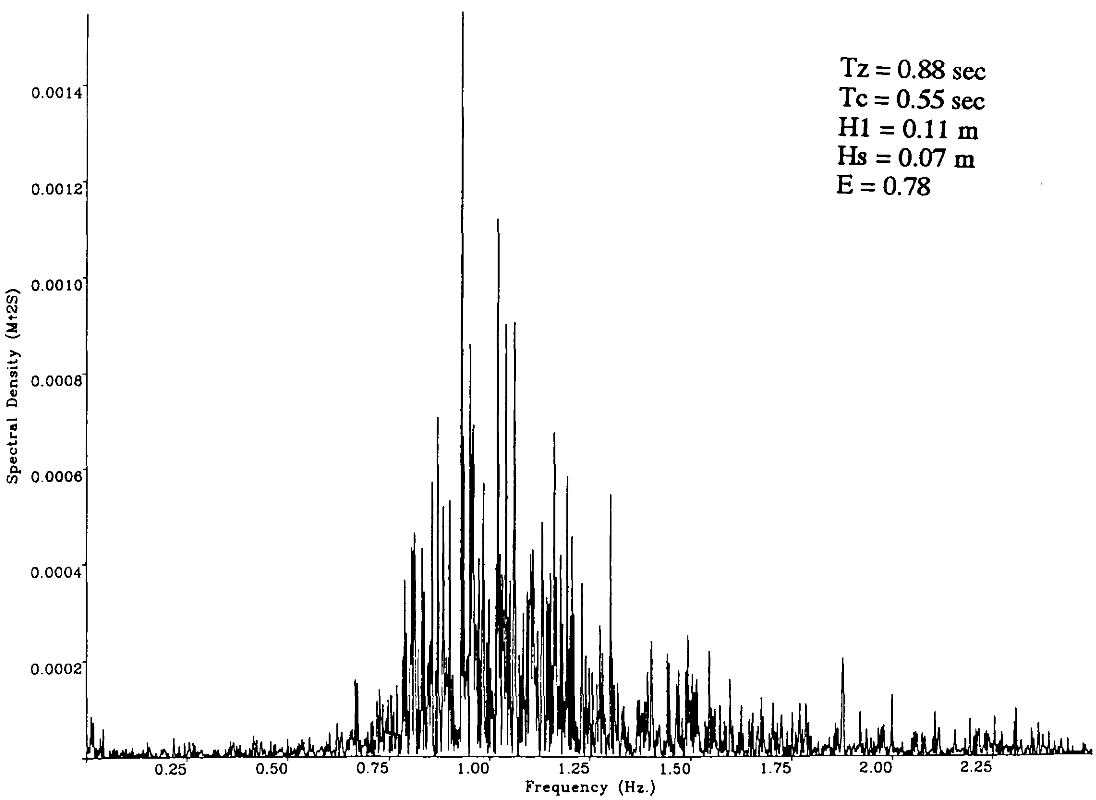


Fig. 4.10a

FILE : aug30020 EXTRACT OF WAVETRAIN, FROM 27-Aug-94 12:00:00 TO 27-Aug-94 12:04:60

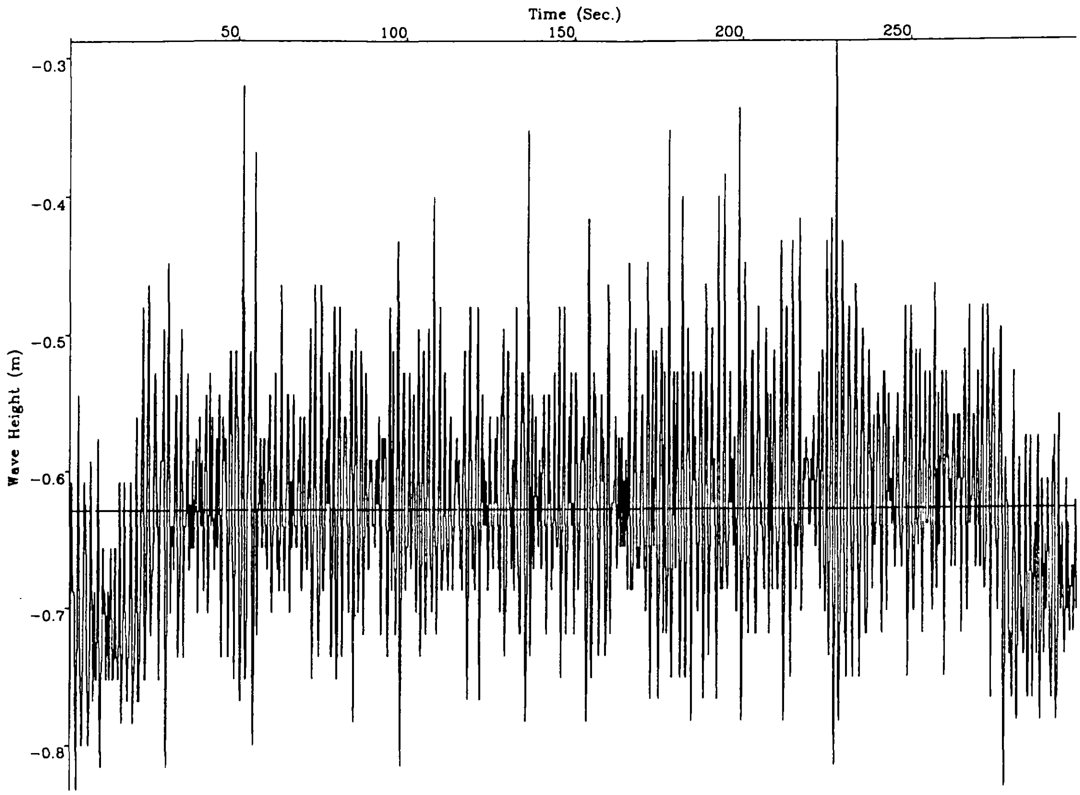


Fig. 4.10b

FILE : aug30020 SPECTRUM OF WAVETRAIN, FROM 27-Aug-94 12:00:00 TO 27-Aug-94 12:04:60

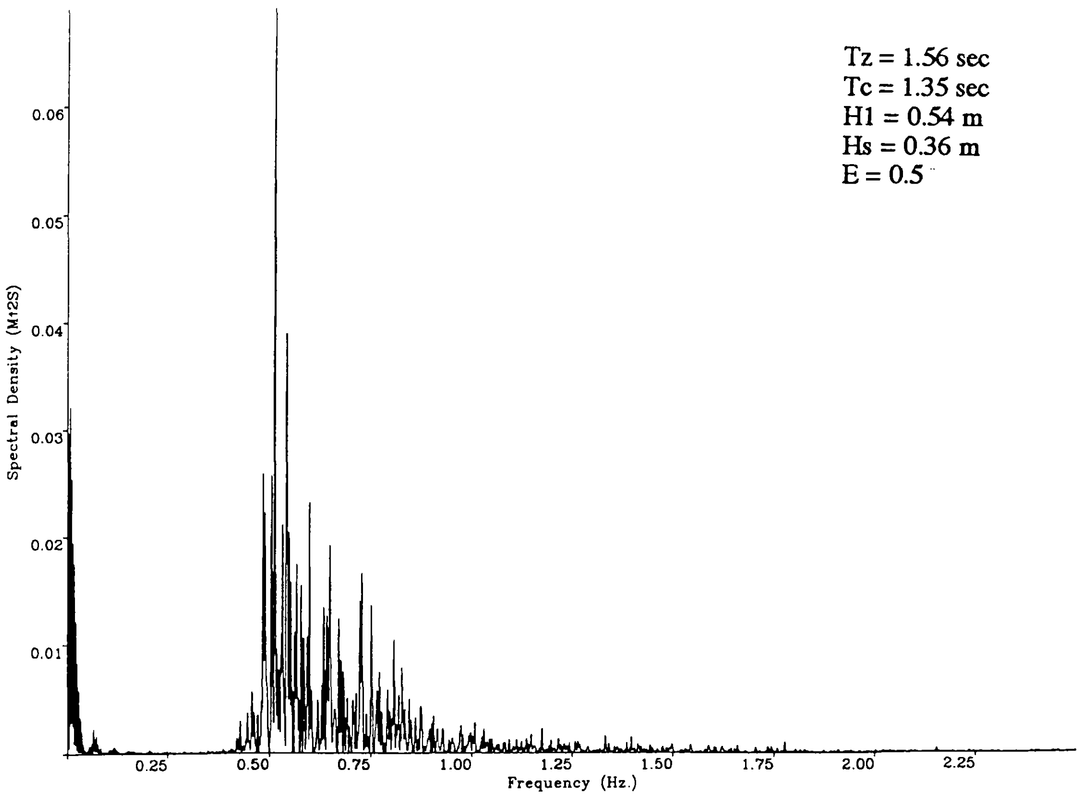


Fig. 4.11a

FILE : dec9004 EXTRACT OF WAVETRAIN, FROM 06-Dec-94 06:00:00 TO 06-Dec-94 06:04:60 (Wave Probe)

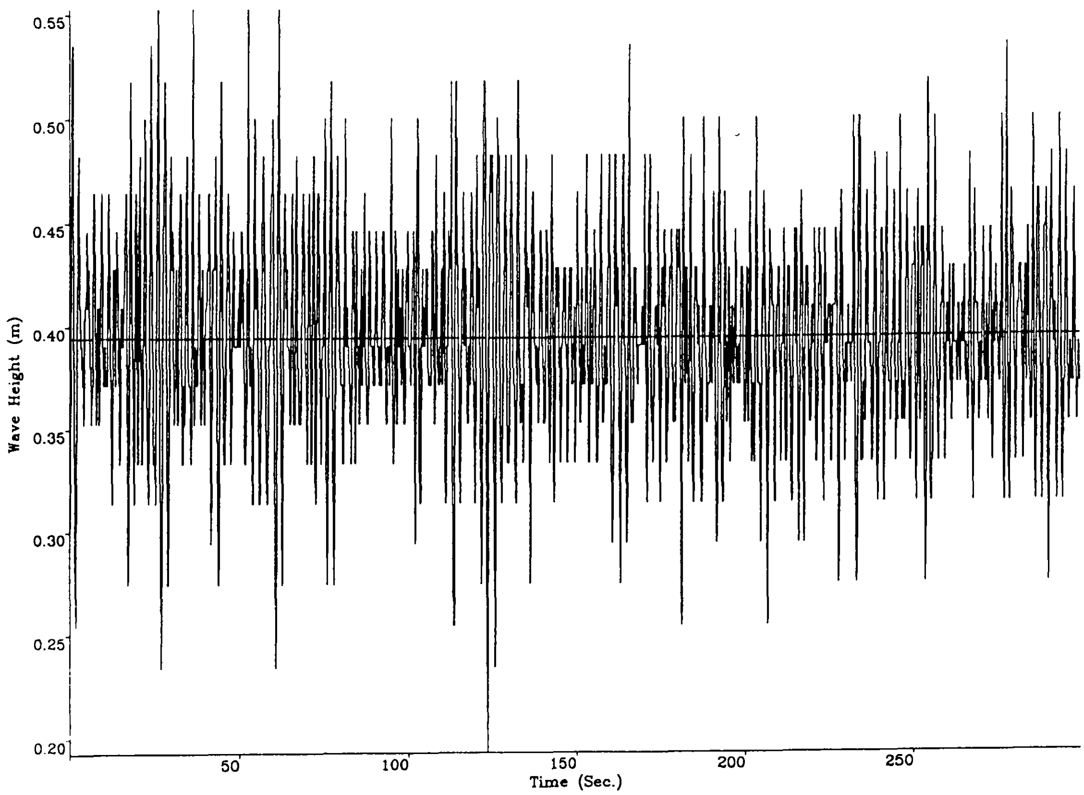


Fig. 4.11b

FILE : dec9004 SPECTRUM OF WAVETRAIN, FROM 06-Dec-94 06:00:00 TO 06-Dec-94 06:04:60 (Wave Probe)

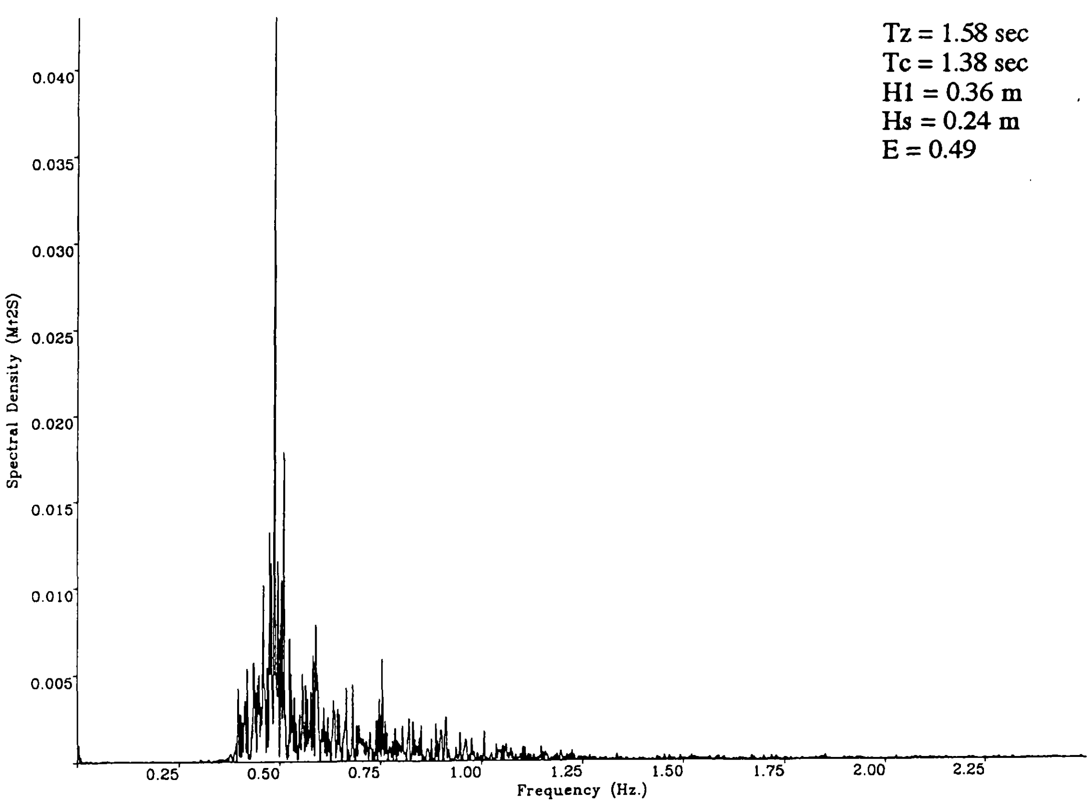


Fig. 4.12a

FILE : aug30021 EXTRACT OF WAVETRAIN, FROM 27-Aug-94 18:00:00 TO 27-Aug-94 18:04:60

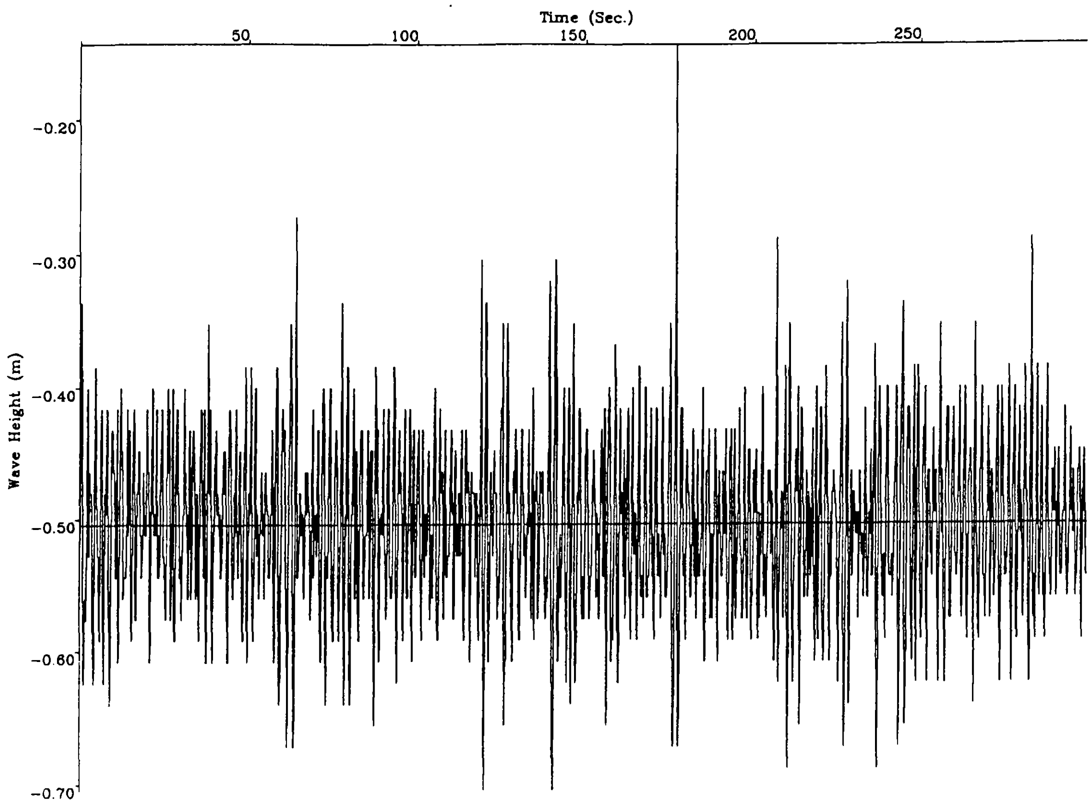


Fig. 4.12b

FILE : aug30021 SPECTRUM OF WAVETRAIN, FROM 27-Aug-94 18:00:00 TO 27-Aug-94 18:04:60

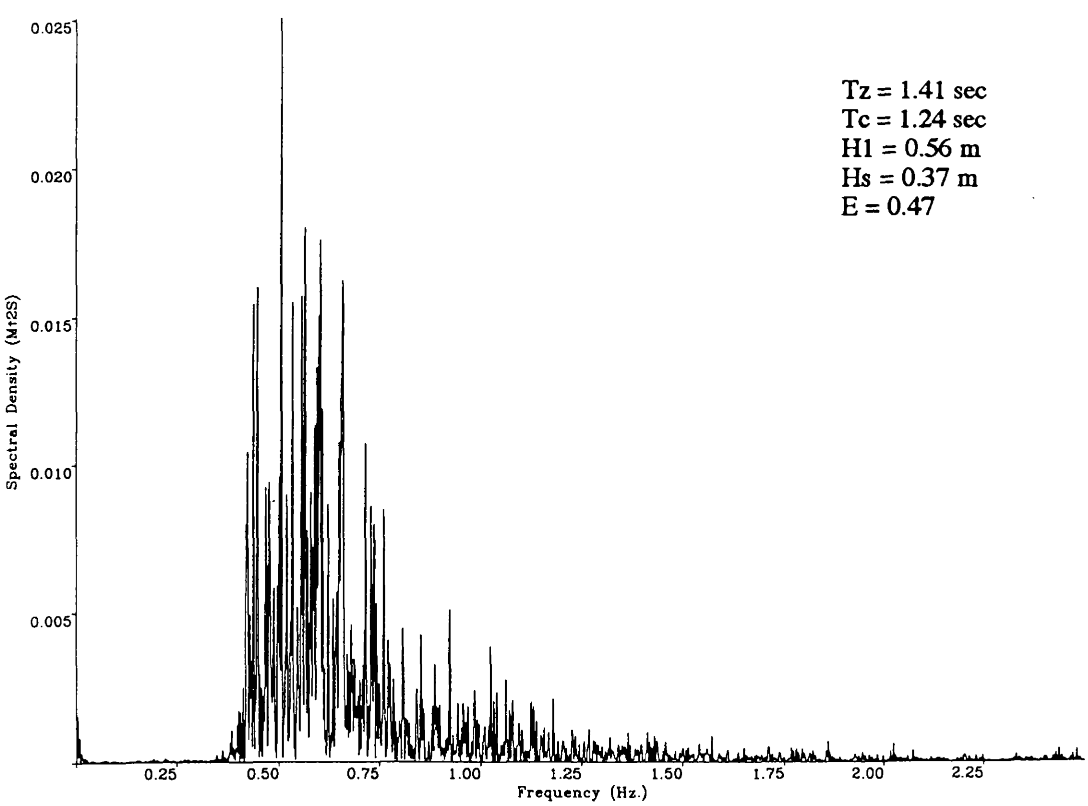


Fig. 4.13a

FILE : jun16016 EXTRACT OF WAVETRAIN, FROM 12-Jun-94 12:00:00 TO 12-Jun-94 12:04:60

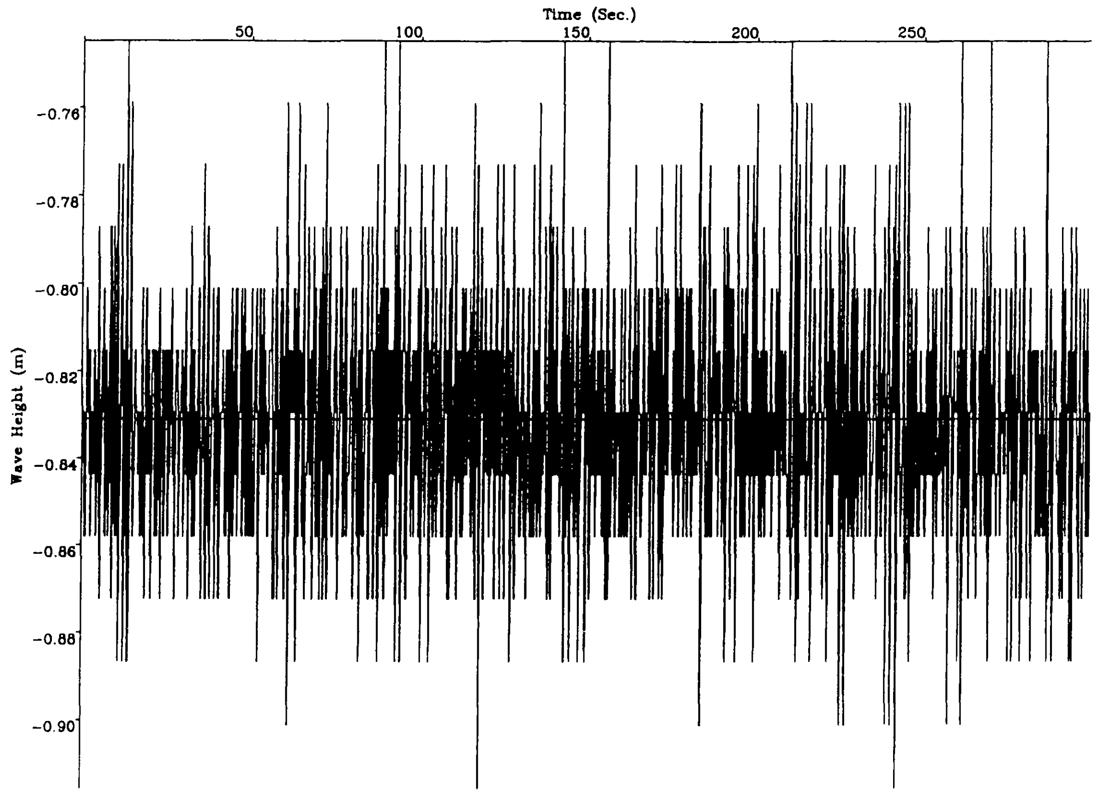
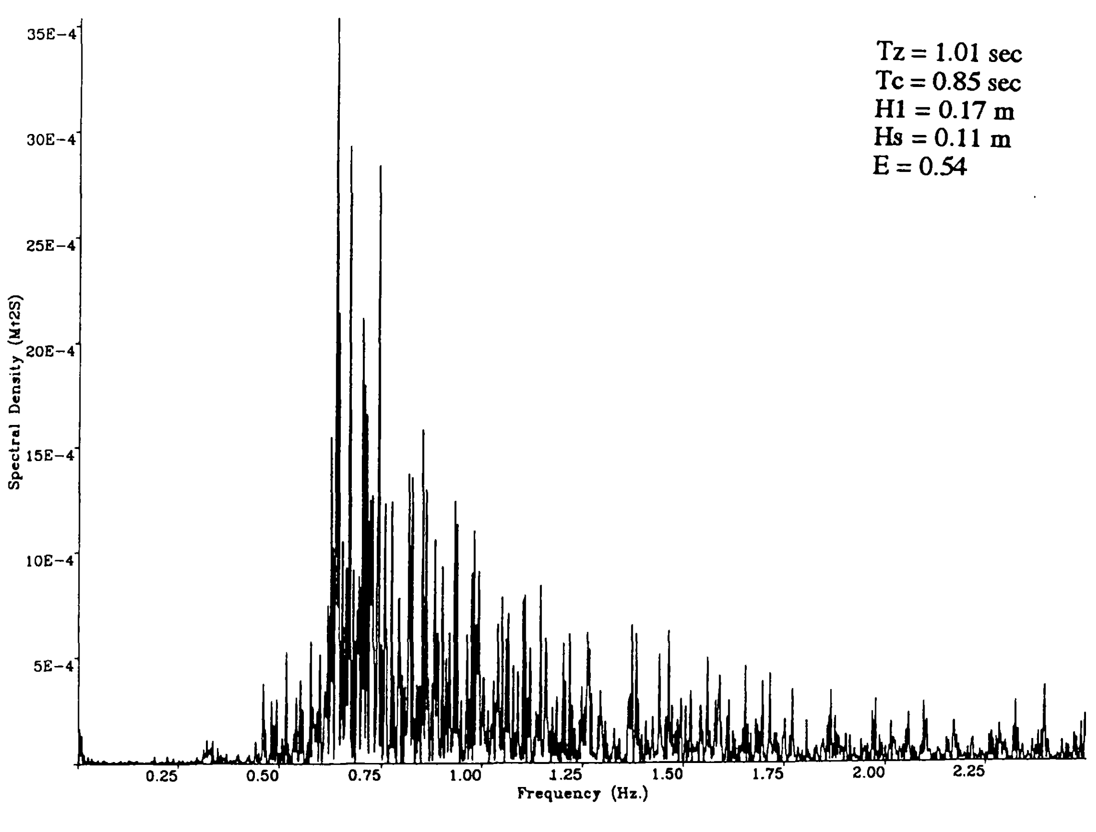


Fig. 4.13b

FILE : jun16016 SPECTRUM OF WAVETRAIN, FROM 12-Jun-94 12:00:00 TO 12-Jun-94 12:04:60



The waves recorded on 27/8/94 at 1800 hours (Fig. 4.12a) show large waves (H_l= 0.56 m; H_s = 0.37 m) and as would be expected, longer wave frequencies (T_z = 1.4 s; T_c = 1.24 s). Closer inspection of the record (at a large scale, not shown here) clearly shows the prominent larger wave approximately 180 seconds into the record. The record from 12/6/94, 1200 hours (Fig. 4.13a) with a significant wave height of 0.11 m shows classic characteristics of Loch Lomond wave types. Firstly it is characterised by high frequency wind waves (T_z = 1 s and T_c = 0.85 s), shown by the density of waves within the 300 second record. Secondly, the wave record illustrates the range of heights. Mean significant wave height is 0.11 m, and the highest waves recorded here are 0.17 m, wind velocity was 6 m/s and direction 280 ^{0} (W).

Having considered some of the detail of these records, the next section focuses on the wave analysis for the complete data set (Appendix C), thus quantifying the wave climate for 1994.

Wave frequency derived from the Tucker-Draper Method (TDM)

Crest period (T_c) and Zero-up crossing period (T_z) statistics were derived from the 5-minute wave records, as described in Chapter 3. T_c and T_z statistically describe the frequency component of the wave conditions. For each wave record the T_c and T_z value is the mean frequency, although this may mask extremes. For example, one lower frequency, large wave may offset the mean value. This can be more of a problem affecting the height calculations.

Throughout the year (1994) the modal wave frequency (T_z) is between 1 and 2 seconds (Appendix C). This is a high frequency compared to the marine coast, where long fetches allow large, lower frequency waves to develop. Crest frequency (T_c) throughout the year is typically between 0.6 and 1.8 seconds. Most months show considerable variation in wave conditions, in response to highly variable wind conditions (section 4.3).

Wave steepness (H/L), is an important component of wave characterisation and can be inferred from a H_s vs T_c plot (Driver 1980) (Fig. 4.14). The results show the spread of wave steepness from the 1994 records. Of interest is the non-homeoscedastic nature of the data (i.e. variance in height increases with longer wave period), probably because lower frequency waves tend to exhibit greater ranges of wave form including height. Waves which exceed s = 0.1 (refer to plot) are particularly steep (steepness parameters which rarely occur on the marine coast, King 1972).

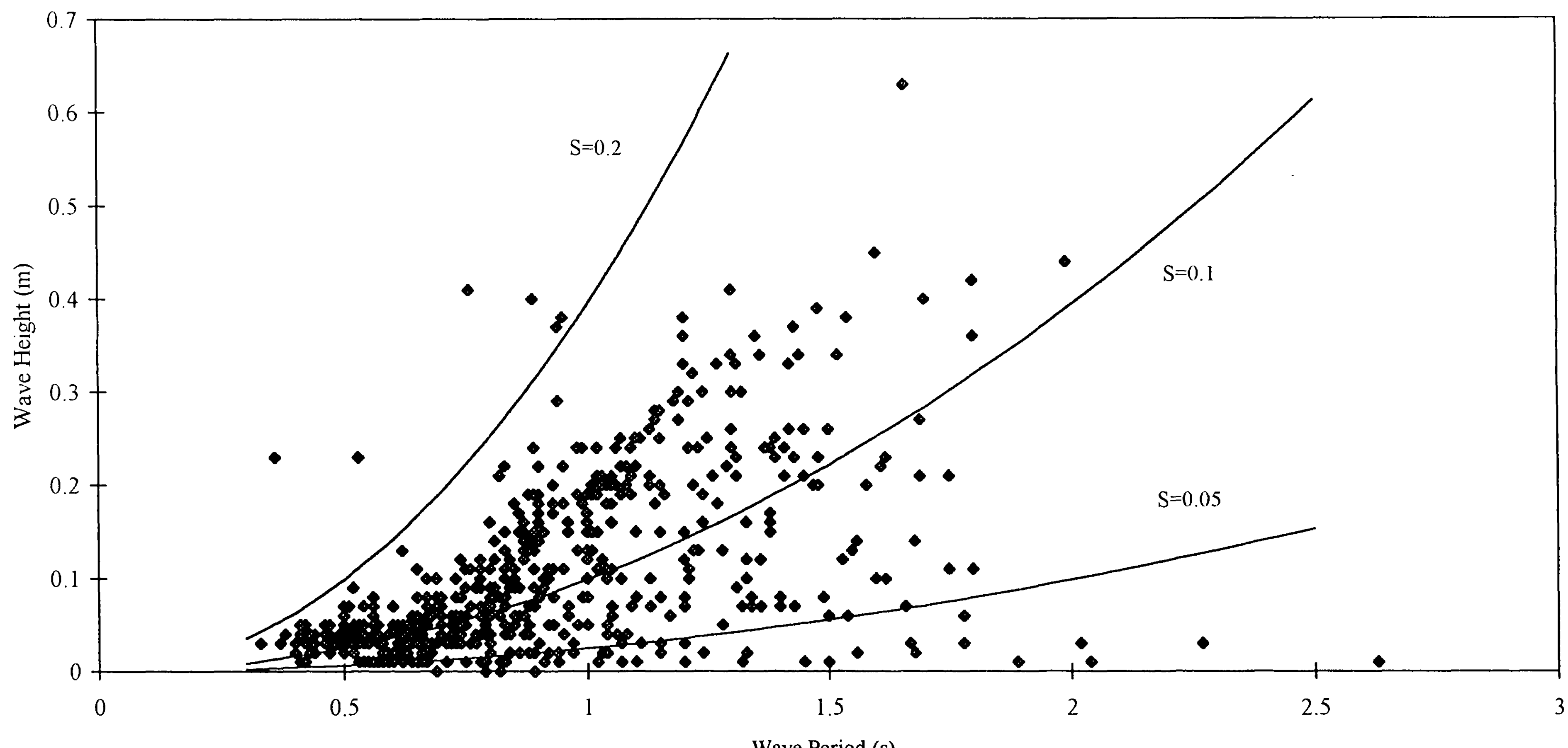


Fig. 4.14 Wave steepness for 1994 using significant wave heights. Lines (s=0.2, s=0.1 and s= 0.05) denote steepness values. Note the spread of data; extremes such as low frequency, low height waves are a function of averaging wave data. These indicate occasional small waves during periods of relative calm, hence the low frequency value.

This is an important finding as it highlights the distinctiveness of the lake wave climate and has important implications for wave behaviour at the shore (section 5.3). Steep waves reaching the shore cause asymmetric currents, which affect the dominant energy at the shore and ultimately the direction of sediment transport. Steep waves (surging and plunging) which break close to the shore are highly asymmetric at breaking. This generates a high potential for shore modification with sediment transport by waves (King 1972).

Figure 4.15 illustrates wave steepness for December 1994, a typical example showing the high frequency, steep waves found. Overall the trend is the expected one where longer wave periods occur with larger waves. However, there are several departures from the trend which show the variation in wave type. Some of the smallest waves have a longer period, which suggests they represent infrequent ripples or capilliary waves (Munk 1951). The high resolution wave recording employed allows this quality of detail to be determined. Of note are the range of wave heights and the consistency of wave frequency.

Significant wave height from the TDM

Significant wave height (H_s) provides one of the most useful parameters of the wave climate, and is widely used in coastal applications (CERC 1984). It is defined as the minimum wave height of the highest third of all waves and is a good descriptor of wave energy. Here, Fig. 4.16 shows the variety of significant wave heights for each month in 1994. The mean significant wave height is 0.08 m.

The January records show relatively calm conditions from the data-logger records. Additional chart recorder records show waves in the 0.1-0.15 m cohort, and the stormy conditions at the end of the month (refer to wind and weather recording section) would have generated larger waves. February shows mostly small waves (during periods of easterly and north-easterly winds) and some over 0.4 m high, (westerly winds). This was a period of high water levels and at one point the small probe A was submerged and therefore rendered temporarily inoperable. The March records illustrate a dominance of smaller waves, although a stormy period of high velocity westerly winds on the 13th was missed due to logger failure. Significant wave heights of between 0.15 - 0.2 and 0.25 - 0.3 m are shown in the April records. May was predominantly calm although during a stormy period significant wave heights of between 0.6 and 0.65 m were recorded. The June

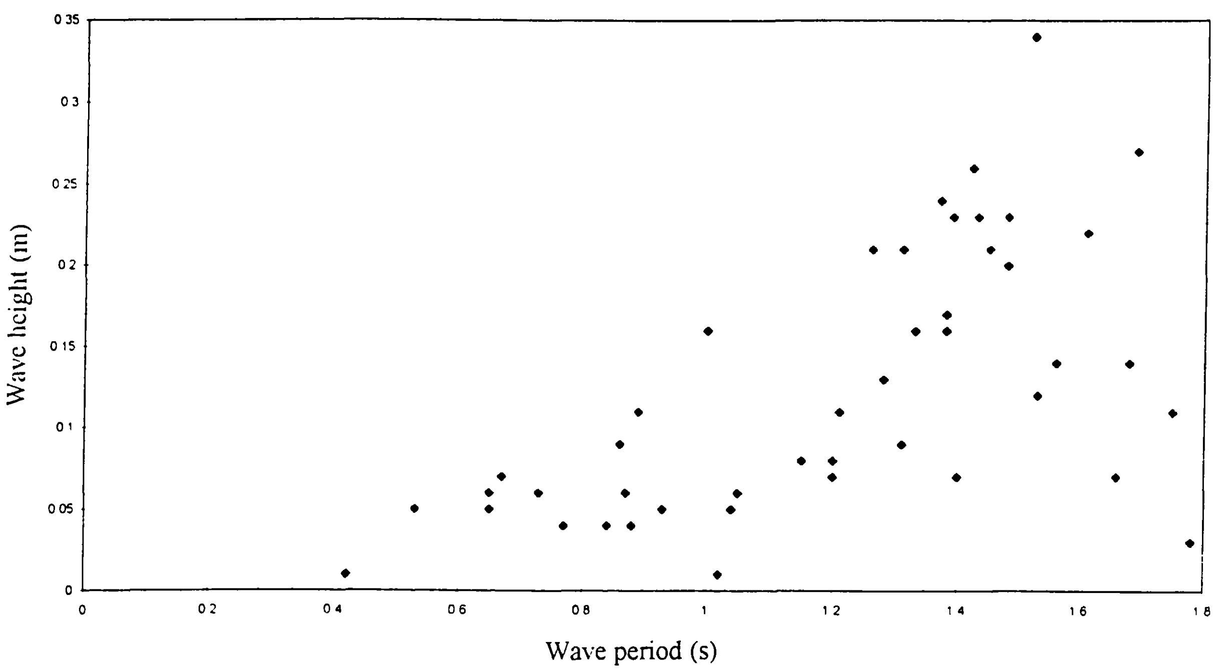


Fig. 4.15 Wave height vs. wave period, December 1994.
This illustrates the range of wave heights and periods.

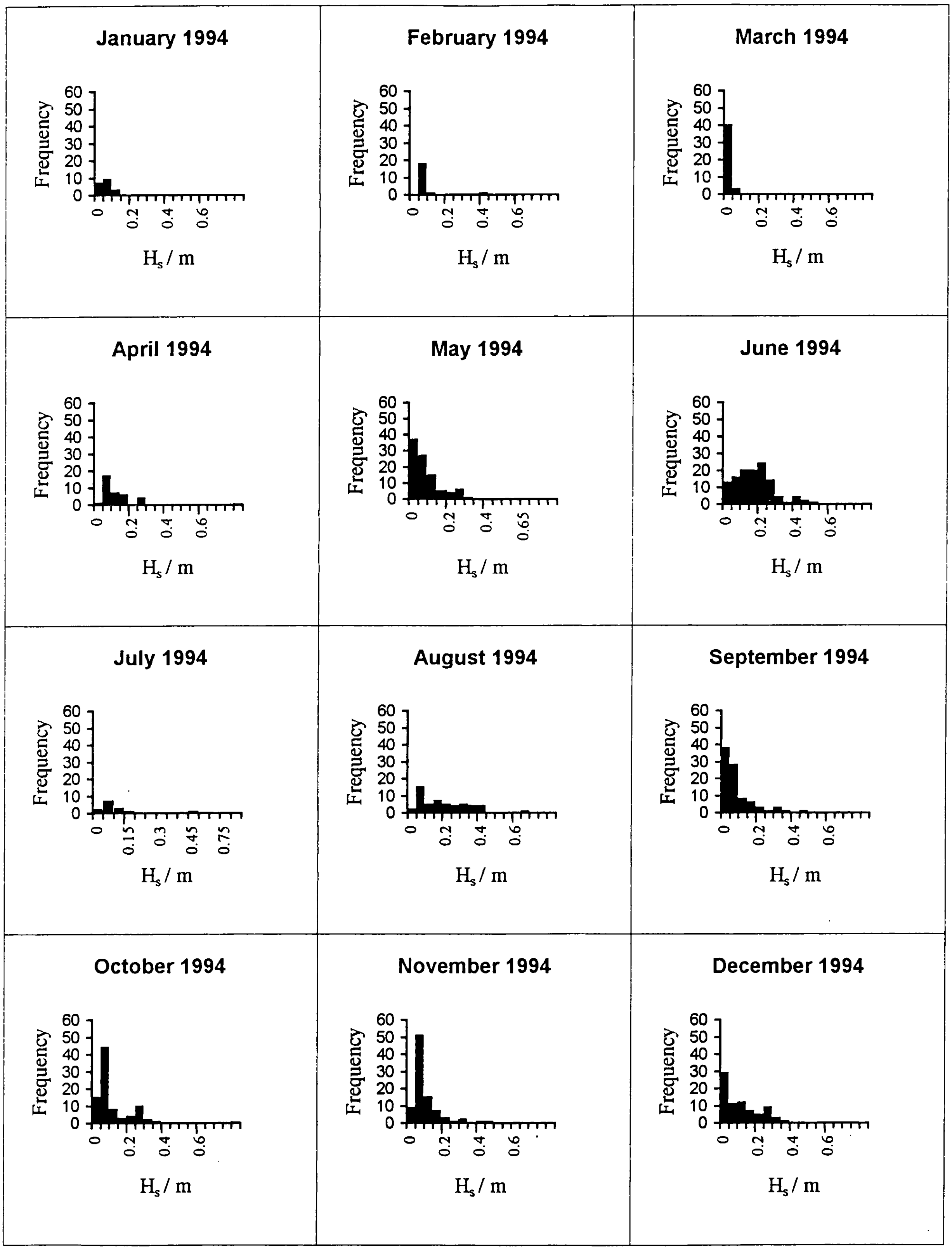


Figure 4.16 Monthly histograms of significant wave height (Hs)

records illustrate a wider range of wave heights reflecting higher wind velocities, and a dominance of westerly winds (i.e. having the longest fetch for wave development). Larger waves of between 0.5 and 0.55 m are recorded and a modal significant wave height of between 0.2 and 0.25 m is shown. The July records are incomplete although a range of wave heights were recorded. The August records included some of the highest waves of 1994. The modal wave height was between 0.05 and 0.1 m. September shows a dominance of calm conditions. Significant wave heights up to 0.5 m were recorded, and most classes are represented between 0 and 0.5 m. The highest significant wave heights in October were between 0.35 and 0.4 m. Fairly large waves were generated in November (between 0.35 and 0.4 m). December waves show a dominance of calm conditions, but all classes up to 0.4 m are well represented.

In summary, Fig. 4.17 shows the skewed distribution of the wave climate in the nearshore for 1 year. A small-medium sized lake wave climate would be expected to have a high occurrence of calm conditions as shown here. The modal group of wave heights generated under a range of wind conditions, is 0.05 to 0.1 m. When the 1994 wave height results are plotted against water levels (Fig. 4.18), the annual variability of wave heights is quite marked compared to the seasonal water level trend. In 1994 the largest waves occurred in Summer.

Maximum wave heights from the TDM

Maximum wave heights (peak to trough) were also recorded and show the extremes of wave heights at Loch Lomond. The highest wave heights (0.94 m) were recorded in August 1994 during stormy conditions and westerly and south-westerly winds (section 4.3). The relationship between maximum wave heights and significant wave heights is such that similar trends are shown (section 3.2.3.3).

Spectral width parameter from the TDM

The spectral width parameter (ε: $0 \leq \varepsilon \leq 1$) gives a numerical description of the variance of the wave surface or 'sea' state. Values closest to zero represent a regular monochromatic sea or sinusoidal, regular waves and higher values (up to 1) represent more mixed distributions of different wave heights and periods closer to a fully developed sea. (Tucker 1963; Carter 1988; Hardisty 1989). The method of calculation is described in section 3.2.4.

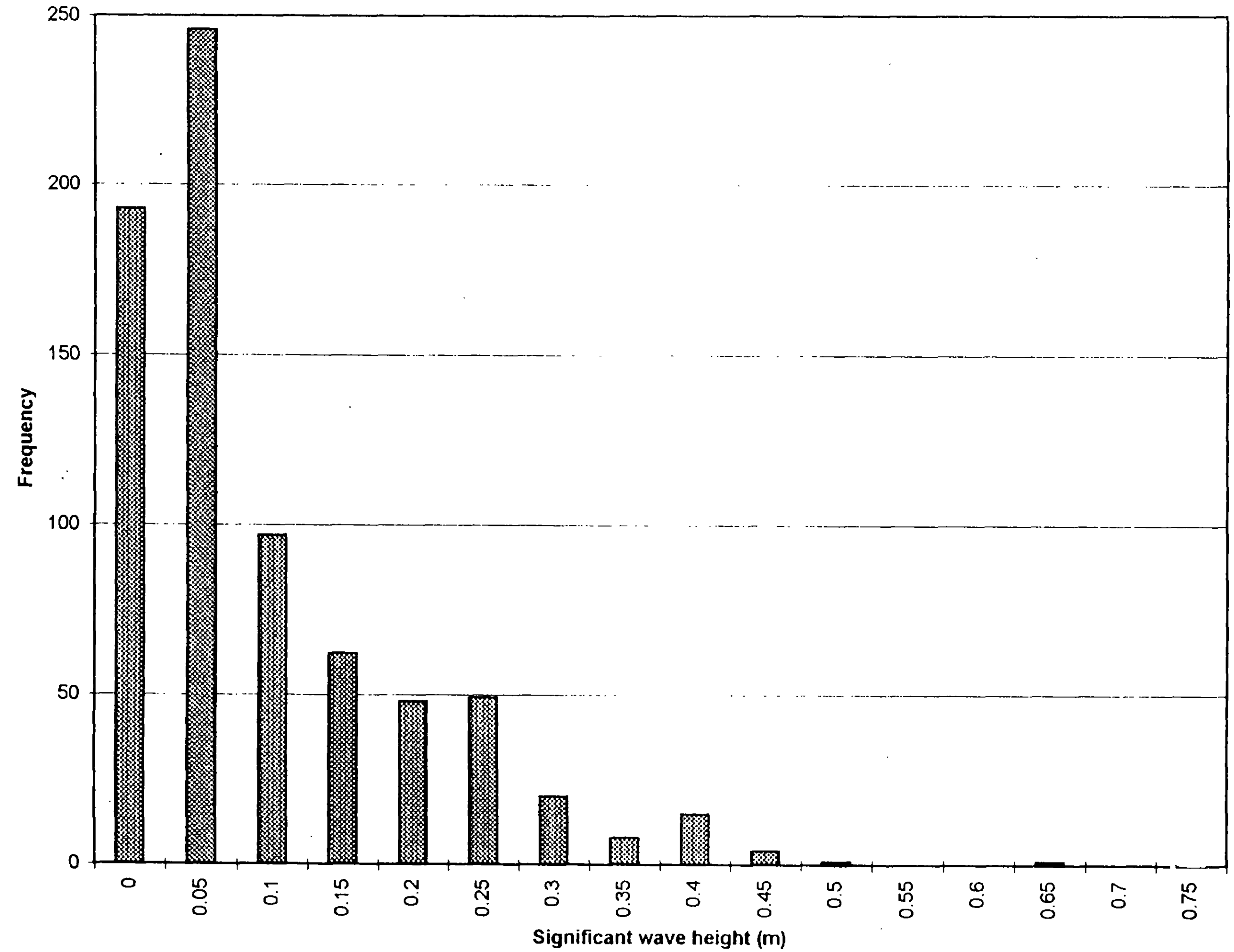


Fig. 4.17 Total significant wave heights in 1994

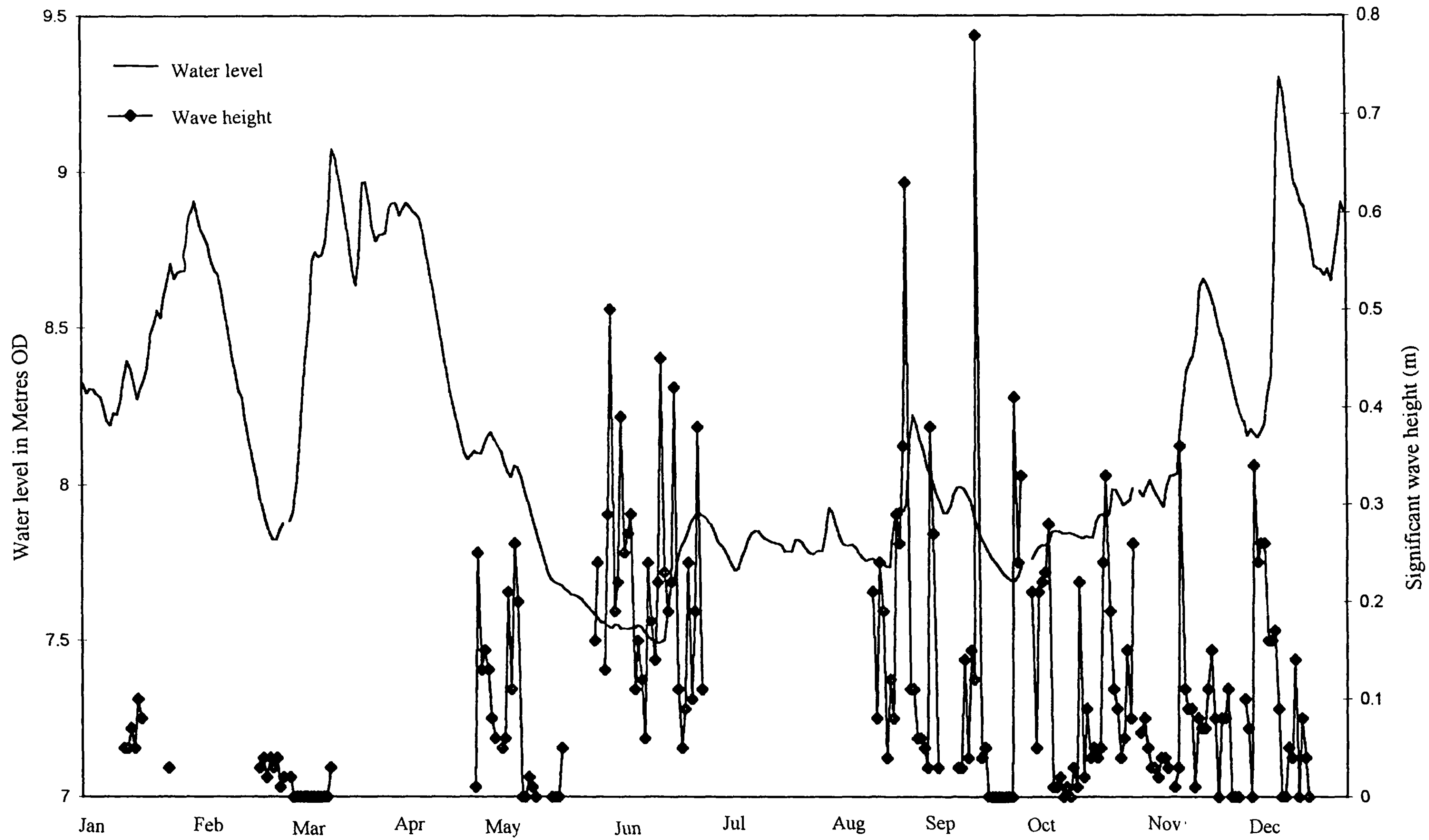


Fig. 4.18 Water levels and significant wave heights 1994.
Note that in 1994 the highest waves occurred during periods of relatively low water levels.

Of interest is the wide range of calculated spectral width parameters (Fig. 4.19) compared to the relatively short range of periods shown by the T_z and T_c results. As an example, the record of spectral width parameters obtained in June 1994 is shown here (Fig. 4.20). The gaps in the line denote calm conditions. The overall trend which is reflected in the complete data set, is for ε to be above 0.4. Swell conditions occur typically when ε is approximately equal to 0.3 (Carter 1988) which is an uncommon occurrence in these records. Overall, examination of the wave records shows the mean spectral width parameter (excluding calm conditions) for Loch Lomond to be 0.77 and the median 0.8. This means that the wave field is mixed, but approaching fully arisen sea, where the wave surface attains an equilibrium independent of fetch and wind duration. This suggests that the nearshore wave field is close to equilibrium conditions where wind is no longer the controlling factor. This is discussed further in Chapter 6.

Overall, the findings from the TDM analysis show a predominantly low energy wave climate characterised by high frequency, short period, steep waves interspersed with periods of calm. The maximum wave height during 1994 was 0.94 m and the maximum significant wave height 0.63 m. Mean period (T_c) was 0.92 seconds. The mean spectral width parameter was 0.77 indicating a mixed wave field although approaching 'fully arisen sea conditions'.

4.3.3 Spectral analysis

Spectra were generated from the 5 minute wave records in order to further characterise the nature of the wave climate. Spectral analysis changes the data from the time domain to the frequency domain. The different perspective allows small but important components of a wave-form, which may be masked by the larger components in the time domain to be distinguished (Carter 1988). The Loch Lomond spectral results highlight the distinguishing features of the lake wave climate, where the dominant wave type is quite different from that of marine wave climates. In the present case, spectral analysis can be used to describe changing wave conditions over a long time period and then this is related to lakeshore morphological changes.

In the previous sections, the Loch Lomond wave climate for 1994 was described from the TDM statistics, particularly the significant wave height. Here, the main types of 'sea' state determined from the spectral analysis are described and examples of individual spectra discussed more fully.

Spectra are usually shown graphically, with energy density ($m^2 s^{-1}$) plotted against wave frequency (Hz). Energy density is the sum of all the wave energies (statistically proportional to the sum of the squares of all the wave heights per m^3 of water, (Michel 1968). Total wave energy is equivalent to the area under the curve (Chakrabarti 1987). Spectral analysis of 747, 5-minute wave records reveals distinct trends. These spectra can be classified into 6 types which describe the Loch Lomond nearshore wave climate during 1994. A Spectral Type classification based on spectral shape was developed from analysis of the Loch Lomond records. This highlights the range of wave frequencies recorded within individual wave records and is important in the characterisation of the wave climate as it shows percentage occurrence of type and dominant wave frequencies. The classification is as follows in Table 4.2:

Table 4.2 Spectral type classification

Type	Sub-Type	Description
Type 1		Narrow banded (<1.5 Hz frequency range)
	1a	Single spectral peak
	1b	Two or more spectral peaks
Type 2		Wide banded (> 1.5 Hz frequency range)
	2a	Single spectral peak
	2b	Two or more spectral peaks (This may include a range of poorly defined spectral peaks)
Type 3		Calm conditions (flat calm and waves of < 0.01 m) (NB. Reliable spectra cannot be drawn from this type).

Classification of all the spectral records showed the following Type occurrence illustrated by Figure 4.21. This classification is appropriate within the relatively small range of wave frequencies and energies found at Loch Lomond. Different environments might require different classifications.

The 28% of the records classified as Type 3 show calm condition, capilliary waves, ripples on the water surface, and surface tension movement. A small proportion of these were completely flat

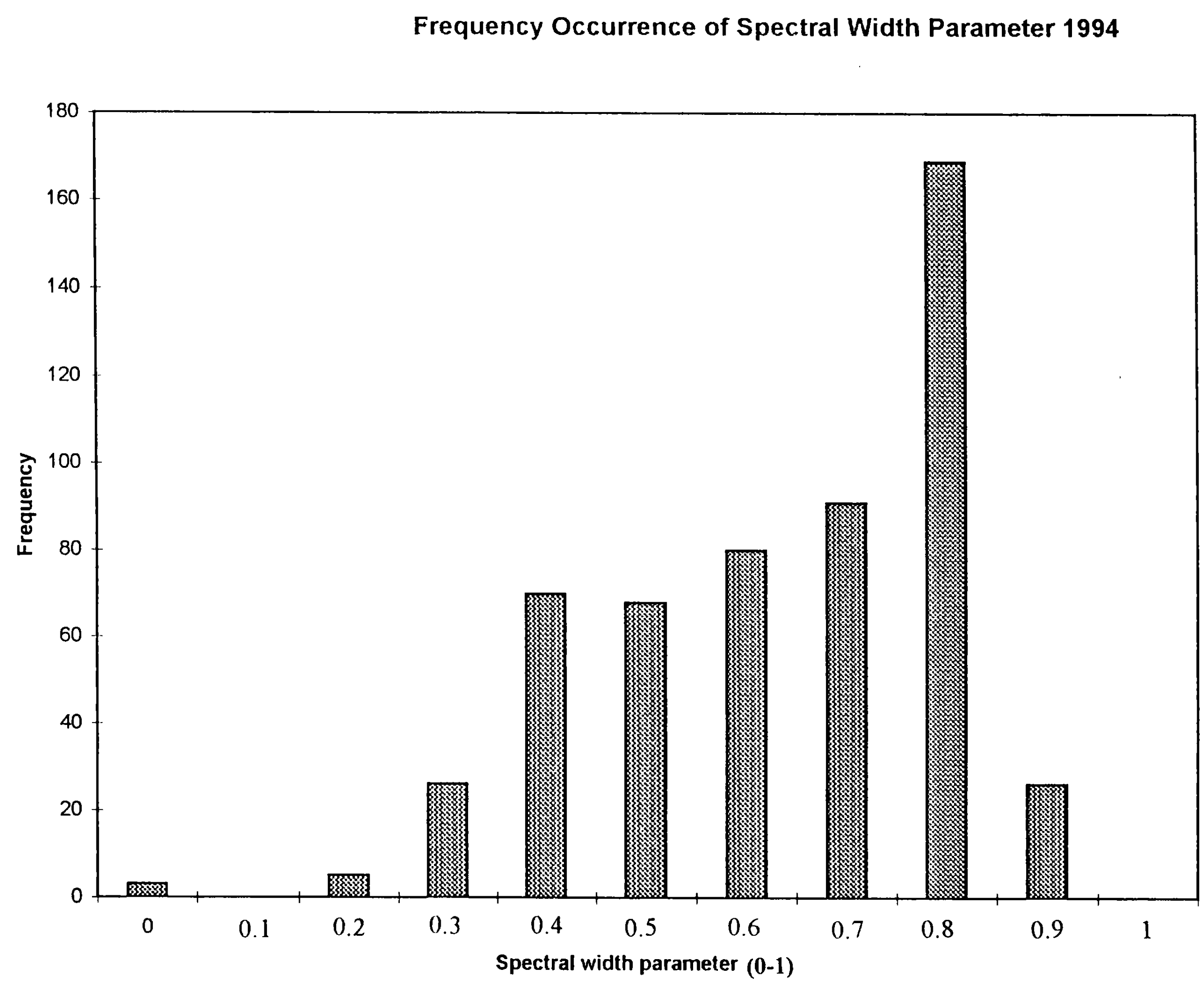


Fig. 4.19 Frequency occurrence of spectral width parameter 1994

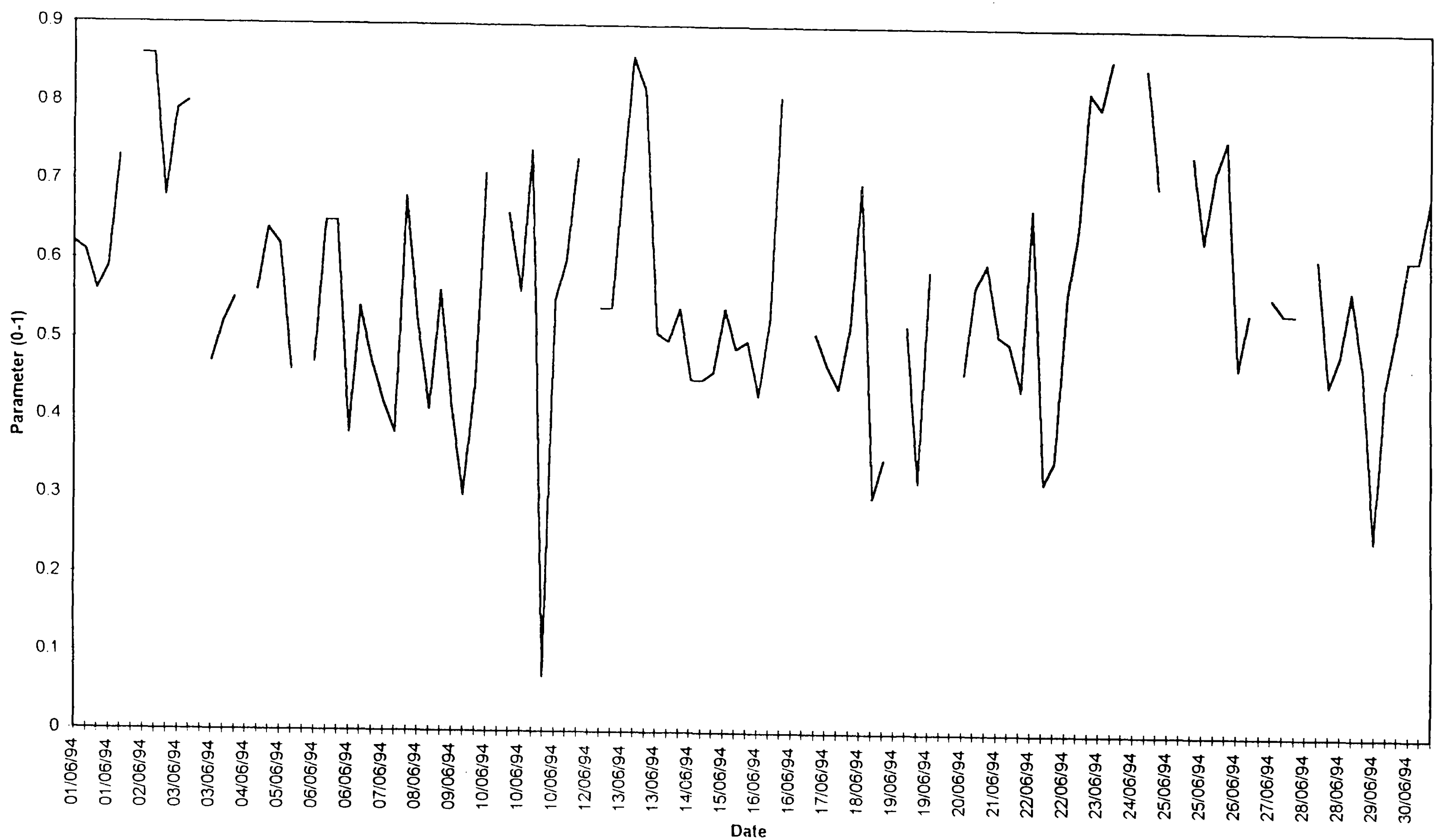


Fig. 4.20 Range of spectral width parameters during June 1994.
Gaps in the record indicate periods of calm.

Idealised spectral shapes

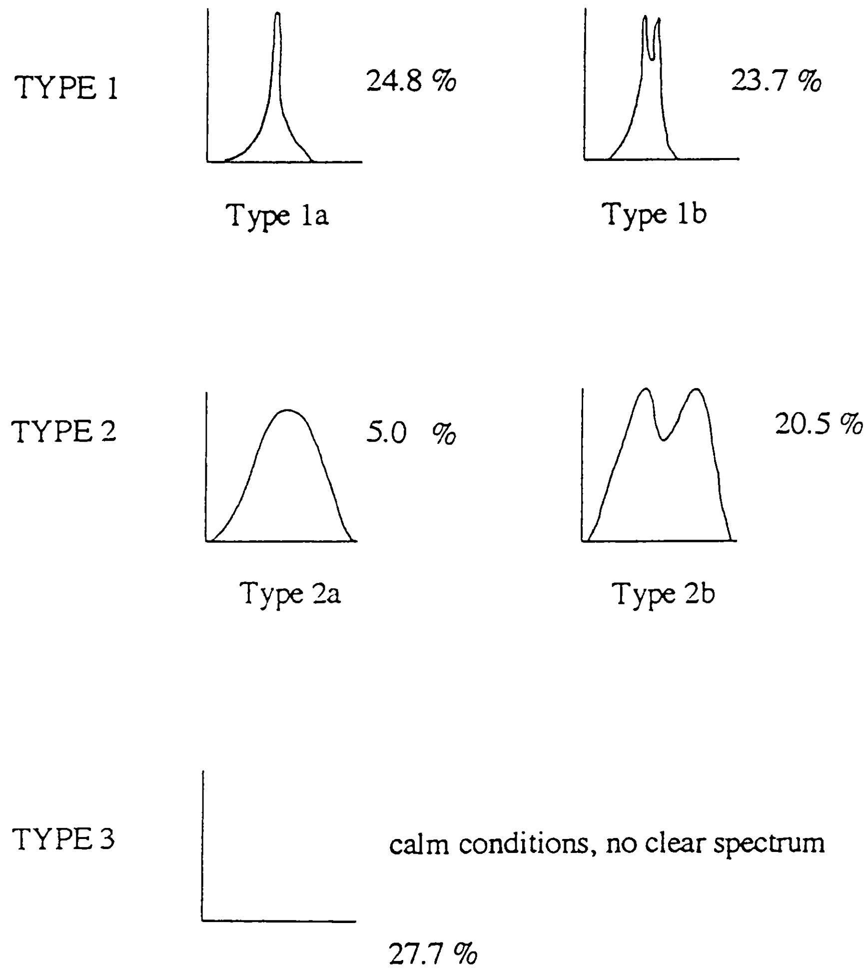


Fig. 4.21 Spectral Type classification (based on spectral shape occurring at Loch Lomond). Percentages denote percentage of type occurrence during 1994.

calm. These records are at the limits of the resolution of the wave probe but are relatively unimportant because they are associated with very low energy densities (e.g. 3×10^{-6} m^2 s^{-1}).

Types 1a, 1c and 2a are the single peaked spectra. Single peaked spectra occur due to the presence of dominant frequencies, or where there is a greater range of frequencies, only one pronounced modal frequency. The very steep spectra (Type 1c) are typical of waves in a very narrow frequency band. Single peaked spectra occur at all wave energies, as do multi-peaked spectra.

Types 1b and 2b are the bi-modal and tri-modal (and occasionally multi-modal) spectra. These spectral forms indicate the presence of two or more groups of waves with distinct frequencies. This occurs where smaller higher frequency waves are superimposed on lower frequency waves as shown on the wave train examples (Section 4.2.1). Some of the spectra classified as **Type 2b** indicate fairly calm conditions with a confused 'sea' state i.e. a whole range of wave frequencies are present, but with no dominant peaks. Generally a rather flat peaked spectrum is produced in these conditions. Other examples of spectra of both Types 1b and 2b show quite distinct multi-peaked spectra.

While it is not possible to reproduce all the spectra here, the following examples have been chosen to illustrate spectral types, the similarities showing that the wave climate can be clearly defined. The quantity of wave data recorded and analysed means that a high degree of confidence can be attributed to the findings. The spectra discussed are shown with the wave record figures presented earlier in this section.

Fig. 4.9a, b (Oct24003) shows the wave record (discussed earlier) and the energy spectrum for small waves (H1=0.1 m; Hs=0.06m). The dominant frequency range is from 0.8-1.3 Hz, with minor spectral peaks outside this range at 1.5, 1.9 and 2 Hz. It is thus classified as Type 1b. These minor peaks signify slightly larger waves with longer frequency, but may each represent only one wave at this frequency during the 5 minute recording period. The spectral density peak at 0.0015 m^2 s^{-1}. This spectrum shows high frequency, low energy waves.

Large storm waves (Hl=0.54; Hs=0.36) are also shown in Fig. 4.10a Here a stormy wave surface is shown by the wave record and the spectrum. The spectrum of Type 2b shows the occurrence of many high frequency steep waves, as well as the presence of much lower frequency waves with greater wave heights, which are fewer in number. Spectral analysis is also important in the identification of long waves (low frequency e.g. 20-300 seconds) (Chadwick *et.al.* 1995). In this example, a wave cycle of approximately 210 seconds can be detected in addition to the relatively high frequency waves. This may be seiche action and is consistent with the Water Board's records (Poodle 1979 notes seiche frequencies of up to 300 seconds). This may represent a much larger wave (swell) which would have a greater potential impact on the shore. However the 300 second record is too short to draw any firm conclusions.

Fig. 4.12b (Aug30021) is an example of a spectrum of type 2b from larger waves (H1=0.56; Hs = 0.37). Several peaks at different frequencies (0.2, 0.4. 0.5-0.7, 0.75, 0.9, 1.2, 1.25 Hz) can be seen, exemplifying the range of frequencies illustrated by the wave train. If the spectrum were smoothed, probably three peaks would be most prominent depending on the type of smoothing used. The larger waves are represented to the left of the spectrum.

The spectrum in Fig. 4.13b (Jun16016) shows a very broad range of spectral peaks and is type 2b. Most of the energy is around 0.0034 m^2/s (Hl = 0.17 m ; Hs = 0.11 m), but subsidiary spectral peaks of a spectral density of between 0.0005 and 0.001.m^2 s^{-1}. These represent the fewer larger waves recorded during the 5 minutes, but it can be seen that they are significant contributors to the wave energy for this run. This wider spectrum is recognised by the lower spectral width parameter of 0.54, denoting a mixed range of waves. The corresponding wave train is shown in Fig. 4.13a.

The most significant finding from the Loch Lomond type spectra is the occurrence of high frequency waves. Because a sampling interval of 0.2 seconds was used, (which is very high frequency for field work) each wave was defined by several sampling points which meant that clear evidence of 2D wave form is produced, except where waves are so small that they fall at the resolution limits as discussed in previous sections. Overall the calculated spectral density is relatively low between 0 and 0.008 m^2 sec^{-1} and encompasses significant waves up to approximately 0.2 m. The most frequently occurring spectral densities are low (e.g. 0- 0.0003) reflecting the low modal wave heights. Higher spectral densities were found with the largest recorded waves ranging between 0.06 and 0.14 $m^2 sec^{-1}$ during late August 1994. These represent spectral densities of considerable wave energy. The high frequency of the waves generates spectra with higher energies than may be initially assumed from viewing significant wave height statistics alone.

A higher frequency of smaller waves increases the energy acting on the shore, which affects rates of sediment transport .The spectra, by highlighting the frequency component show a higher energy regime than would be expected by looking at the standard significant wave height parameter alone, which is generally used in coastal applications. Here there is evidence for relatively high energy input to the shore zone considering the wave height. Thus lake wave frequency is significant. It is the detail from all the TDM statistics which shows the high frequency, steep waves, and these data which are enhanced with the spectral information which emphasises the distinctiveness of the wave climate. In Chapter 6 these results are compared with wave climates from elsewhere.

Summary

The wave recording programme produced a detailed and largely complete record of Loch Lomond waves in 1994. The wave probe produced high quality and detailed records in a difficult recording environment. Statistical analysis of the wave records using TDM analysis provided clear summaries of records. The spectral analysis demonstrated the nature of wave frequency and spectral density, and gave excellent summaries of wave conditions allowing inter-site comparison. The dual analysis of records in the time and frequency domains highlighted the distinctive characteristics of the waves. The wave climate is characterised by high frequency, steep, relatively low energy waves interspersed with periods of calm. In conclusion, this data set helps to alleviate the dearth of lake wave information, and provides valuable information for geomorphological applications.

4.3.3 Wave direction and storminess

Winds were recorded at the wave recording site primarily to establish wave direction and are used from hereon as a surrogate for wave direction. The 60 second mean wind velocity and direction, was recorded hourly through 1994. Rather than the 6 hourly sampling interval (used for wave records) this more frequent interval was used to quantify wind and wave variability. The relationship between wind and wave directions is complex. Ideally wind measurements from the whole of the generating area give the best indication of wave conditions at the host shore (Darbyshire 1952; Phillips 1957; Miles 1965). However winds in a mountainous, topographically varied area, can be generated from every direction and spatial correlation is difficult. Local winds may not match the broader wind directions. In the marine environment, the dominance of prevailing winds blowing over an unrestricted ocean, enables distant wind records to be used with reasonable confidence. However, the relationship between wind direction and wave direction is far from fully researched, and should be viewed with caution. To further complicate the task of wind recording, thermal effects, the wind profile (vertical variation in wind velocity and direction and altitude) and surface roughness (the type of land/water element over which wind passes), must be taken into account (Linacre 1992).

Wind records were also used to identify periods of storminess (at a monthly scale) and later, (section 5.3) to investigate relationships with beach behaviour. The Loch Lomond catchment, and especially the foreshore, is characterised by squalls and gusts of wind. Field observations show these can influence waves significantly if they persist for 10 minutes or more. Linacre (1992) defines squalls of wind as short bursts exceeding 11 m s^{-1}, lasting at least a minute. In Britain, a gust is defined as wind persisting for at least 10 minutes (Linacre 1992). Stormy conditions are defined as persistent winds at over 10 m s^{-1} (close to the Beaufort Scale 5) (Linacre 1992). The dominant (modal) wind directions from which dominant wave directions are inferred are given in Table 4.3.

Table 4.3 Wind records for 1994 (Records are incomplete due to an unreliable logger, giving variable numbers of records per month).

Month (1994)	Total no of readings (hourly records)	Modal wind direction (%)
January	88	Westerly (44%)
February	108	North-easterly (40%)
March	114	Westerly (33%)
April	104	North-westerly (24%)
May	No data	

June	36	Westerly (67%)
July	No data	
August	53	South-westerly (26%)
September	82	North-easterly (26%)
October	28	Northerly (32%)
November	85	Easterly (28%)
December	141	South-westerly (23%)

Over the entire year (839 readings), the modal wind direction was westerly (42%), followed by north-easterly (19%). The westerly waves are potentially more significant in beach modification as shown in section 4.1 and discussed further in section 4.4. From these results significant beach modification would be expected.

Storminess

Wind records can also be used to identify stormy periods, including during periods for which there were no wave records. Table 4.4 shows details of the main storm occurrences. The wave (wind) directions and wind duration during antecedent conditions are noted. In summary, 21 days with storm conditions were detected from the 1994 wind record.

During 1994 a high degree of wind variability was recorded. In terms of the wind wave relationship two particularly stormy periods stand out. At the end of August (28/8/94), the high waves (e.g. H1 = 0.94m; Hs = 0.63 m at 0600hrs) were recorded during a period of south-westerly and westerly winds (the highest fetch lengths for the wave recorder). Antecedent conditions included three days of westerly and south-westerly winds, mostly in excess of 4.0 m s^{-1}. During other stormy periods, high wind velocities and winds from one direction were short-lived, and waves of this size did not have time to develop.

The second period is 10-12/12/94 where there was flooding and high winds in the Glasgow area. Here, because winds were easterly and north-easterly very large waves did not develop at the eastern nearshore (wave recorder site).

Table 4. 4 Summary of storms in 1994

In January wind speeds included readings of above 40 m/s on the 19th, 22nd and 23rd. Some of the highest wind velocities were recorded on the 29th and 30th of January with westerly (279 ^{0}) wind speeds reaching 43.8 m s^{-1} at 0500hrs on 30/1/94. Wind speeds remained above 40 m s^{-1} for 14 consecutive hours. Low velocities were recorded for most of February, although on the 9th, wind speeds exceeded 40 m/s for three readings, falling to 9 m s^{-1} in between. These were westerly winds.

March had a number of stormy periods. On the 3rd wind velocities of 40 m/s were recorded at 1600hrs from 278 ^{0} (W). On the 5th between 14 and 1700hrs south-westerly winds of 10-11 m/s were recorded. The 10th showed variable westerly winds some exceeding 40 m s^{-1}. On the 13th and 14th winds up to 47 m s^{-1} were recorded. The morning of the 14th showed storm winds of several hours duration. The 23rd showed high winds greater than 40 m s^{-1} and briefly on the 24th at 0700hrs, but the latter is not reflected in the wave records. The 31st March and 1st April showed high winds veering to the NE. April 9th had two incidences of winds greater than 10 m s^{-1}.

The available wind records show relatively calm conditions for May to July.

August 28th shows 10m s^{-1} winds at 0800hours. The 23rd and 24th of September show some readings between 30 and 40 m s^{-1} from the west and north-west. On November 1st winds between 10 and 13 m s^{-1} from the west were recorded. On December 8th winds of 11 m s^{-1} were recorded at 1700hrs, velocities fell until 2100 hours where 12.6 m s^{-1} was recorded. These were South-west and westerly winds. December 12th shows several readings which exceed 10 m s^{-1}.

Note the 40 m s^{-1} figures are viewed with some caution, because of logger difficulties and the tendency for anemometers to 'free wheel' at high wind velocities (Linacre 1992). However, a second anemometer in the vicinity recorded similar values; winds were certainly high enough to generate large waves at these times.

One of the most significant point to emerge from the wind-wave relationship in this restricted fetch environment, is that a long duration of one wind direction over a longer fetch gives rise to the development of larger waves. This would be expected from the literature of development of a fully arisen sea (e.g. King 1972; Carter 1988; Chakrabarti 1987).

Overall, the wind results highlight the variable weather conditions. As continuous recording was not employed, the rate at which conditions can change is not fully explored, although the hourly records show the variability. Hand held anemometer records and field observations have shown that wind and wave conditions can change significantly within a 10 minute period. The variability of lake conditions is poorly documented, but Sly (1978) and Carter (1988) note the responsiveness of small water bodies to energy input. This means that if wind conditions are highly variable (as in a mountainous climate), lakes surrounded by mountains are subject to a high degree of variability in wave conditions, with the attendant effects on the shore zone. Long duration winds give rise to larger waves.

The wind records show a high degree of variability (direction, velocity and duration) which is reflected in the wave variability shown in the previous sections. The largest waves develop when winds persist from one direction for a long period of time, rather than being especially high velocity. The 1994 records show westerly winds to be dominant. A tendency for westerlies to replace the prevailing south-westerlies has been noted elsewhere (Werritty 1995, *pers. comm.).* Under these conditions the eastern shoreline is particularly vulnerable to wave action. This leads to the effects of wave action and shore modification, considered in the next sections.

4.4 Wave refraction and modification of incident waves

Having established the nature of the nearshore, deep water wave climate, the next stage is to examine the interaction of waves with the shore. Wave refraction is important because it provides a link between nearshore conditions (waves) and shore response to those conditions (e.g. King 1972; May and Tanner 1980; Pethick 1984). Generally as waves approach the shore they are refracted by bottom topography which further affects the angle at which they break and sediment transport.

The wave records have shown the predominance of small amplitude, short period, high frequency waves. The bathymetric surveys show deep water very close to the shore. Small short waves have a limited wave base, which means that refraction only occurs very close to the beach. These two factors combine to suggest that wave refraction at the study beaches may be very limited. To quantify the significance and extent of wave refraction at Cashel and Milarrochy, the graphical refraction technique described in sections 2.3.1 and 3.3.4 was used (a technique normally used on marine rather than lacustrine coasts).

Both beaches are largely protected from the full force of north and south winds and waves (section 4.1). Easterly winds are unimportant because of the eastern shore location of the beaches. Thus the principle approach directions are north-westerly, westerly and south-westerly waves for which refraction was calculated. Using the methods and selection described in section 3.2.3.4 wave examples were chosen for refraction calculation.

Westerly incident waves

The westerly wave refraction calculation at <u>Cashel</u> used a significant wave height of 0.24 m and wave period of 1.38 seconds. The whole beach is affected by westerly waves, but these are refracted little (Fig 4.22). The spatial distribution of potential wave energy is summarised in Table 4.5. Higher potential energies (max. 42.36 J m s^{-1}) reach the southern section of beach, profiles A to E1 (Fig. 3.1) and orthogonals 1-6.

The westerly waves at <u>Milarrochy</u> (Hs = 0.24 m, T = 1.38 s) show little refraction. The wave orthogonals (i.e. energy) are evenly spread over the whole bay, leaving the beach vulnerable to modification by waves from a westerly direction.

North-westerly incident waves

All of the beach at <u>Cashel</u> is vulnerable to north-westerly wave action. Using a significant wave height of 0.24 m, and wave period of 1.06 seconds, refraction calculations showed little divergence or convergence of orthogonals at the shore (i.e. no major high energy or low energy areas). Wave approach was oblique, and wave shoaling rather than refraction was dominant, except at the area between profiles B, C and D where wave crest approach was shore normal ($\alpha = 90^0$). The area by profiles F, E and G was subject to higher refraction, affected by more irregular

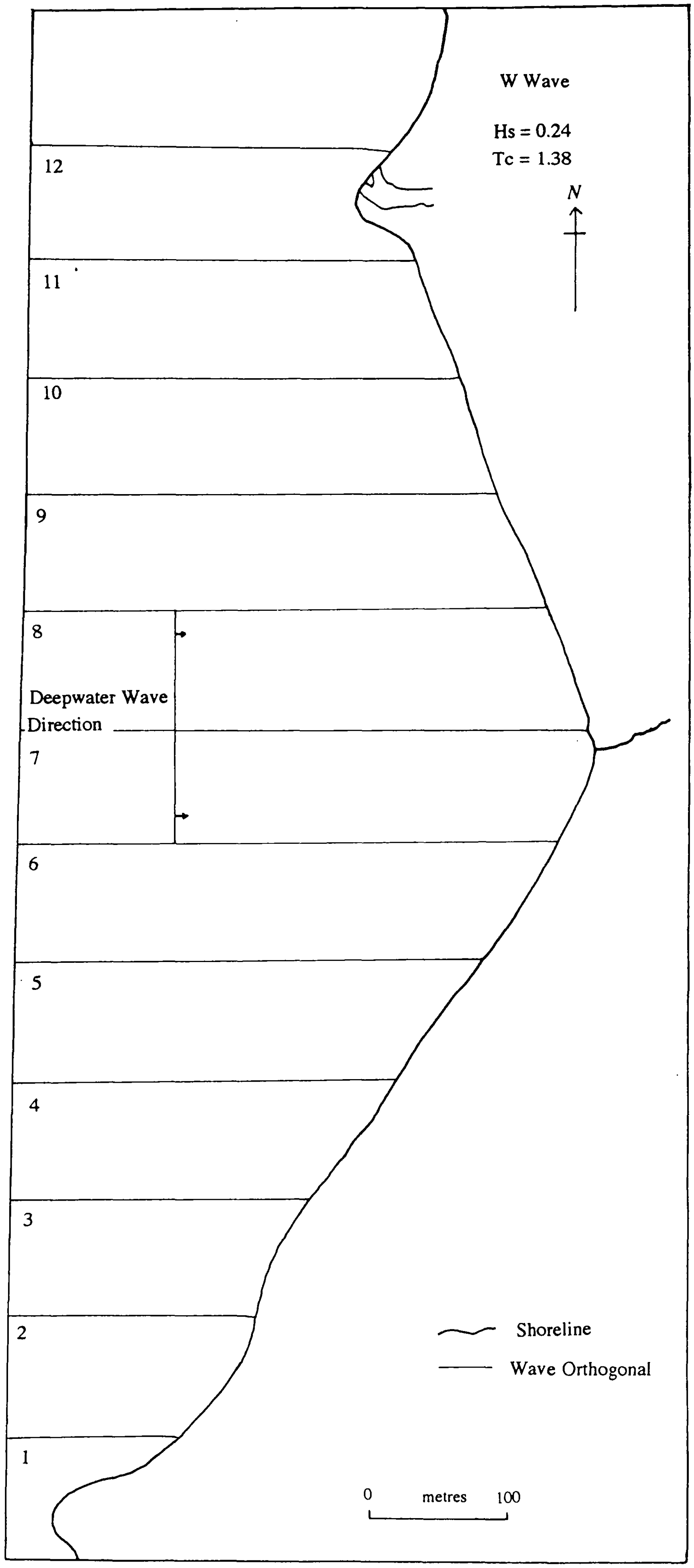


Fig. 4.22 Refraction diagram for westerly waves at Cashel.
Note how little refraction occurs

Table 4.5

Cashel NW Wave (Hs=0.24, Tc=1.06)			
Orthogonal	Angle of wave crest approach (degrees)	Potential longshore power (PL in J/m/s)	Potential sediment transport (IL in J/m/s; refer to sec. 4.5.2)
1	12	23.98	18.47
2	13	24.87	19.15
3	90	no refraction	
4	90	no refraction	
5	90	no refraction	
6	90	no refraction	
7	90	no refraction	
8	90	no refraction	
9	11	21.7	16.71
10	56	54.17	41.71
11	44	57.63	44.37
12	49	57.69	44.42
13	30	50.69	39.03
14	7	13.84	10.66
Cashel W Wave (Hs=0.24, Tc=1.38)			
1	42	55.01	42.36
2	11	2.11	1.62
3	35	51.8	39.89
4	28	46.04	35.45
5	28	46.04	35.45
6	17	32.18	24.77
7	31	49.45	38.08
8	19	34.32	26.42
9	19	34.32	26.42
10	15	27.86	21.46
11	17	30.76	23.69
12	36	53.02	40.83

Table 4.6

WAVE REFRACTION			
Milarrochy	SW Wave (Hs=0.21 m; Tc=1.05 sec.)		
Orthogonal	Angle of wave crest approach (degrees)	Potential longshore power PL in J/m/s)	Potential sediment transport (ILin J/m/s; refer to sec 4.5.2)
1	17	24.8	19
2	64	35.37	27.24
3	48	44.52	34.28
4	32	40.28	31.02
5	30	38.72	29.81
6	37	42.85	32.99
7	21	29.94	23.05
8	3	4.64	3.58
9	0	no refraction	
10	20	28.75	22.14

bathymetry around the Cashel Burn delta. Table 4.5 shows the potential longshore wave power (P_L), from these calculations, total wave power is 0.016 J m s^{-1} a very small value.

North-westerly wave refraction at Milarrochy shows orthogonals (Hs = 0.24 m, T = 1.06 s) converge slightly mid shore at profiles 3, 4 and 5. This means that a higher incidence of wave energy focuses on this part of the shore (Fig. 4.23). The northern beach is more sheltered under these conditions, except at the headland (a function of orientation). The total potential wave power is 0.039 J m s^{-1}, again very small. Potential longshore sediment transport calculated from the refraction values is discussed in section 4.5.

South-westerly incident waves

The southern headland at Cashel and the arcuate beach orientation protects most of the beach (profiles A-E1) from south-westerly waves (Fig 4.24), although conditions for longshore currents are set up with waves running obliquely to the shore. The northern section receives fairly evenly spread incident waves and refraction is minimal, being greatest at the delta of Cashel Burn, but the northern section of Cashel beach receives most of the wave energy.

All of Milarrochy beach is affected by south-westerly waves, although refraction is minimal except in the area illustrated by orthogonal 4 where the bathymetry is shallower and flatter (Fig. 4.25). For large waves (Hs = 0.62 m T = 1.66 s) refraction is extremely small. Table 4.6 shows alongshore potential energy from the refraction calculations.

Summary

For wave approach from NW and SW directions, the northern section of Cashel beach (profiles E-I) receives potentially more wave energy. Under westerly winds and waves the southern section of Cashel beach receives potentially greater wave energy.

At Milarrochy waves from NW, W and SW directions affect the beach. Only the areas immediately adjacent to the headlands are at all protected from incident waves.

This analysis shows how little refraction actually occurs, because of which only a few results are included here for illustration. There are a number of reasons for the limited refraction which

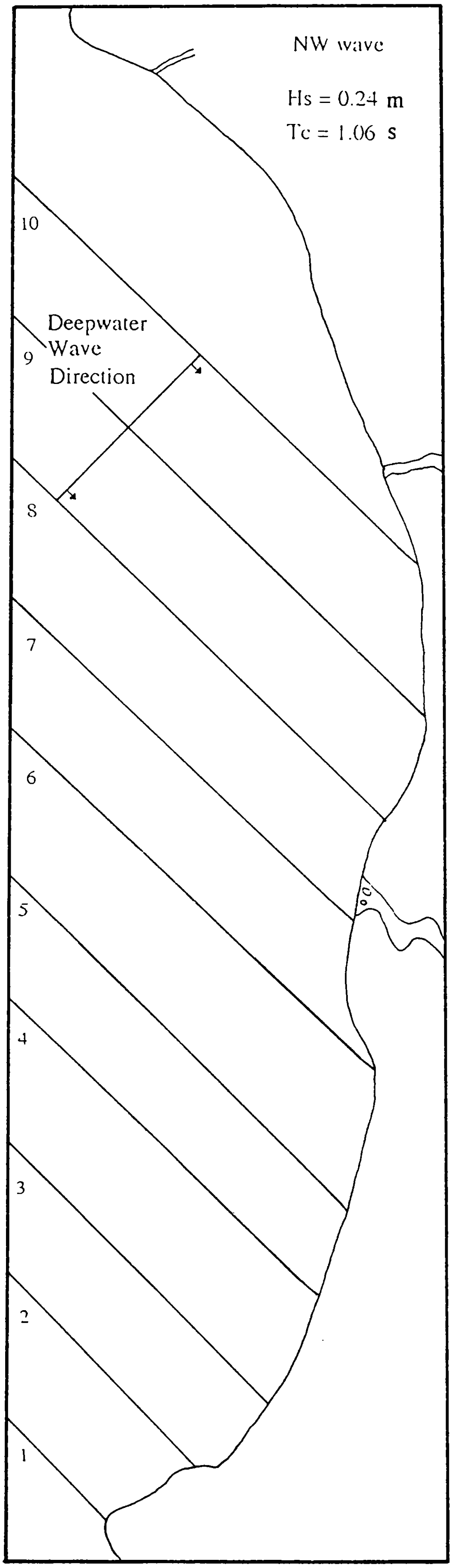


Fig. 4.23 Wave refraction diagram for north-westerly wave at Milarrochy. Note the limited refraction.

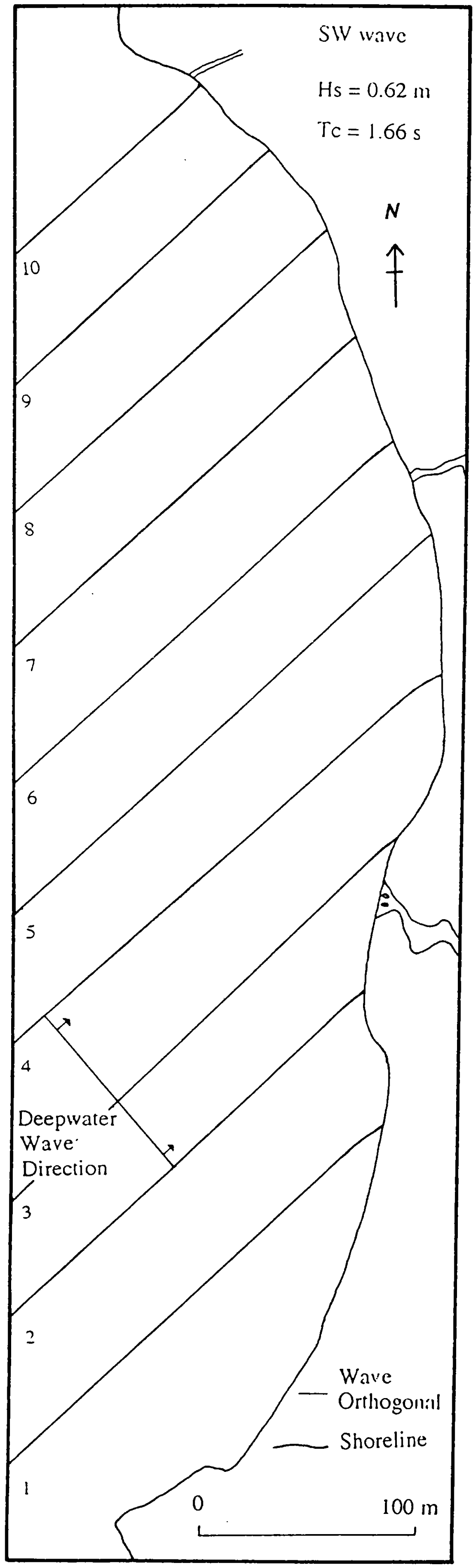


Fig. 4.25 Wave refraction diagram for south-westerly wave at Milarrochy. Orthogonal 4 shows area of greatest refraction.

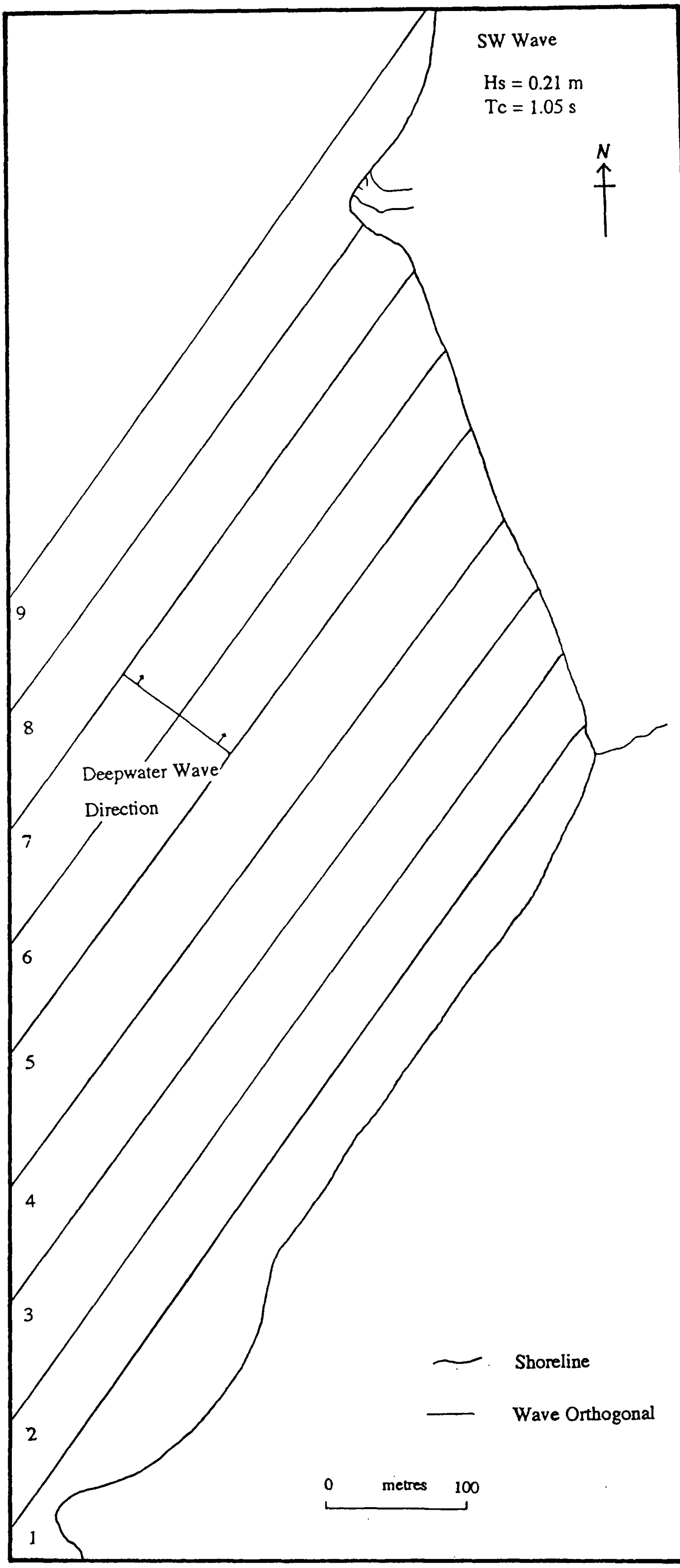


Fig. 4.24 Wave refraction diagram for south-westerly wave at Cashel. Note the limited refraction.

highlight some of the differences between the lacustrine and marine nearshore environment. Long period waves experience much more refraction than short period waves. For the former, bottom effects occur in deeper water and therefore there is a longer distance over which refraction takes place (Pethick 1984). As the Loch Lomond waves are short period waves they are only affected by steeply shelving bathymetry very close to the shore. Field observations suggest that when water levels are higher, if the nearshore bathymetry is less steep (where flatter parts of the beach are flooded), marginally more refraction occurs. However the resolution of the refraction modelling is not finely tuned enough to identify this and for the purposes of this analysis, refraction differences between high and low water levels are negligible. Because refraction is so limited, the angle of wave approach relative to shoreline angle assumes greater importance. Where this is in the region of 30^0, the energy available for longshore sediment movement is maximised.

Shoreline plan varies with water level on both beaches. At low water levels, both show arcuate beach plans whereas at higher water levels these are more linear. As wave behaviour near the shore is modified by shoreline plan, different wave refraction would be expected at different water levels. At higher water levels, not only is sub-areal beach area reduced, but the overall beach plan is much narrower giving a reduced sediment buffer to absorb breaking wave energy.

Refraction modelling is often used to try to identify cells of potential sediment circulation. At Loch Lomond such cells could not be identified from the refraction calculations as so little refraction takes place, natural barriers such as headlands and stream exits are more important in defining sediment circulation.

In summary, the wave refraction calculations show that wave refraction is relatively insignificant, unlike on the open coast. However the refraction diagrams and calculations provide a spatial assessment of potential energy levels. No clear cells of potential sediment circulation can be determined from the wave refraction results. The angle of wave approach is significant. Valuable information has been gleaned from the refraction exercise in highlighting exposed sections of beach (c.f. sec. 4.1.) and the potential wave energy affecting them. Higher potential alongshore energy rates are more likely to result from oblique incident wave directions than from refracted waves as refraction is so small. For the modelled waves, potential longshore energy values are very small, typically less than 0.1 J m s^{-1} for both Cashel and Milarrochy .

4.5 Sedimentology

4.5.1 Nearshore sediment sampling programme

The investigation of nearshore sediments was primarily to determine made in order to delimit the sub-aqueous beach and to gain indirect information on sediment transport in the nearshore zone, which aids understanding of nearshore/shore interaction and sediment budget processes. As described in section 3.2.7, systematic point sediment sampling was used at both bays and the resultant summary sediment analysis is presented on interpolated composite maps which contour mean sediment intervals of 1ϕ (Figs. 4.26 and 4.27). Further detail of nearshore sediment sizes were determined from beach sediment sampling at low water levels (section 5.5.1) and shallow water boat surveys (section 3.2.6). The boat sediment sampling locations and the offshore limit of the coarse sediment (as defined by the -1 ϕ contour) are given on the overlay. The results of the detailed sedimentological analyses from the boat sampling are in Tables 4.7 and 4.8.

In both bays there is an overall trend of offshore fining. The immediate nearshore zone is less well defined sedimentologically, showing mixed sediment distributions. Map insets give more detail of the trends of mixed sediment size grading within the immediate nearshore. These illustrate a complex depositional pattern within the nearshore area of changing water levels and wave conditions.

Of particular note is the clear offshore limit of the coarse sediment (< -1 ϕ/ >2 mm) (Figs. 4.26, 4.27). This transition can be said to mark the limit of the high energy hydraulic regime. (e.g. Hakanson 1977; Sly 1995). At Cashel this limit was 3.5 m deep in the northern bay (profiles I-E1) and 2.5 m deep in the southern bay. At Milarrochy the transition depth was 2.5 m. In bays of such steeply shelving bathymetry, deep water is very close to shore. The different depths for this coarse sediment limit at different parts of the bay are associated with different energy regimes. Sections 4.1.1 and 4 2.3 have established the variations in potential fetch lengths and therefore wave energy. Since sediment size is broadly associated with energy available for entrainment and transport (e.g. Komar 1976; 1987), the margin of coarse clastic material is associated with a decrease in hydraulic energy available for sediment transport. This would co-

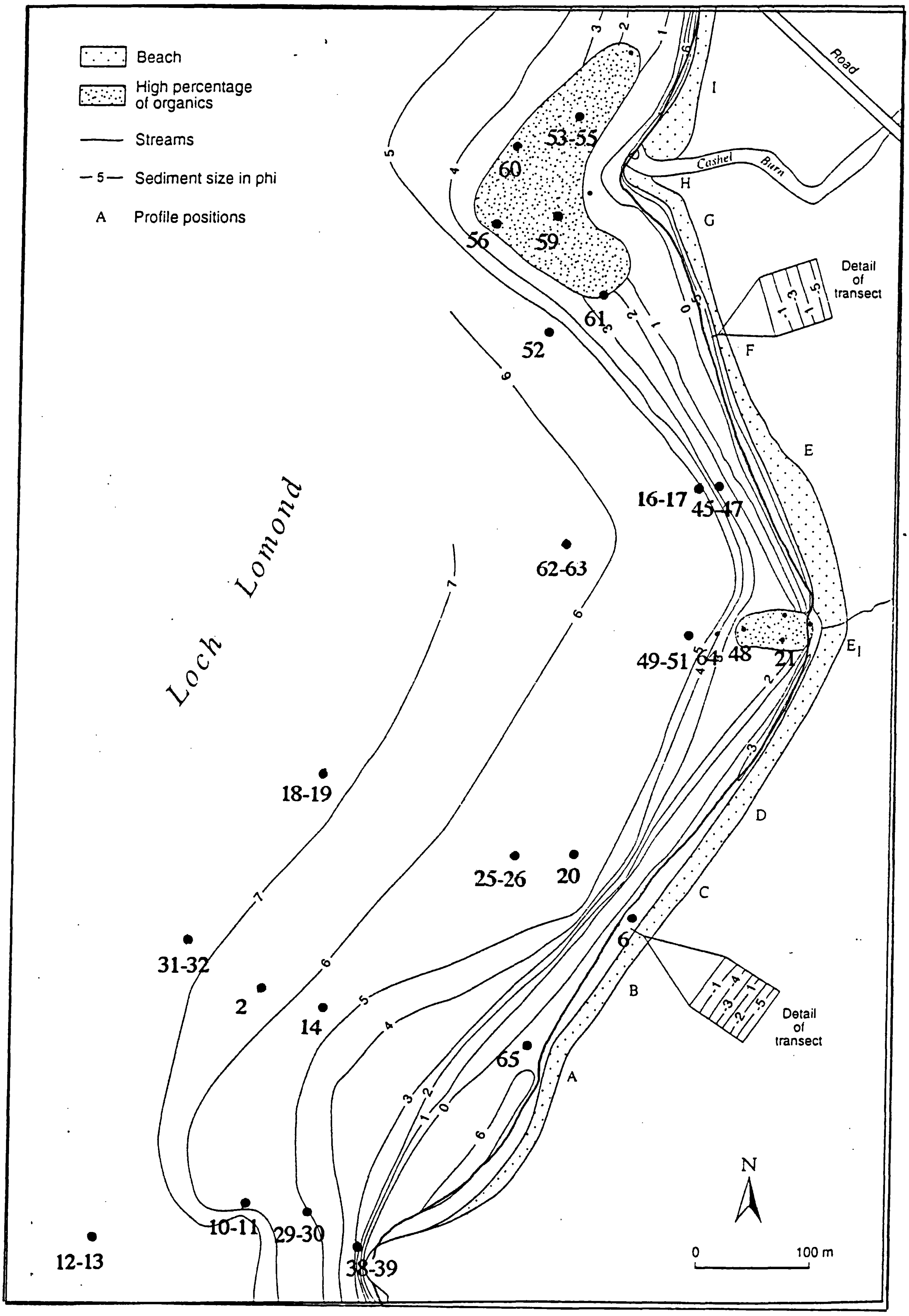


Fig. 4.26 Nearshore/offshore sediment size at Cashel.
Samples were taken on 7/1/94. Detail of transect shows range of sediment sizes in immediate nearshore. Overlay shows sampling points, sample numbers and 1ϕ contour.

Sample Number Organics 1ϕ Contour

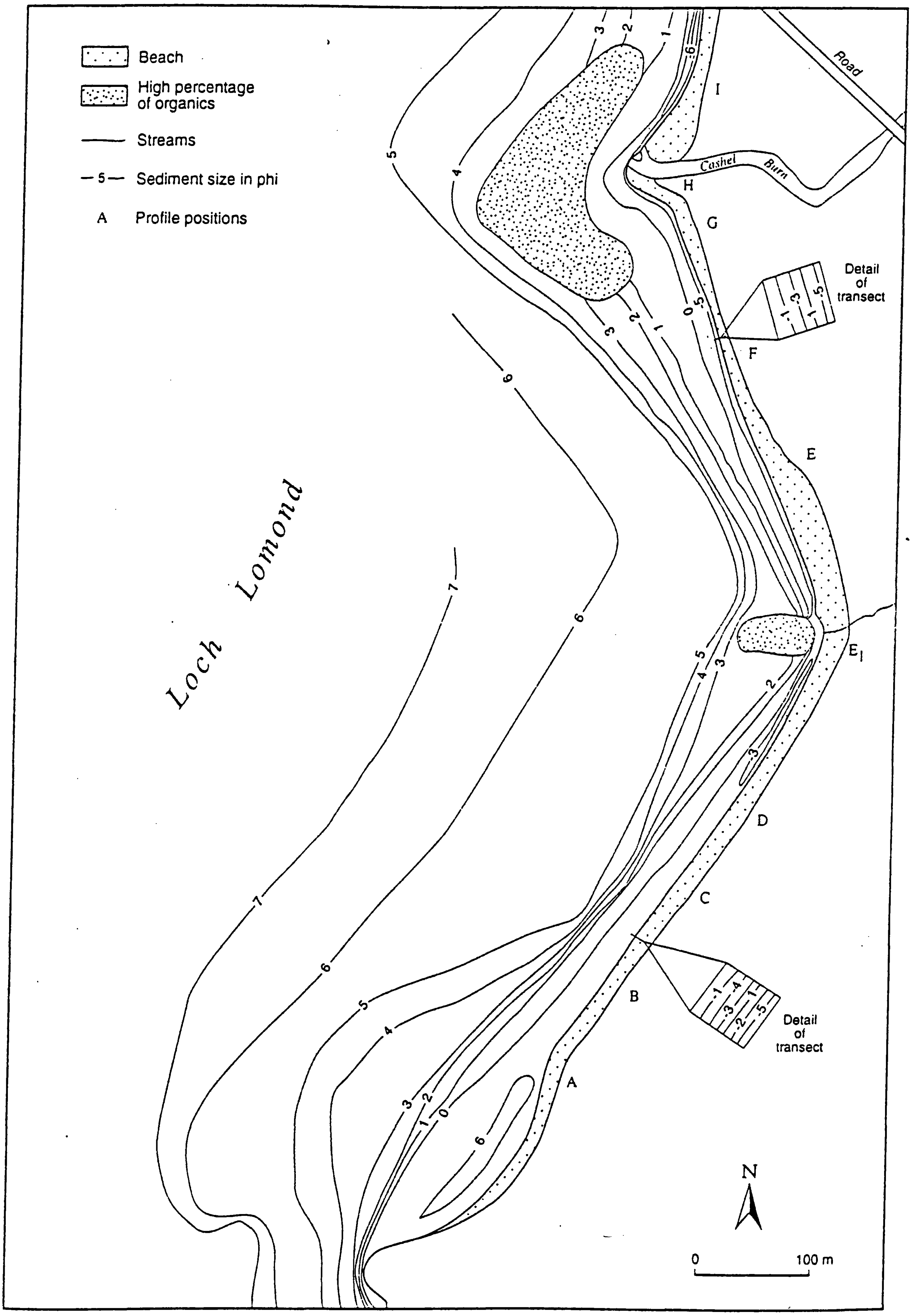


Fig. 4.26 Nearshore/offshore sediment size at Cashel.
Samples were taken on 7/9/94. Detail of transect shows range of sediment sizes in immediate nearshore. Overlay shows sampling points, sample numbers and 1ϕ contour.

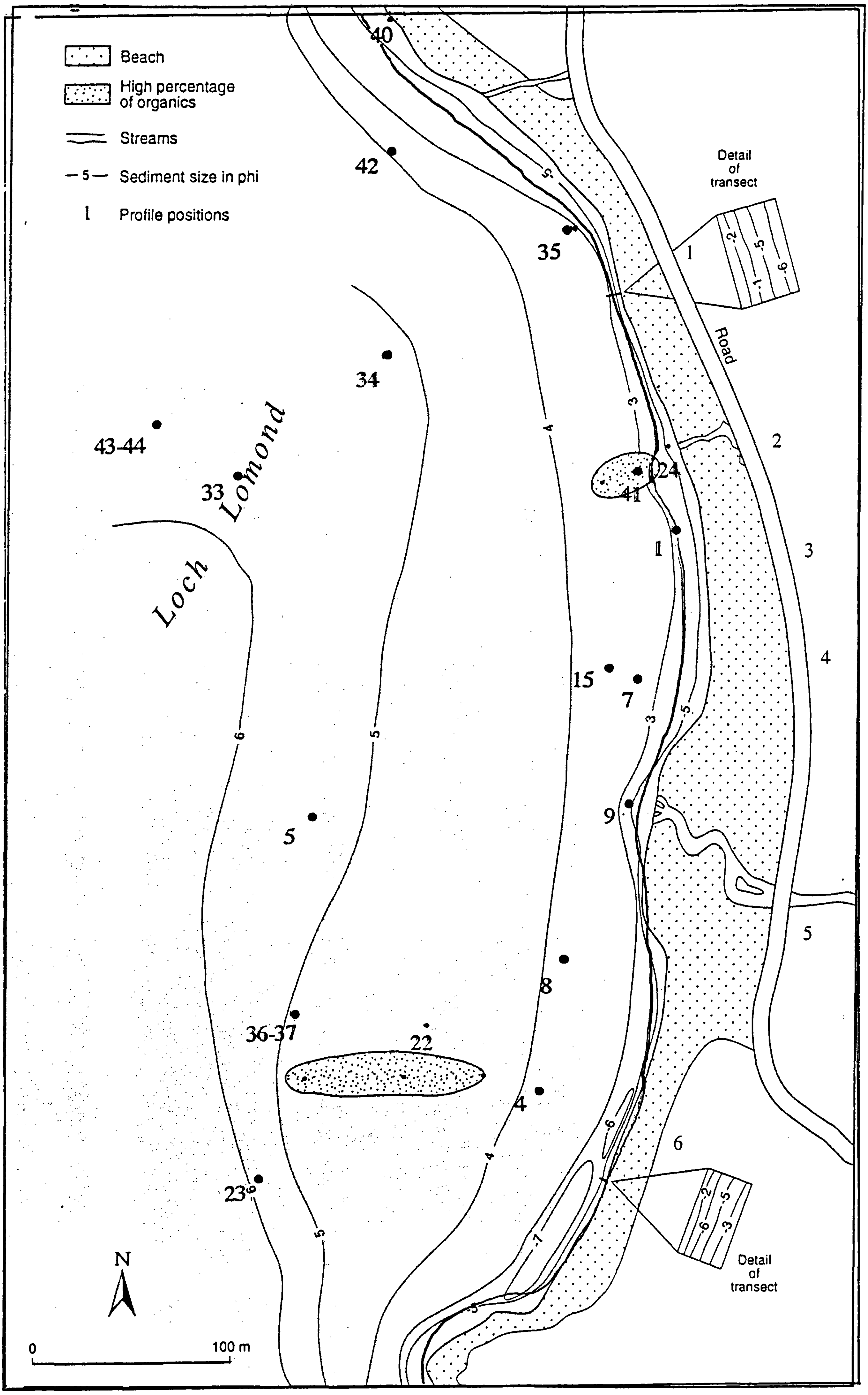


Fig. 4.27 Nearshore/offshore sediment size at Milarrochy. Samples were taken on 7/9/94. Detail of transect shows range of sediment sizes in immediate nearshore. Overlay shows sampling points, sample numbers and 1ϕ contour.

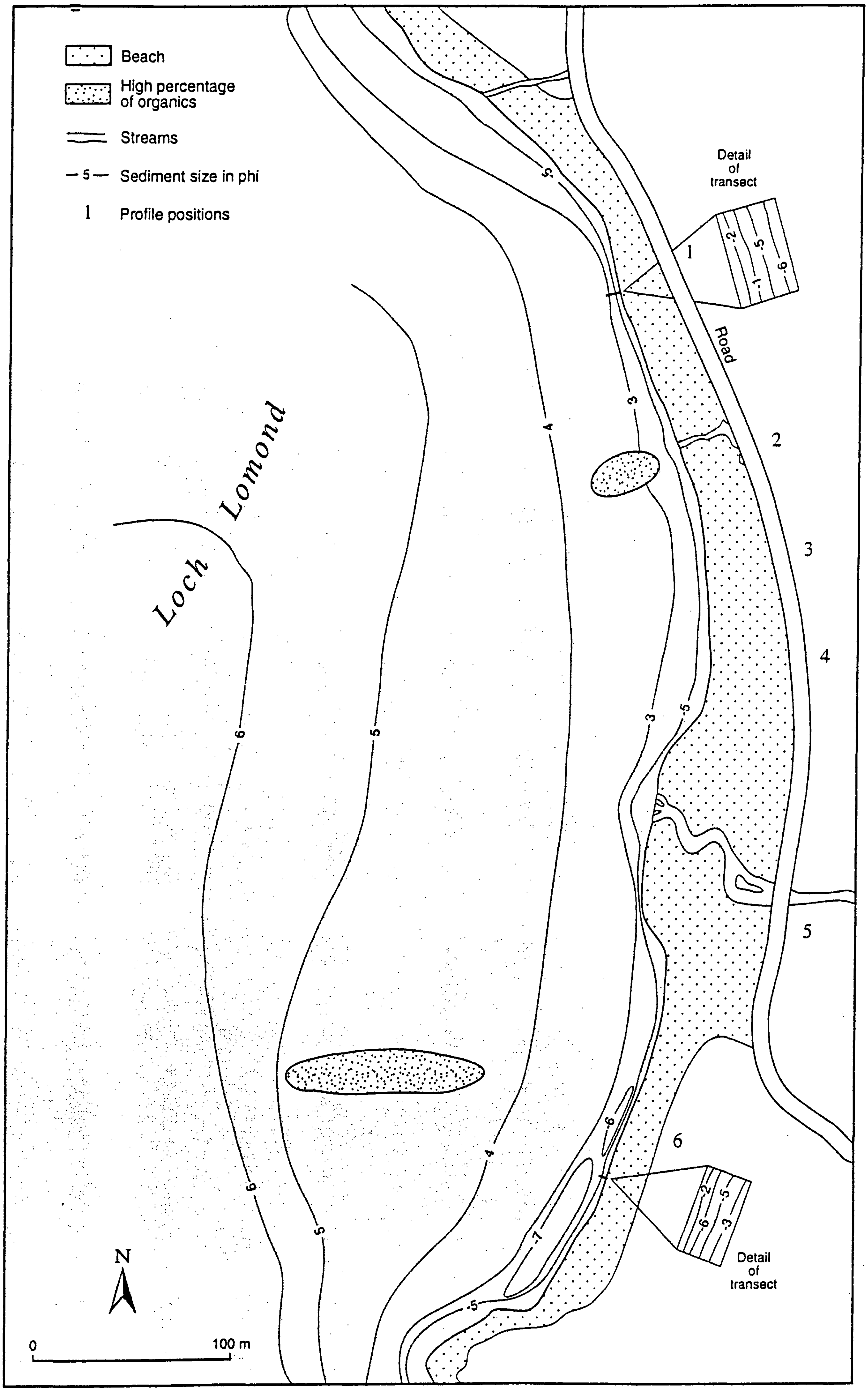


Fig. 4.27 Nearshore/offshore sediment size at Milarrochy. Samples were taken on 7/9/94. Detail of transect shows range of sediment sizes in immediate nearshore. Overlay shows sampling points, sample numbers and 1ϕ contour.

Sample	Depth (m)	Mean phi	Sorting	skew	d16	d50	d84	sample mass g
2	14	6.72	1.9	0.34	8.588	7.3	4.28	129.9
6	3	-0.88	2.56	0.17	1.63	-0.33	-3.95	581.21
10 11	15	7.17	1.74	0.34	8.71	7.53	5.26	66.1
12 13	16	7.47	1.47	0.19	8.81	7.54	6.05	115.28
14	6	5.69	1.97	-0.24	8.15	5.4	3.52	100.09
16-17	8	5.69	1.97	-0.24	8.15	5.4	3.52	313.75
18-19	15	7.14	1.77	0.31	8.79	7.47	5.15	124.84
20	13	5.31	1.81	-0.39	7.46	4.93	3.53	58.41
21	3	2.33	1.13	0.19	2.5	1.64	0.42	343.1
25-26	14	5.47	1.67	-0.16	7.61	5.28	3.53	251.79
29-30	6	silts						181.57
31-32	20	7.04	-1.79	0.07	8.95	7.04	5.13	145.97
38-39	3	3.84	-0.62	-0.81	4.08	3.77	3.7	158.1
45-47	19	3.85	-0.62	-0.81	4.08	3.77	3.7	223.74
48	10	organics 98%						52.83
49-51	18	5.95	-1.8	-0.1	8.12	5.85	3.88	229.31
52	34	5.36	-1.74	0.65	7.78	4.52	3.78	84.66
53-55	23	organics 95% + sand						169.47
56		sample too small						43.34
57-58		1.21						238.51
59		organics						135.11
60		4.73	-1.28	-0.89	6.51	3.91	3.75	139.94
61								76.84
62-63	30	silts						202.86
64	9	organics						59.7
65	3	organics						321.07

Table 4.7 Nearshore/offshore sediment samples: Cashel
Note sample numbers (1 or 2 numbers) refer to sampling positions in Fig. 4.26.

Grain size formulae used for nearshore/offshore sediment samples (after Briggs 1977).

$$\text{mean} = \frac{(\phi 16 + \phi 50 + \phi 84)}{3}$$

$$\text{sorting} = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

$$\text{skew} = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Sample	*Depth (m)*	*mean phi*	*Sorting*	*Skew*	*d16*	*d50*	*d84*	*Sample mass g*
1	5	6.29	1.9	0.1	8.31	6.47	4.1	223.8
4	3	3.74	-0.1	-3.9	3.78	3.74	3.69	421.33
5	28	5.22	-1.82	-0.91	7.97	3.94	3.75	102.13
7	3							326.52
8	2.5	3.74	-0.1	-0.39	3.78	3.74	3.69	379.66
9	4	5.22	-1.82	-0.91	7.97	3.94	3.75	224.6
15	7	3.76	-0.19	-0.43	3.82	3.76	3.7	53.75
22	17	organics						85
23	15	6.03 (+ orgs)	-1.91	0.08	8.12	6.25	3.72	78.75
24	5	3.9	-0.68	-0.82	4.26	3.79	3.71	72.9
33	21	6.39	-1.52	0.23	8.01	6.63	4.53	149.69
34	12	5.48	-1.77	-0.34	7.57	5.13	3.72	76.92
35	5	organics						293.92
36-37	31	silt	sample too small					91.68
40	1.5	1.52	-1.13	0.19	0.18	0.32	0.75	101.4
41	8	organics 95%						172.57
42	1.5	3.74	-0.08	0.33	3.79	3.74	3.7	73.97
43-44	18	6	-1.74	0.05	7.76	6.22	4.01	179.83

Table 4.8 Nearshore/offshore sediment samples: Milarrochy
note sample numbers (1 or 2 numbers) refer to sampling positions in Fig. 4.27.

incide with increased depth where wave base no longer significantly affects bottom sediments. This observed coarse sediment offshore limit is commensurate with those different fetch lengths at Cashel and Milarrochy (and therefore potential wave energy) and those suggested by Hakanson (1977b) and Sly (1995). The coarse sediment limit provides a stark contrast to the finer sediments which are found offshore. Further implications of this transition are discussed in section 4.6 and in the following chapters.

The following discussion is primarily devoted to the trends of mean grain size at Cashel and Milarrochy which relate most closely to the aims of this analysis. Further detail of the sedimentological analysis is presented in Tables 4.5 and 4.6

At Cashel beyond the mixed sediment of the immediate nearshore, the mean grain size decreases. Exceptions to this trend occur at the stream mouths (e.g. samples 56, 59 and 60 at the mouth of Cashel Burn are silts/sands rich with organic material). At the mouth of the stream at Profile E1 samples of organic material were found and sample 49-51 is a coarse silt showing significant deposition of fines in this area. Fluvially derived and transported sediments are deposited at the river mouths forming deltas. These sediment supplies are ongoing and have therefore not undergone the same degree of sorting by waves and currents as other sections of the beach.

In the southern section of the bay (Profiles A and B) there is a gentler gradient of offshore fining which is associated with bathymetry (Figs. 4.3, 4.4). Samples 18-19 and 31-32 for example, show the finest mean sediment sizes of 7.14 ϕ and 7.04 ϕ (fine silts) furthest offshore. Coarser samples of mean size 5.47 ϕ (e.g. sample 25-26) are closer to the shore in shallower water. One band of silt (6ϕ) was identified close to profile A possibly associated with lower hydraulic energies in the lee of the headland.

The northern section of the bay shows a steeper fining gradient except for the region of delta development at Cashel Burn mouth. Here is a wide area of deposition of organic material (the source of which may be the heavily vegetated hinterland of the Burn). Again sediment fining is broadly correlated with increasing water depth. Most samples show poor sorting. This may be associated with bulk (i.e. the mixing of 2 populations, surface and sub-surface) rather than surface sampling of the grab or relatively low hydraulic energy.

The sediment immediately off the southern Cashel headland is characterised by large blocky clasts derived from the headland rock (mean size -8 ϕ). There was no around headland transport of these clasts during the research period. At Milarrochy sediment trends are similar to those of Cashel with an overall trend of offshore fining beyond the mixed immediate nearshore zone associated with increasing water depth. The finest sediment sizes, samples 43-44 and 23) have a mean sizes of about 6 ϕ with a standard deviation of 1.75 (poor sorting) and 0.08 (moderately well sorted) respectively and are found the furthest distances offshore.

Samples from the stream exit at profile 2 contain organic materials largely leaf litter and twigs, which are presumed to be fluvially transported material from the densely vegetated hinterland. Such an area is not found at the other two stream exits although all three stream catchments are densely vegetated. An area with high organic content has been identified offshore from profile 6 (Fig. 4.27). As at Cashel, at Milarrochy there is an anomaly to the overall trend of offshore fining (from the coarse sediment limit) where silts and fine sands are found e.g sample 9 (mean 5.22 ϕ, silts) and sample 24, (mean 3.9 ϕ fine sands).

In summary these results show a clear trend of offshore fining beyond a very distinct margin beyond which coarse clastic sediment is not found. This limit is used to define offshore limit of the beach. These results are also important for understanding sediment transport patterns in the nearshore zone.

4.5.2 Sediment delivery to and from the nearshore zone

Beach development is affected by nearshore sedimentology and sediment transport on/off shore and alongshore. This section examines the inferences from the nearshore sediment sampling and implications of the tracer experiments in the understanding of sediment delivery to and from the nearshore zone (fluctuating water levels and changing wave conditions mean there is overlap between nearshore and shore zones). This section aims to draw together the results to indicate sediment transport trends in relation to beach sediment budgets.

4.5.2.1 Tracer results

These results of the 4 tracer experiments (section 3.2.6), from the direct measurements of sediment transport and represent an overlap between the nearshore and shore results. They are fundamentally linked to beach processes described in the following chapter where transport processes from indirect evidence are referred to.

The tracer experiments aimed to establish the spatial extent of sediment movement on the beaches, giving a field calibration figure for alongshore sediment transport and an indication of the depth of beach disturbance during wave action. Four tracer experiments were conducted in February 1994, two on each of Cashel and Milarrochy beaches. Conditions during the tracer experiments are shown in table 4.9.

Table 4.9: Wind and wave conditions during the tracer experiments.

Day	Wind velocity ($m\ s^{-1}$).	Wind direction	Wave height (m)	Wave frequency (Hz)
1 (2/2/94)	1	200^{0} (SW)	≤ 0.03	1.2
2 (3/2/94)	1	200^{0} (SW)	≤ 0.03	1.2
3 (4/2/94)	6, gusting to 9	90^{0}(E)	0.02	$\cong 1$
4 (5/2/94)	1	80^{0} (NE)	0.01/calm	0.8
5 (6/2/94)	2-3	0^{0} (N)	0.03	0.8
6 (7/2/94)	1	235^{0} (SW)	0.02	0.85
7 (8/2/94)	1	225^{0} (SW)	0.04	1.1

Figures 4.28-4.32 show summary spatial and temporal variation of sediment concentration at recovery for each experiment site. These should be referred to in conjunction with the description below as more detail is given in the text. During the experiments the wind and wave conditions were low energy and therefore only limited confidence can be placed in the generality of these results.

In Experiment 1, at *Cashel* Profile E (Figure 4.28) the tracers remained in the injection grid on day 2. By day 3 (4/2/94) there was an onshore movement of tracers, 34 of which had moved up to 2 m onshore of the injection point. Ten of these were buried up to 0.04 m deep and 10 were partially buried. By day 5, 92 tracers were found onshore of the injection point reflecting the change in the wave conditions with waves breaking onshore (with local wave this was at a 15^0 angle). This is tangential to the deposition positions, but reflects the general wind trend. The tracers were deposited in lines parallel to the water's edge. By day 7, 76 tracers were found alongshore up to 1 m, 3 of these were buried and a further 2 tracers were recovered up to 2 m alongshore. By day 9, none of the tracers was found, possibly due to human removal.

Experiment 2 at *Cashel* (Pr D, Figure 4.29) revealed an alongshore movement of tracers on the second day, trending northeast, parallel with the shoreline. All the tracers recovered were found in the nearshore zone thus reflecting wave conditions of the previous day. By day 3 (4/2/94), with the changing wind and wave conditions, the tracers changed direction and moved south and onshore; 40% were recovered between 1 and 2 metres from the injection point. By day 5, 64% were recovered and 41 were discovered buried mostly at a depth of less than 2 cm but 2 tracers were found at 0.04 m depth. These tracers were found deposited in distinct rows parallel to the waters' edge, a phenomenon noted regularly during field observation, which is discussed further in section 5.7. The trend of movement reflects the change in wind direction. By day 7, (8/2/94) only one tracer was recovered in the square directly onshore from the injection point and it was assumed that the rest of the tracers had been buried.

For Experiment 3, *Milarrochy* Pr 6, (Figure 4.30) the sample of 100 was injected on 2/2/94. By day 2, 88% were found up to 1 m onshore from the injection zone, 13 of which were buried. The refracted waves in the nearshore were breaking in an easterly direction which is consistent with the location of the tracers. By day 3 some of the tracers had moved, 5 back into the injection zone and 1 into the next grid square alongshore and 35, 3 grid squares along from the injection zone. By 6/2/94 only 1 tracer was recovered and human removal of the rest was suspected. No tracers were discovered offshore.

In Experiment 4, *Milarrochy* Pr 3 (Figure 4.31) on day 2 (3/2/94) there had been alongshore movement of tracers of up to 4 m. At this site there was no clear response to the change in wave conditions, possibly because the tracers were stranded onshore. On day 5 (6/2/94) 34 tracers were recovered and it is hypothesised that the rest had been buried. There was no evidence of tracers in the nearshore/offshore zone. By 8/2/94, 11 were recovered all buried on the beach.

Fig. 4.28

Results of Tracer Experiment 1: Tracer Concentration

(Cashel Pr E, 2/2/94-8/2/94)

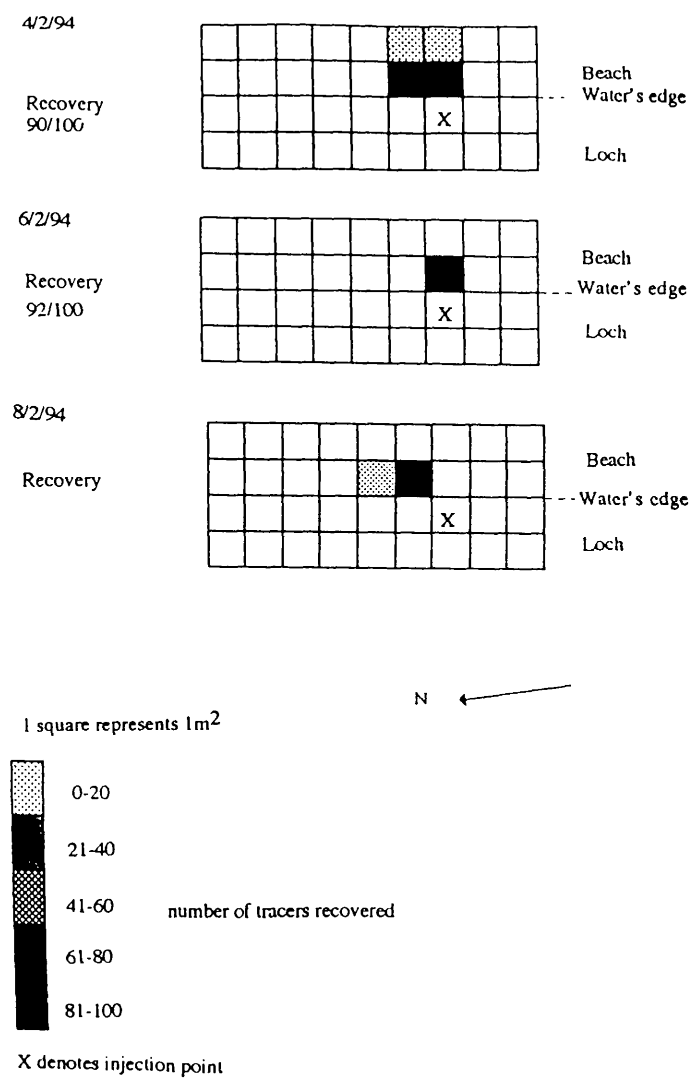


Fig. 4.29

Results of Tracer Experiment 2: Tracer Concentration

(Cashel Pr D, 2/2/94-8/2/94)

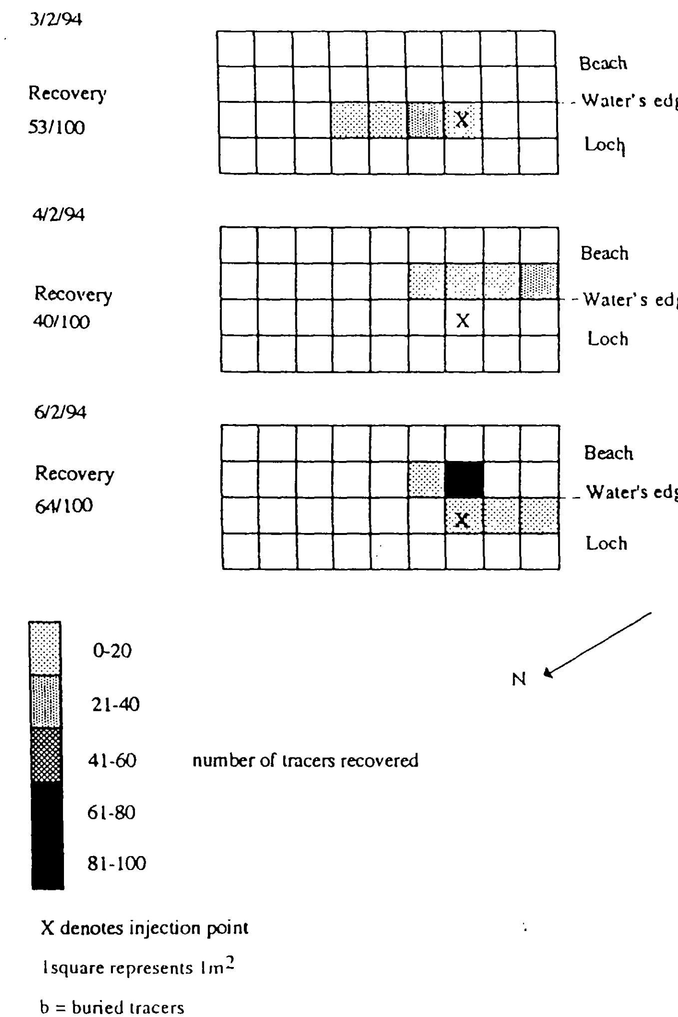


Fig. 4.30

Results of Tracer Experiment 3: Tracer Concentration

(Milarrochy Pr 6, 2/2/94-8/2/94)

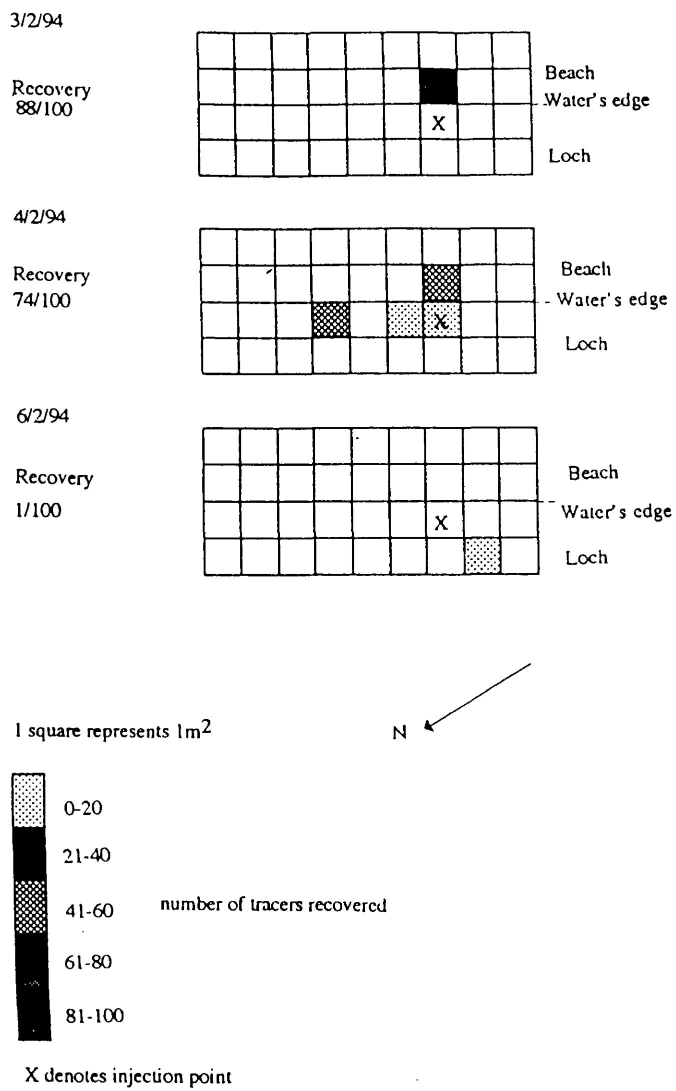
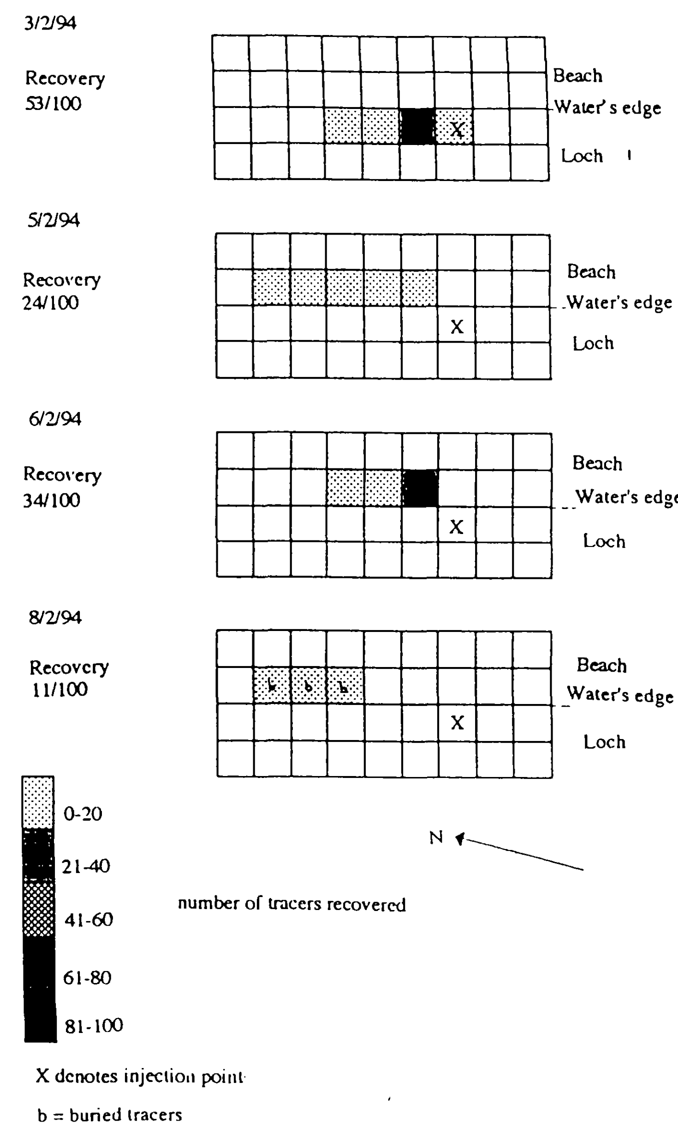


Fig. 4.31

Results of Tracer Experiment 4: Tracer Concentration

(Milarrochy Pr 3, 2/2/94-10/2/94)



As the conditions under which the four experiments were carried out were extremely calm, little information other than the direction of movement can be made from these results. There was no relationship between tracer size and distance travelled. The average maximum tracer velocity from the combined results (Cashel and Milarrochy) is 3.4 m per day.
In summary a number of points bearing in mind the calm conditions during the experiments can be made on the basis of these results.

The four locations highlighted the different sediment behaviour at different beach locations, resulting from beach orientation and exposure. Sediment movement is responsive to wind and wave conditions and was observed to move alongshore in both directions. Little offshore movement was noted and during these experiments the distance of sediment movement did not exceed 5 m per day in any direction (because of the conditions). The pilot study carried out in more severe wave conditions showed similar trends and that greater distances of movement did occur. The depth of beach disturbance was shown to be a maximum of 0.04 m; and the recovery rate for these experiments was high compared with other studies.

4.5.2.2 On/offshore sediment transport

The offshore sediment sampling results (section 4.5.1) showed an overall trend of offshore fining, as well as a clear limit to the coarse sediment ($<-1\phi$ / >2mm) of the sub-aqueous beach. This finding has important implications for understanding sediment transport in the nearshore zone. It is inferred from the latter that there is no significant offshore transport of coarse sediment. Thus, sub-aqueous (and sub-aerial) beach sediment is entrained and transported within a relatively small spatial area of the nearshore (and shore) zones. This assumption is supported by the wave results presented in section 4.3. As wave energies are relatively low, entrainment and transport of coarse sediment over any great distance is unlikely. Steep, high frequency waves break close to the shore and therefore will only entrain and transport sediment close to the waters' edge, in the shallow water. This sets up highly asymmetric current velocities with the potential to move sediment offshore and onshore rather than alongshore. The very limited wave refraction suggest the dominance of on/offshore processes in 1994 with the dominant (largely shore normal) westerly waves. Where waves approach the shore obliquely, alongshore currents are set up. Overall these factors combine to show that coarse sediment transport, other than in the immediate nearshore zone, is unlikely. On/offshore processes for sediment transport are potentially stronger than alongshore processes because wave shoaling is more signifcant than wave refraction. Incident wave direction is therefore critical in determining beach behaviour.

The tracer results (although under calm conditions) also show limited coarse sediment transport. Nearshore sediment sampling showed very mixed sediment sizes in the high energy nearshore, but with a clear margin of coarse sediment (defined by the -1 ϕ contour) before fines (sands, silts and clays) predominate further offshore. This suggests a different pattern of sedimentation from many marine environments, although one commensurate with lakes of similar fetch lengths (Sly 1995).

The offshore limit of the coarse sediment, is used to delimit the sub-aqueous beach in this study. In the sediment budget calculations the offshore sub-aqueous beach limit is used to determine the offshore limit of coarse sediment movement (the closure depth). A high degree of confidence can be placed in this because of the clear sedimentological trend.

It is difficult to quantify offshore loss of fines beyond calculating the estimated loss from cliff erosion, compared with volumes of fines on the beach, the deficit being the volume lost offshore (section 4.5.1). The nearshore sediment sampling shows the predominance of fines in the offshore areas. This trend indicates cross bay rather than alongshore transport processes. Such trends are also indicated by the wave refraction results. Field observations were made of plumes of suspended sediment carried offshore from the stream exits during periods of high flow. These fines effectively by-pass the beach system under conditions of high stream discharge and thus are transported directly offshore.

Onshore sediment transport (which delivers sediment to the sub-aerial beach) is shown by the tracer experiments (section 4.5.2.1) and indirectly by the beach morphological change results (section 5.3). This is further discussed in the next chapter.

4.5.2.3 Alongshore sediment transport

Coarse sediment is mobile only within the area of the immediate nearshore zone. Sediment sorting is poor because of varied wave conditions, bathymetry and water levels which affect the locations and ways in which waves break and transport sediment. The results from bathymetry, wave recording, wave refraction and the tracer experiments all suggest limited nearshore coarse clastic sediment transport, particularly alongshore.

Investigation of sediment around the headlands at both beaches indicated no coarse sediment transport around the headlands. In the nearshore at the southern Cashel headland, lithologically distinctive clasts occur. No evidence of these clasts is found in adjacent bays or beyond the coarse sediment limit. Vegetation was found in the nearshore zone around the headlands indicating a low energy environment and therefore an area of little sediment movement. A similar pattern was found at Milarrochy with coarser stable sediment in the headland area and vegetation in the nearshore zone. These results suggest limited alongshore transport and that sediment transport is restricted to within the bays.

4.6 Chapter Summary

This chapter has reported the results from the investigations into nearshore coastal zone. Waves were successfully recorded during 1994 enabling characterisation of the wave climate. The wave climate is distinctive being predominantly low energy but with high frequency, low amplitude steep waves interspersed with periods of calm. The high frequency waves means that energy is higher than might be suggested solely by wave heights. As nearshore bathymetry is very steep the waves break close to the shore with the potential for maximum damage to the shore zone. Water levels are highly variable and provide the underlying control to the extent of wave activity. Of particular note is the rapid bi-annual rise/fall of water level in spring and autumn, as well as a daily fluctuation in level. These changes therefore control the spatial influence of wave action.

Wave refraction is limited and, together with the wave records and bathymetry indicates the dominance of shore-normal processes. Incident wave direction exerts a significant control on potential shore modification. During 1994 the dominant wind/wave direction was westerly followed by north-easterly. Westerly waves are potentially more significant in beach modification at both Cashel and Milarrochy as the longest fetches are from the west.

There is mixed sediment deposition in the immediate nearshore, but a clear offshore limit to the coarse (-1 ϕ) sediment beyond which fines (sands, clays, silts) are found. Overall there is clear offshore sediment fining. Coarse sediment transport distances within the nearshore are estimated to be relatively small and are within the bay headlands at each site.

This chapter has provided details of the characteristics of the nearshore and defined the processes operating within the nearshore according to the aims set out in chapter 1. The next chapter presents the results from investigations in the shore zone and the ways in which processes described here interact with the shore.

Chapter 5 RESULTS: THE SHORE ZONE

5.0 Introduction

This chapter presents the results of shore zone investigations derived from both field work and secondary sources as described in Chapter 3. Shore zone characteristics, processes and variability are presented from which future change can be assessed. Using nearshore data from the previous chapter, linkages within the whole coastal zone are explored and sediment budgets constructed. The combined and closely inter-linking results (Chapters 4 and 5) are fundamental to an interpretation of contemporary geomorphological process and overall understanding of shore zone process and change (aims 2, 3 and 4). As explained in Chapter 4 there is some overlap between the two chapters.

This chapter begins with a brief description of the geology, general geomorphology and vegetation of the field sites in order to set the context of the shore zone. The evidence for shoreline change is then presented, including beach morphological change, sedimentology, sediment delivery estimates and construction of the sediment budgets. The final section summarises the main findings. The information presented in this chapter will enable full discussion of contemporary coastal change in Chapter 6, encapsulating the broader aims of the study.

5.1 Characteristics of the shore zone

5.1.1 Geology

The locational contexts of the field sites were briefly described in section 1.3 and the geology and Quaternary history in 2.5. Here to set the context of macro-scale morphology and beach planimetry, the significance of the salient geological characteristics of the field areas are given.

Beach macro-scale morphology is defined by the headland-bay sequence with hard rock geology (of the headlands) providing resistance against short-term erosion (over the time-scale of this research). Beach planimetry is broadly determined by the bay structure at the macro-scale. The overlying glacigenic sediments (tills) will be less resistant to erosional processes and are likely to be significant sources of sediment supply to the beaches. The presence of cliffs also provides both a back beach barrier. Sections of cliffs (maximum 2 m high) are present at both Milarrochy and Cashel characterising the back beaches. These cliffs are mostly fine grained (density 1.92 kg m^{-3}; mean size 6.03ϕ) with the occasional gravel to boulder sized clast within the fine grained matrix constituting less than 10 % of the cliff in the present exposures. The presence of a shore platform at Cashel is likely to have a limiting influence on profile development and variation.

The variety of lithologies in the hinterland of this coastline which has undergone extensive metamorphism, is reflected in a great range of terrestrial derived beach sediments.

The controls on macro-morphology by the bay-headland system are important and likely to exert a significant effect on beach characteristics, affecting profile development because of the relationship between planimetry and profiles (as sections of beach plan). The varying lithologies will also affect potential erosion rates, sediment supply and beach behaviour, the latter being determined in part by sedimentology. Thus geological controls affect macro-scale form as well as meso and micro-scale influences on beach sediments and beach behaviour.

5.1.2 Shore zone morphology

Geomorphological surveys were made at Cashel in May/June 1993 and in May 1993 at Milarrochy (Figs.5.1 and 5.2, in back pocket). These surveys characterise the beaches, set the context for the shore zone results and provide baseline information for monitoring future change in the shore zone. The Cashel shore descriptions are followed by those at Milarrochy.

Backshore and vegetation: Cashel

The map shows the broadly arcuate narrow coarse clastic (gravel) beach and southern headland. The northern limit of the beach is the hard rock (Leny grit) and there is rip-rap for shore protection adjacent to the road. The beach is fed by two steep gravel-bedded mountain streams (which exit at profiles G and H and at profile E1, Fig. 3.4). The immediate hinterland is vegetated. The northern section (behind profiles I to E1) is predominantly grass (a campsite) with deciduous trees flanking both the stream and some of the backshore immediately behind profiles G, F and E (predominantly oak, silver birch, ash and rowan). The southern section of beach (profile E1 to the headland) is pasture with a belt (20 m wide) of deciduous trees behind and on the backshore. Clearly visible in the area of pasture is a shore-parallel grass ridge. It extends northwards from the southern beach (beyond the headland) to the stream close to profile E1 (both sites giving sections through the ridge). The ridge elevation is 12.386 m OD at its' most southerly point and 11.132 m OD close to profile E1, both approximately 3 m higher than the beach berm.

The cliff and shore platform: Cashel

The cliff extends for 70.9 metres alongshore, reaching a maximum height of 0.75 metres (c. 8.8 m OD). It is located towards the northern end of the bay, close to the Cashel Burn delta (Fig. 5.2). The cliff is comprised of a series of embayments which are largely vegetation controlled and is composed of fine sediment (mean 6 ϕ) with the occasional included cobble-sized clasts constituting approximately 2% of the cliff face. The roots of trees and bushes (mainly brambles) seem to give a greater resistance to erosional processes. However, at high water levels the cliff foot and face can be submerged and during periods of wave activity the cliff is subject to direct wave action. There is evidence of toppling, rotational slumping and undercutting along the cliff. A lower shore platform extends offshore for approximately 9 m (maximum visible extent). This is exposed periodically throughout the year when overlying gravels are removed by wave action.

The beach: Cashel

The beach at Cashel is relatively narrow and predominantly composed of gravel (the sub-aerial width depending on water level). The beach can be divided into 2 sections by the stream at profile E1 (Fig. 3.1) which divides the northern beach from the southern beach. The southern section (E1-B) has a particularly well developed back berm, but this is much reduced at profile A (8.9 m OD at profile E1 and 11.132 m OD at profile B). The beach face slopes steeply towards the shore (gradients are shown on Fig. 5.1). A suite of ridges runs sub-parallel to the shore. At profile A where there is a change in shore orientation towards the headland, beach gradient is lower and the beach is narrower. At the stream mouth (profile E1) a small delta has formed (area approximately 343 m^2). Most of the delta topsets are gravel although foresets of finer sediments, especially silts, are observed in the nearshore. Beach ridge development frequently blocked the stream mouth (Plate 5.1). Overall the morphology of this southern section of beach bears close resemblance to an open coast marine beach.

The northern section of the beach has a less well defined back berm (in places because of the presence of the cliff) and beach gradients tend to be slightly lower than in the southern beach section. Smaller suites of shore-parallel ridges (0.05-0.1 m high) are found in this area. Their development between profiles G and E is partly limited by the cliff embayments and the presence of boulders on the beach surface. Longer stretches of beach ridges develop between profiles H and I. Vegetation on the beach encourages sediment accumulation.

The stream mouth at profile G (Cashel Burn) has a large delta, approximately 914 m^2 (Plate 5.2). It shows two main channels which have dominant seasonal use. The Burn exits at a Summer orientation of 300^0 between May and September and at 220^0 (from N) during the winter between mid September and May. The delta distributary channels have gravel and sand bars. The delta topset beds are mostly horizontal gravels, and the foreset beds which slope with an incline of typically -7^0 are mainly sands and silts. The role of the deltas is further discussed in section 5.3.2.

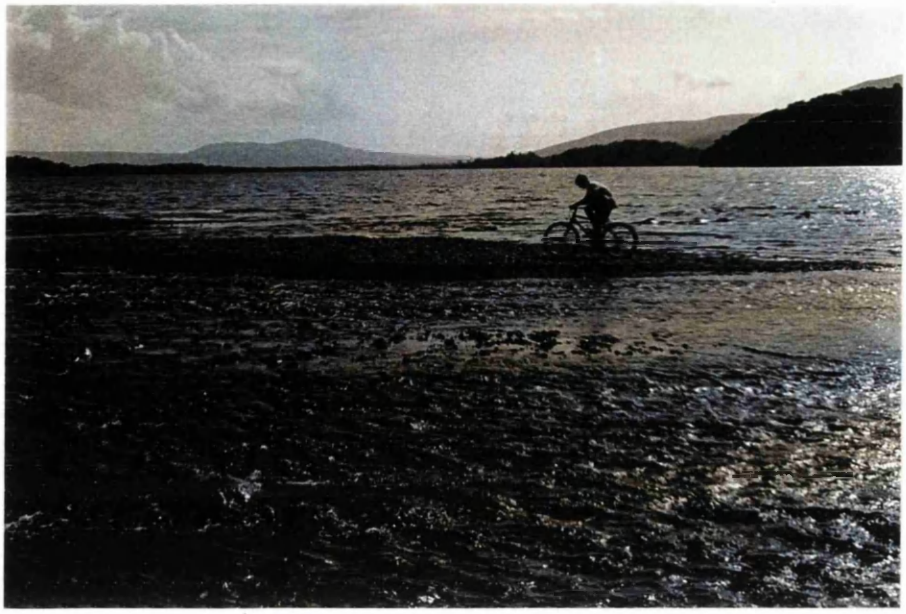


Plate 5.1 Part of Cashel Burn mouth and delta: an area of considerable sediment storage. Photograph facing 300^0. (Bicycle for scale)

Plate 5.2 Stream mouth adjacent to Profile E1 at Cashel blocked by ridge development. Photograph facing 215^0. (Scale: log = 1.2 m)

Backshore and vegetation: Milarrochy

Fig 5.2 (in back pocket) shows the narrow arcuate beach of Milarrochy within headlands. The southern headland (Arrochymore Point) has an offshore small island. The beach lies much closer to the Balmaha-Rowardennan road than Cashel and so the hinterland is affected by engineering structures. The area between the back beach and the road is vegetated (deciduous woodland, predominantly oak). In the southern section of beach the hinterland is more extensive as the road veers away from the coastline where there is a hill rising to 40 m OD which is cliffed at the beach. This hinterland is mixed deciduous woodland and a Site of Special Scientific Interest (SSSI). Three steep gravel-bedded streams enter the Loch at Milarrochy exiting between the northern headland and profile 1, adjacent to profile 2 and close to profile 5 (Fig. 3.4) (further details of which are given in section 5.4.1.1). Periodically, beach ridges tend to impede the exit of these streams, especially at profile 2.

The cliff

The southern end of the beach is cliffed and these extend for 216 m until close to the headland. The cliffs rise to a maximum height of 2.5 m and as at Cashel they are embayed with trees and roots providing significant strengthening of the matrix. As described in section 5.1.1 the cliffs comprise a fine matrix (mean = approx. 6 ϕ) with occasional cobbles and boulders constituting approximately 7-10 % of the cliff face.

The beach

The beach is characterised by a back berm (this is close to the road between profiles 1 and 4). The beach gradients (shown on Fig. 5.2) are generally less steep than the Southern part of Cashel. The beach sediments are predominantly gravel with some sections of surface sand and clays. The upper beach adjacent to the cliffs is periodically rich in fines from weathering and erosion of the cliffs. Suites of shore-parallel ridges occur on the beach. During much of the year a large section of the beach is underwater thus reducing the extent of the sub-aerial beach.

Human influence

It should be noted that there is human modification of upper beach morphology with vehicle access and parking on the beach (mainly in summer) causing compaction. Shore defence structures (rip-rap) of 73 m long were built in winter 1992/93 to protect the road and a car parking area in the northern section of beach further constraining beach sediment mobility.

Summary

The coastal morphology results highlight the narrow gravel beaches flanked by headlands which provide macro-scale controls on beach development. The Cashel hinterland is much more extensive than Milarrochy, the latter being constrained by the headlands, the road and shore protection structures. The only unconstrained backshore and hinterland area is the SSSI beyond the cliffs. Should recessional processes be dominant, from these results, this SSSI area is expected to show the most marked change.

5.2 Historical shoreline change

5.2.1 Map evidence

The available maps show a landward retreat of the shoreline at both sites. Only two land surveys have been published, in 1860-61 and 1975, although Ordnance Survey maps were produced in 1864, 1899, 1923 and 1977 with some revisions. Compilation maps were drawn to show shoreline change at Cashel and Milarrochy (Figs. 5.3, 5.4 and 5.5).

Cashel

The main trend at Cashel (Fig. 5.3) is a recessional northern section and a largely stable southern section of beach. The southern headland position seems to be different in the earliest maps reflecting either accretion, differing water levels or inaccurate cartography. Between 1899 and 1923 there was no change in delta plan, but erosion between 1923 and 1977 totalled 15 m. The increased delta area at the stream at E1, particularly after 1977, which by 1992 matched the original 1860/61 shoreline.

Between the stream at profile E1 and Cashel Burn at profile G, the maps show clear evidence of recession throughout the period 1860-1992. Immediately to the north of the stream at E1, the shoreline retreated 10 m between 1860 and 1899 (an average rate of 0.39 m yr^{-1}). Further north by profile E, the shore position shows little change between 1860 and 1923, but between 1923 and 1977 there was 20 m recession, and between 1977 and 1992 13 m recession. The mean recession rate (1923-1992) for this area is 0.25 m yr^{-1}.

In the vicinity of the delta at Cashel Burn, there has been a fluctuation between recession and progradation. The delta with has prograded 26m since 1923 (0.39 m yr^{-1}). North-east of the Cashel Burn delta at profile I, the shoreline positions are varied. Recession between 1860 and 1923 is approximately 10 m whereas between 1977 and 1992 there was an apparent progradation of 10 m. The progradation could be due to fluvial sediment transfer from Cashel Burn or to shore protection structures built at the road side in 1992.

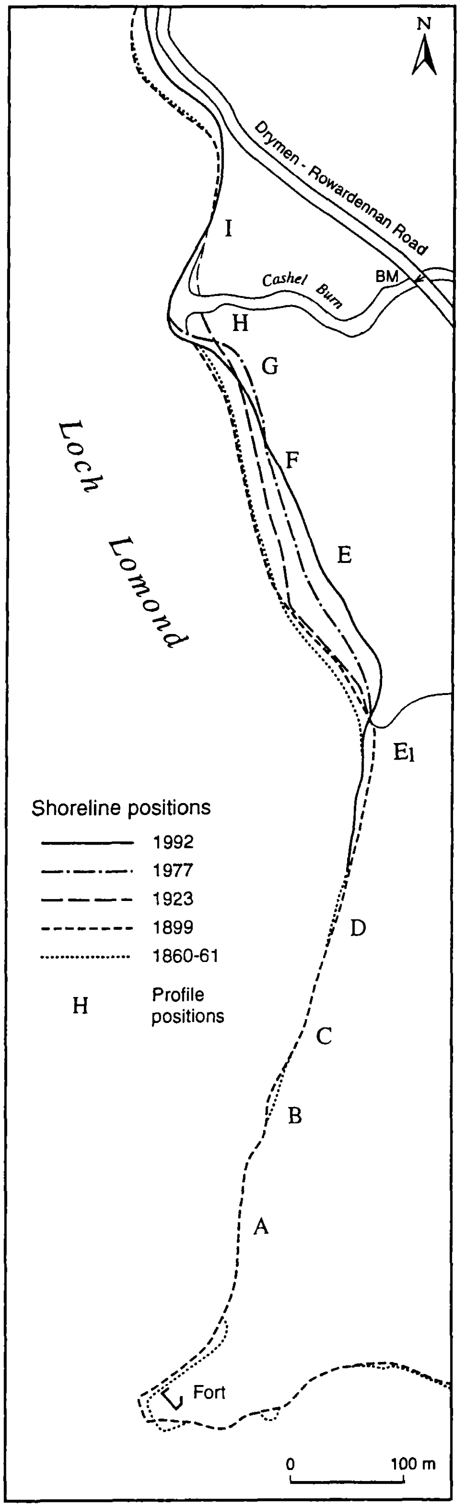


Fig. 5.3 Shoreline change at Cashel

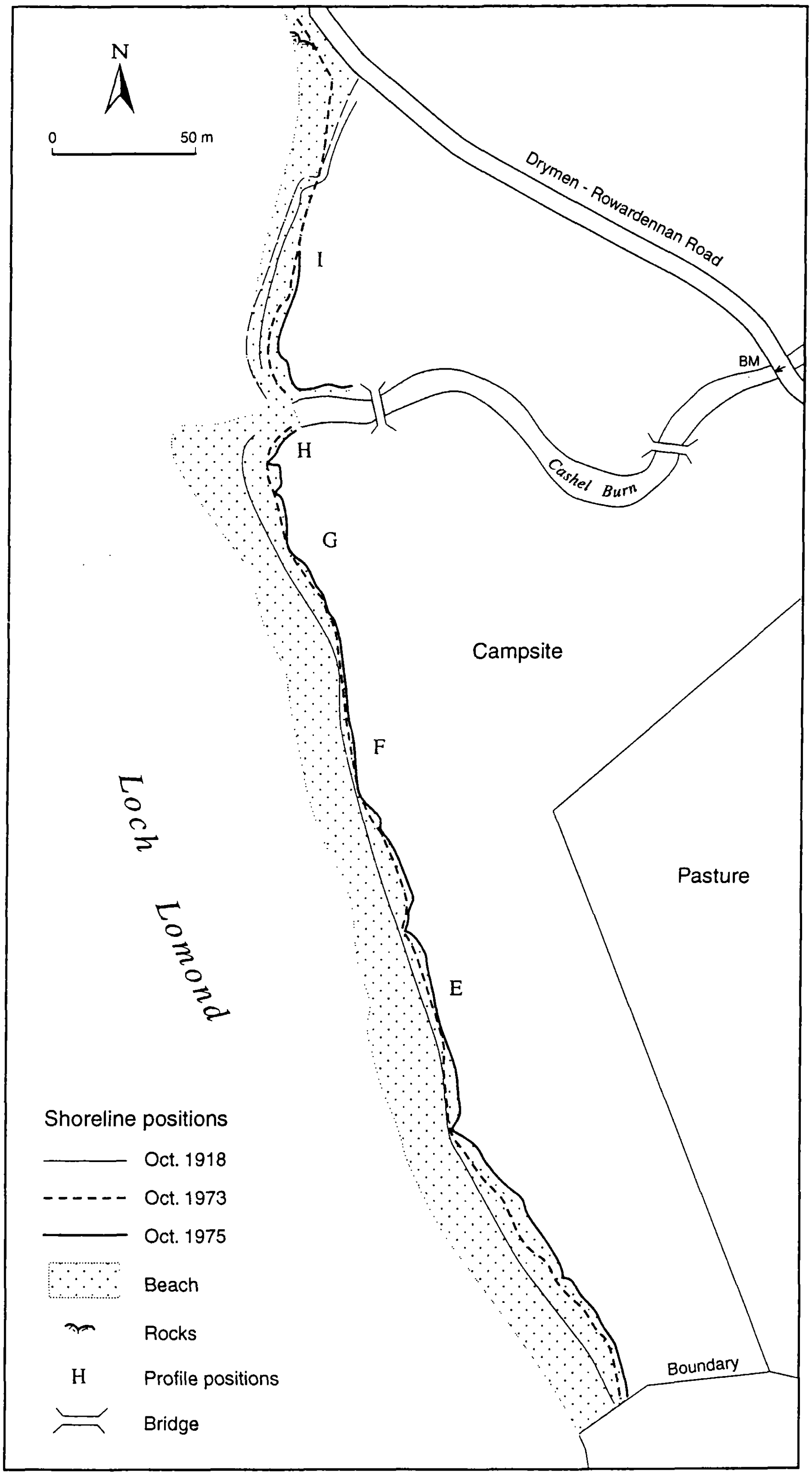


Fig. 5.4 Shoreline change at Cashel: northern section of beach

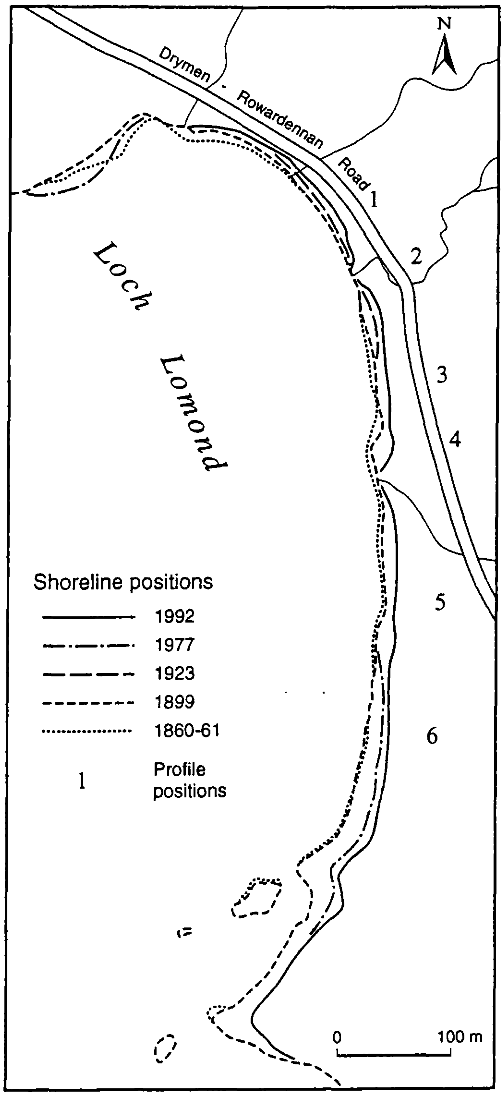


Fig. 5.5 Shoreline change at Milarrochy

The most detailed map of Cashel is from the Forestry Commission (Fig 5.4), which is of the northern section of beach. Although the source of initial shore survey (1918) is not confirmed, the 1973 and 1975 surveys were Forestry Commission surveys. Exactly what is represented by each shore 'line' is not clear, although the dated lines probably signify the margin between the grass hinterland and the back beach or cliff.

At the Cashel Burn mouth, what is taken to be a low water mark signifies the presence of a well developed delta. Between this delta and the most southerly section of this map, the mean annual recession between 1918 and 1975 was 0.2 m yr^{-1}. This increased to 1.2 m per year between 1973 and 1975. To the north-east of the delta, (profile I) the map shows a recessional shoreline. This is different from the OS map results, although the 1992 shore position is not plotted on Figure 5.5. Because of the small scales of the OS maps, and possible inaccuracies indicated by the changing position of hard rock headlands in earlier maps, greater confidence is placed in the Forestry Commission results.

The most recent survey (1992) plotted on Fig. 5.4 shows an undulating shoreline. This is probably vegetation controlled erosion as observed during field surveys (section 5.3) with vegetation giving support to the cliff fabric. This level of detail supports the greater confidence in the Forestry Commission map.

Milarrochy

At Milarrochy (Fig. 5.5) shoreline change is more pronounced at the southern end of the bay. The composite map shows shore recession in the southern part of the bay. To the south of profile 6, recession of approximately 20 m occurred between 1860 and 1977. Between 1860 and 1923 there was virtually no change. Between 1923 and 1977, the linear rate in the area south of profile 6 was 0.37 m yr^{-1}. Between 1977 and 1992 the mean erosion rate here was 0.4 m yr^{-1} (shore recession = 6 m). Immediately north of profile 6, recession rates increase from approximately zero to 14 m in 15 years (0.93 m yr^{-1}).

There was little or no recession between 1860 and 1877 and 1977-1992 in the area of shore adjacent to profile 5. In the intervening period, the shoreline was recessional and approximately 14.3 m was lost.

Between profiles 2 and 5 about 10 m recession occurred between 1977 and 1992 (0.66m yr^{-1}). At the stream exit at profile 2 the shoreline change was consistent with adjacent areas, possibly reflecting a limited sediment supply. Although between 1977 and 1992, this area prograded by approximately 5 m so more sediment was available in this area for that time period.

In summary at Milarrochy the northern section of the bay (north of the stream near profile 5) has shore recession of approximately 13 m over 132 years or 0.02 m per year. The recession in the southern part of the bay (south of the stream near profile 5) is 27.4 m over 132 years and therefore a higher rate.

Variables such as sediment supply and water level affect shore position, but are not accounted for by averaged recession/progradation rates. Uncertainties in the quality of cartographic representation reduce the confidence which can be placed in some of the results. However, the composite picture obtained from the map analysis is useful because no such figures have been presented previously for Loch Lomond and they establish a long term recessional trend in spite of considerable longshore variability.

Available aerial photographs were poor quality and small scale (1:24000), and so were of limited value for this investigation. Shoreline positions were traced from each photograph for both Cashel and Milarrochy and recession rates calculated. The errors in this rendered the results of little quantitative use (section 3.3.1), but confirmed shore retreat.

Summary

The results from the analysis of map and aerial photograph evidence establish that:

1) there is a long term overall trend of shore recession at Milarrochy and on the northern section of beach at Cashel;

2) recession rates vary temporally, but they seem to have increased considerably in some places between 1977 and 1992;

3) recession rates vary spatially. A recessional section of beach may become stable at different times; and

4) delta sedimentation and progradation between 1977 and 1992 was higher than previous periods.

5.3 Beach morphological change

5.3.1 Beach profile results

Field evidence of contemporary shoreline change is best seen in the variation of beach profiles. The primary reasons for repeat measuring beach profiles (morphological change) were to assess the magnitude of beach variability (aim 2) and to construct a sediment budget for 1994. This section describes profile variation for the two gravel beaches, and the magnitude of volumetric change between surveys. Beach variability is analysed, and a first approximation of links with generating processes is made (aim 3).

5.3.1.1 Beach profile form

In this section, the results from the beach profile surveys are presented. Firstly, the main findings from *all* the surveys are described and profile forms classified; secondly, there is detailed analysis of examples of profile change at Cashel and Milarrochy.

A number of authors (e.g. Shepard 1950; Huntly and Bowen 1975; Sonu and van Beek 1971; King 1972; Wright *et al.* 1979; Mason and Hansom 1989) have recognised trends in marine beach profile type. To describe the lake beach profiles, a classification of profile form (shape) was developed as there are no pre-existing ones. The classification was based on the geometric macro-form of slope angle that appeared regularly in the beach profiles, the profile positions are shown in Fig. 3.1. Profiles were classified into types based on straight, concave, convex, and multi-barred forms although some types consisted of combinations of these basic forms. The classification is designed to be expanded should longer temporal surveys reveal further types. Presence or absence of a back berm was also noted. The classification could be applied quantitatively (based on dominant angles of back berm, mid and foreshore slopes) or qualitatively. The classification fully describes the large data set obtained and also incorporates an appropriate level of detail within the observed variability.

The classification is intended to enable identification of sequences of profile development, sediment loss and gain to the overall profile. It should be mentioned once again that the profiles provide 2-dimensional representation of more complex 3-dimensional beach geometry.

Eight types of profile were defined (a-h), each of which has a subsidiary type (Fig. 5.6). The main types are:

Type a	straight profile (slope > 0^0);
Type b	concave profile;
Type c	convex profile;
Type d	multi-ridged profile, steep and concave;
Type e	multi-ridged profile, steep and with a straight slope or stepped;
Type f	straight flat profile ($\approx 0^0$);
Type g	multi-ridged profile, steep and convex;
Type h	concave-convex.

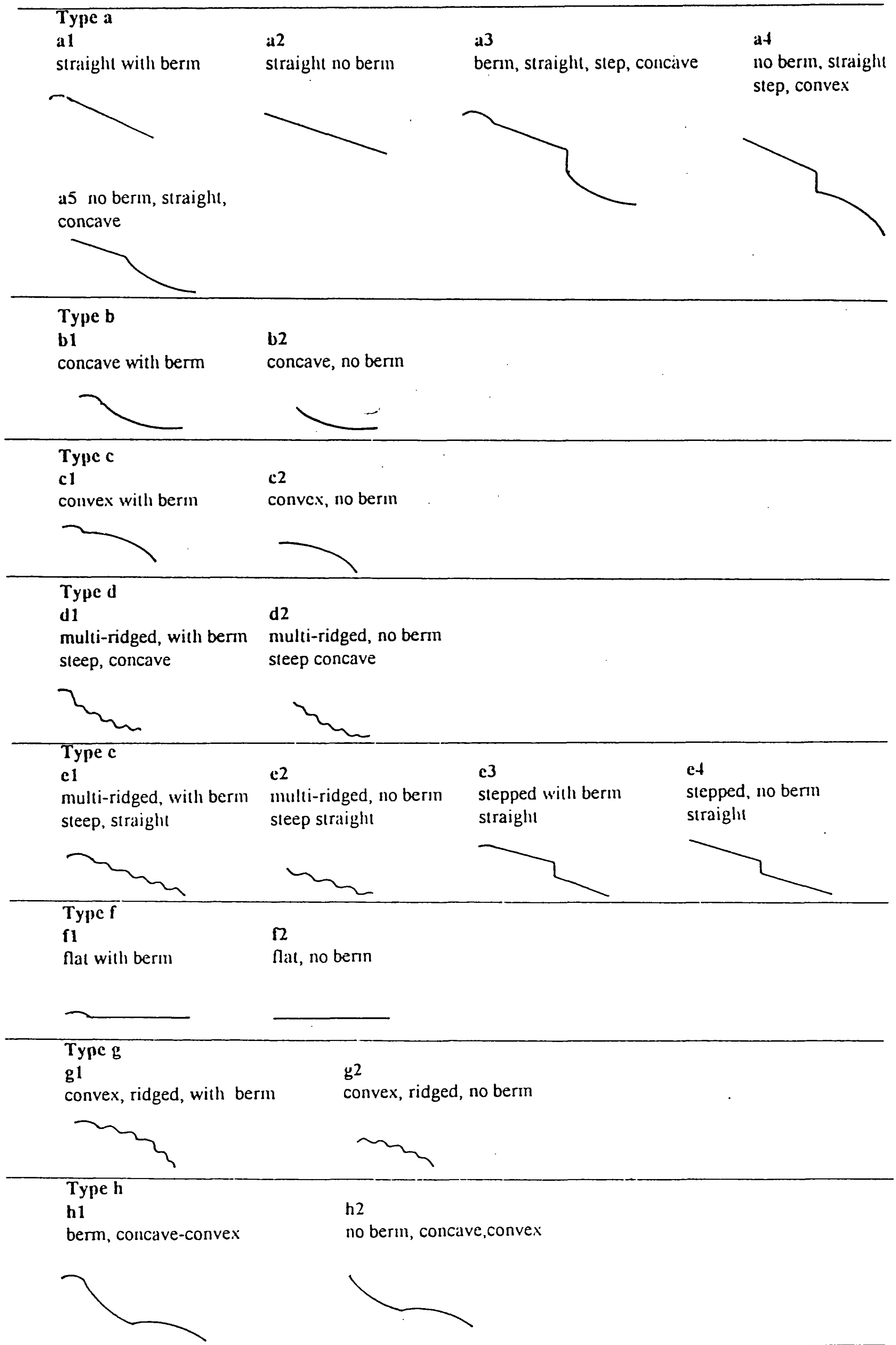


Fig. 5.6 Gravel beach profile type classification.

The profile classifications for each month in 1994 for both Cashel and Milarrochy (Tables 5.1 and 5.2) show considerable variability in beach types but spatial trends of profile type can be identified. There is considerable variation in profile type on both beaches identified at the outset (section 3.3.2.2). Most profiles exhibit a limited range of types showing that variation at individual profiles is limited.

From the results, two periods where profile type change occurred are noted: 1) between April and May, where 7 out of 9 profiles at Cashel, and 6 out of 6 at Milarrochy show change in type; and 2) between August and September, where 5 out of 9 at Cashel, but only 1 out of 6 at Milarrochy show a change in type. Intervening periods tended to be more stable.

The behaviour of some profiles was affected by external factors. The profile type at Profile H (which although near the delta) comprised a stream bank profile and remained constant. Profiles 4 and 5 at Milarrochy were affected by car-parking on the beach, so trends of increasing concavity in profile development may be attributable to sediment compaction rather than sediment removal. An artificial berm was constructed in March 1994 at profile 5 with sediment consisting of rubble, mixed grain sizes especially sand, clay and silt which contributed to profile change. At Cashel Profile I, an artificial trench was dug as a storm protection measure in November 1994.

Overall, the summary results show a high degree of variation alongshore, spatially and temporally. Individual profiles show a more limited temporal variability.

Examples of profile variation: Cashel

Some examples of beach variability are discussed here. These have been selected to illustrate the detailed characteristics of profile and the degree of variability at both Cashel and Milarrochy. In order to show maximum detail, the actual profile results are illustrated (closure depth extensions used for the sediment budget are not shown here). Varying profile lengths reflect varying water levels.

The northern section of Cashel beach shows a higher degree of profile variability than the southern section. Adjacent profiles E and F and G might be expected to show some similarities, as they share the same exposure. On examination, profile E (Fig. 5.7) shows greater variability of form during the early part of the year (January to March). The concave beach (type b and a5) persists for the rest of the year, becoming less pronounced towards winter. The presence or

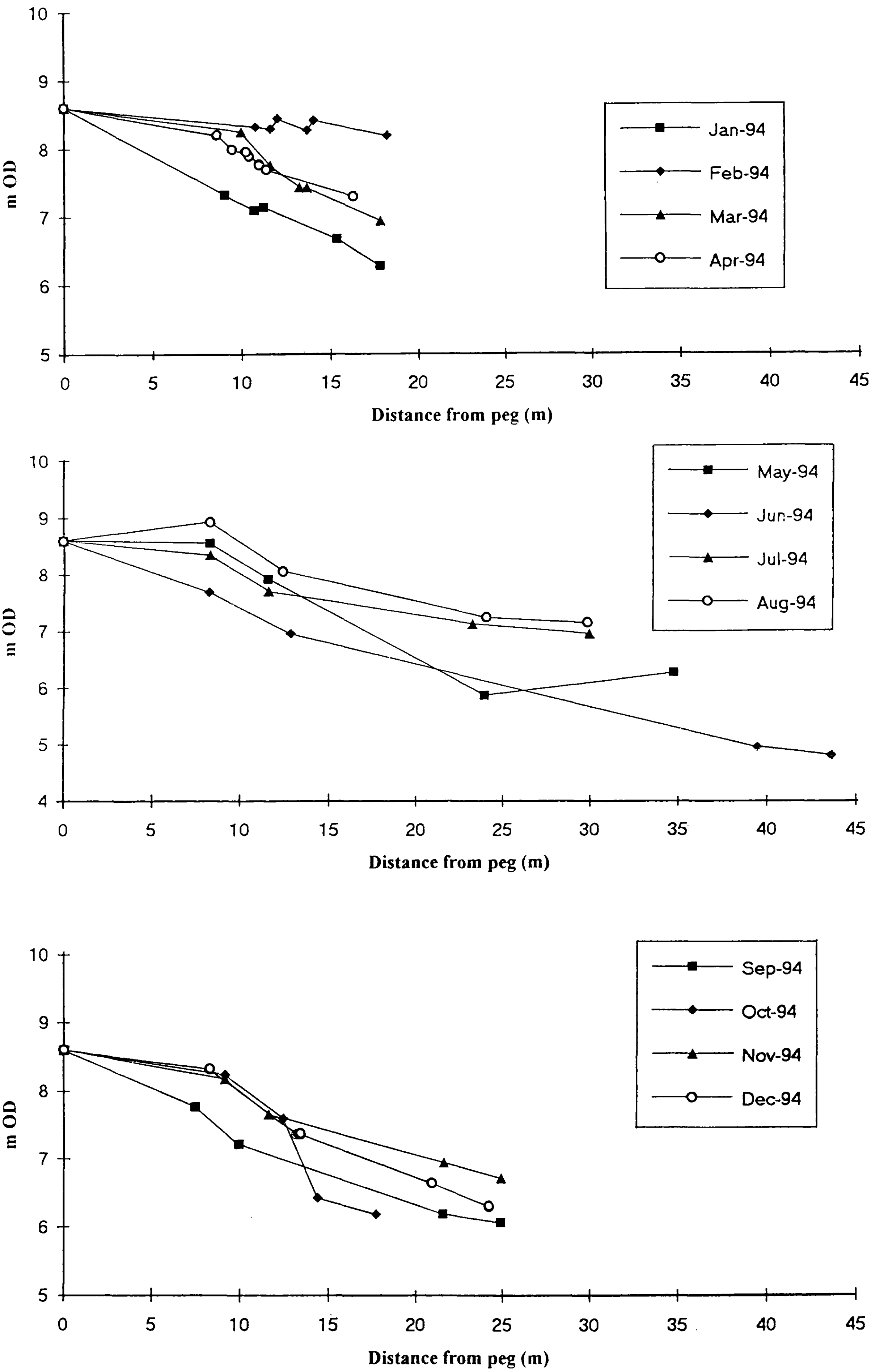


Fig. 5.7 Beach profile variability at Profile E, Cashel.
Surveyed lengths of profile are shown. Profile length was dictated by water levels.

absence of the berm is related to sediment redistribution up and down profile. A back berm developed between the April and May surveys, remained during the summer months (May to August) and was removed by the September profile. Profile F, which is constrained by a cliff and shore platform, shows a similarity in classification type from January to April. Examination of profile data shows that whilst the basic form remains, sediment undergoes redistribution (Table 5.1). In May, there is a transition in type, from straight to convex (a2-c2) as sediment is moved up-profile. By the July survey sediment has been removed and the resulting convex (b2) type remained until September from when the flat profile type (f2) prevails. As at Profile E, the last four months show a greater stability in type, and April-May, and August-September seem to be transitory periods in beach type. Profile G is similarly exposed, but has the proximal fluvial sediment supply. Here there is a much greater degree of variability (Fig. 5.8), most probably attributable to sediment supply.

On the whole, the southern section of Cashel beach (profiles E1-A) is relatively stable with little variation in profile form. Profile B shows this in more detail (Fig. 5.9). The beach is steep with a large and stable back berm. From January to March, type a1 occurs. In April there is a transition to type c1 as more sediment is deposited on the upper and middle beach. May and June show type a1 again and July shows the concave-convex form (h1) where sediment is redistributed up and down the profile. The transition occurs once more between August and September, but the October to December profile type is a1, showing this pattern of dominant profile form (also found at profiles A, C and E1).

Profile A illustrates the most stable profile form with the types a1 and h1 occurring (Table 5.1) This profile is protected from most wave activity by the headland.

Examples of profile variation: Milarrochy

Overall, there is slightly less variability in profile form at Milarrochy than at Cashel. Profiles 1 and 6 (Figs. 5.10 and 5.11), at either end of the bay, show the least variation in type. Profile 1 remains type a throughout the year, with a straight profile for the upper and mid beach. Variation is in the presence or absence of a berm, and the development of gravel steps (related to sediment availability and steep breaking waves). At the southerly end of the beach, Profile 6 shows more variability in macro-form. Here, the profile is type a2 in January, March and April, but in February sediment moves on-shore giving the convex sediment-rich profile (c2). From May to November, the concave sediment-poor profile (b2) occurs and December shows a return to type c2.

	Months											
Profiles	J	F	M	A	M	J	J	A	S	O	N	D
I	a4	a4	h1	h1	h1	h1	h1	c1	c1	c1	c1	e3
H	b2	b2	b2	b2	b2	b2	b2	b2	b2	b2	b2	b2
G	b1	e1	a3	d1	a1	h1	h1	h1	b2	h2	b2	e3
F	a2	a2	a2	a2	c2	b2	b2	b2	f2	f2	f2	f2
E	a2	f2	b2	b2	b1	b1	b1	b1	b2	a5	b2	b2
E1	No data			a1	a1	a1	c2	a1	a1	a1	h1	a1
D	h1	h1	e1	e1	a1	b1	a1	a1	a1	c1	c1	h1
C	b1	b1	a1	a1	a1	a1	a1	h1	h1	a1	h1	a1
B	a1	a1	a1	c1	a1	a1	h1	a1	h1	a1	a1	a1
A	h1	h1	a1	h1	a1	a1	a1	a1	a1	a1	a1	a1

Table 5.1 Cashel profile types 1994.
Refer to text for details of classification.

	Months											
Profiles	J	F	M	A	M	J	J	A	S	O	N	D
1	a3	a1	a1	a1	a4	a4	a1	a4	a4	a4	a4	a1
2	f1	c1	a1	h1	e1	a1	e1	h1	c1	e3	h1	e3
3	h2	h2	h2	a4	a1	b1	a1	a1	a1	a1	a1	a1
4	e3	a1	h2	b1	h1	h1	a1	b1	a1	c1	c1	a1
5	h2	h2	h2	a1	e3	a1	c1	c1	h1	c1	c1	c1
6	a2	c2	a2	a2	b2	b2	b2	b2	b2	b2	b2	c2

Table 5.2 Milarrochy profile types.
Refer to text for details of classifcation.

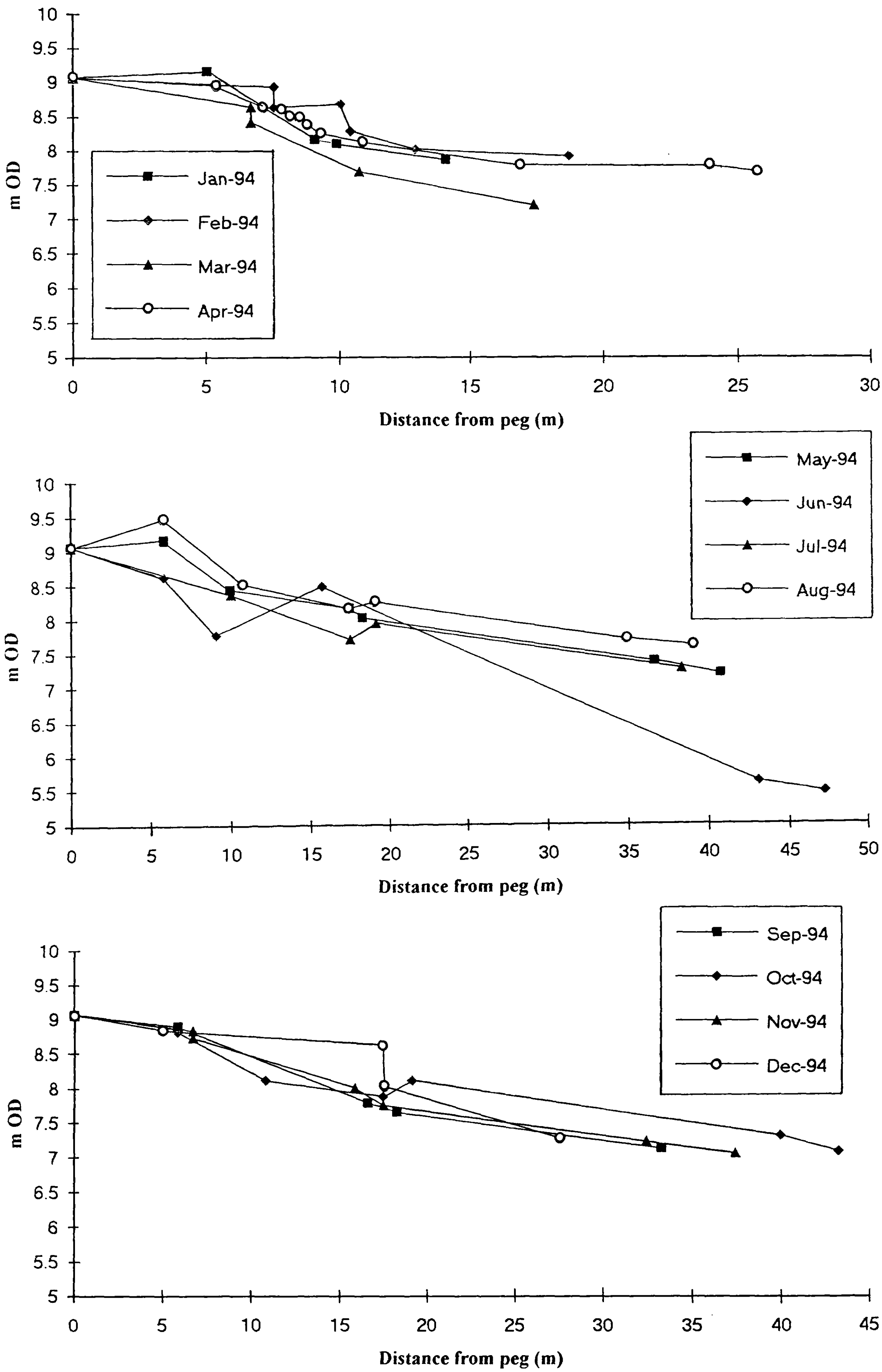


Fig. 5.8 Beach profile variability at Profile G, Cashel.
Surveyed lengths of profile are shown. Profile length was dictated by water levels.

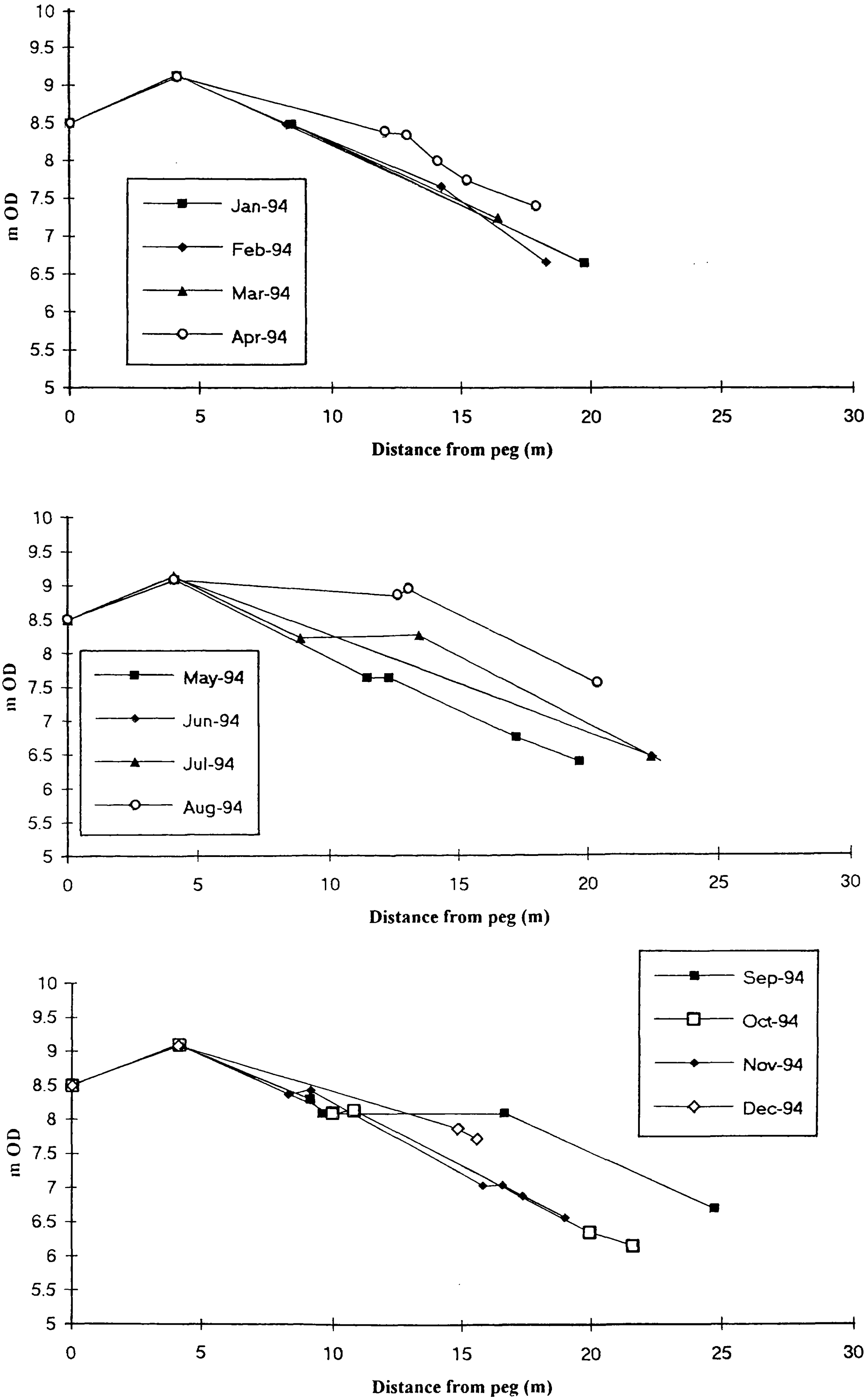


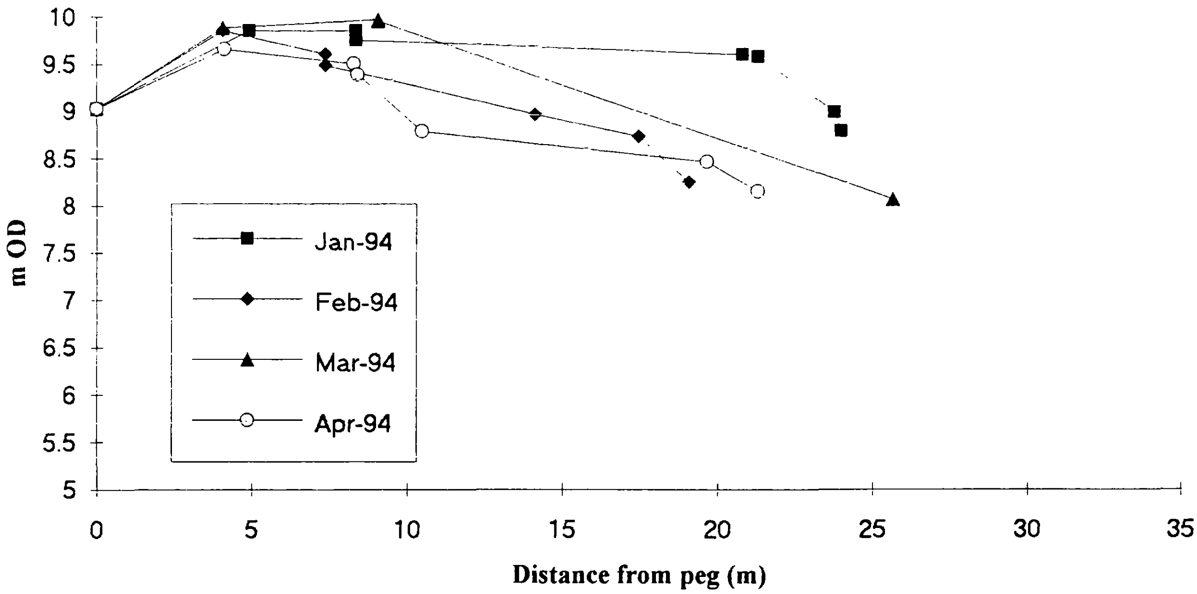
Fig. 5.9 Beach profile variability at Profile B, Cashel.
Surveyed lengths of profile are shown. Profile length was dictated by water levels.

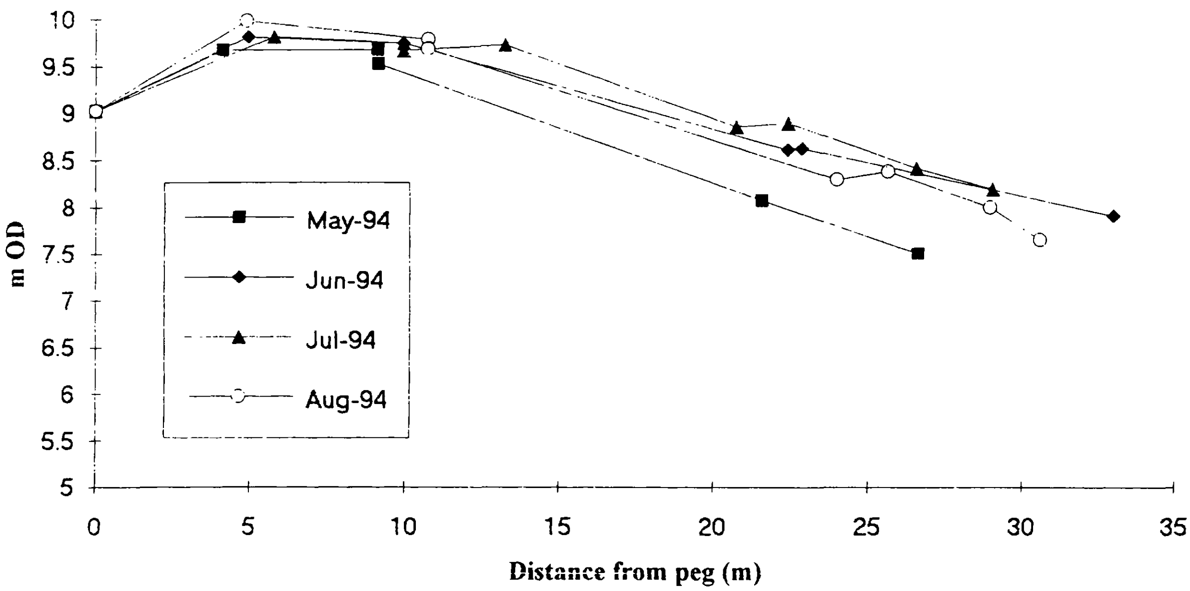
Profile 2 (Fig. 5.10) shows high variability. The flat January profile (f1) is followed by the convex form (c1) in February, where sediment is redistributed and has moved onshore. By March the profile is straighter (a1), and the concave-convex form in April (h1) shows a redistribution of sediment up and down the profile. May and June show a multi-ridged beach (e1) and then a combing down to the straight flat profile (a1). In July the multi-ridge form (e1) recurs. August shows the concave-convex (h1) sediment re-distribution followed by the convex profile in September. October shows a flatter profile with a gravel step (e3). November shows type h1, concave-convex. December shows the flatter straight and stepped profile (e3). As the profile is adjacent to a fluvial sediment supply the variability may be related to sediment availability for reworking by waves.

Although having a similar exposure to profile 2, the mid-beach profile 3 shows less variation remaining type a1 from July to December. From January to March it was type h2, the concave-convex form. April (a4) shows the development of a berm and gravel step. By May sediment had been redistributed up and down profile to produce the straight type a1. June shows the concave form (b1) which may be related to sediment availability.

Linkages between the profile forms can be established by considering the sediment re-distribution implied by profile changes. Examination of any of the profile figures shows profile evolution, and generally a tendency for a preferred profile form. The main trend in individual profile form changes appear to be for sediment to be redistributed up and down the profile, and this is supported by the on-offshore process trends identified in chapter 4.

The profile results emphasise the spatial variation in beach macro-form within a relatively small spatial area. Type a1 was the most frequently occurring type at Cashel (33 times) and Type h1 (16 times) the second most frequent type. At Milarrochy, Type a1 (19 times) and a4 (8 times) were the most frequent. Types h1 and h2 occurred 8 times each (Tables 5.1 and 5.2). The most frequently occurring forms are either straight with a berm (a1) or concave-convex with a berm (h1). Neither profile type is especially sediment rich (as with a convex form). From the results, Type h1 can often be seen to follow Type a1, as sediment is re-distributed further down the profile. Whilst the profile form at any point on the beach may show a persistent dominant type in form, this may hide volumetric variation which is presented in the following section.





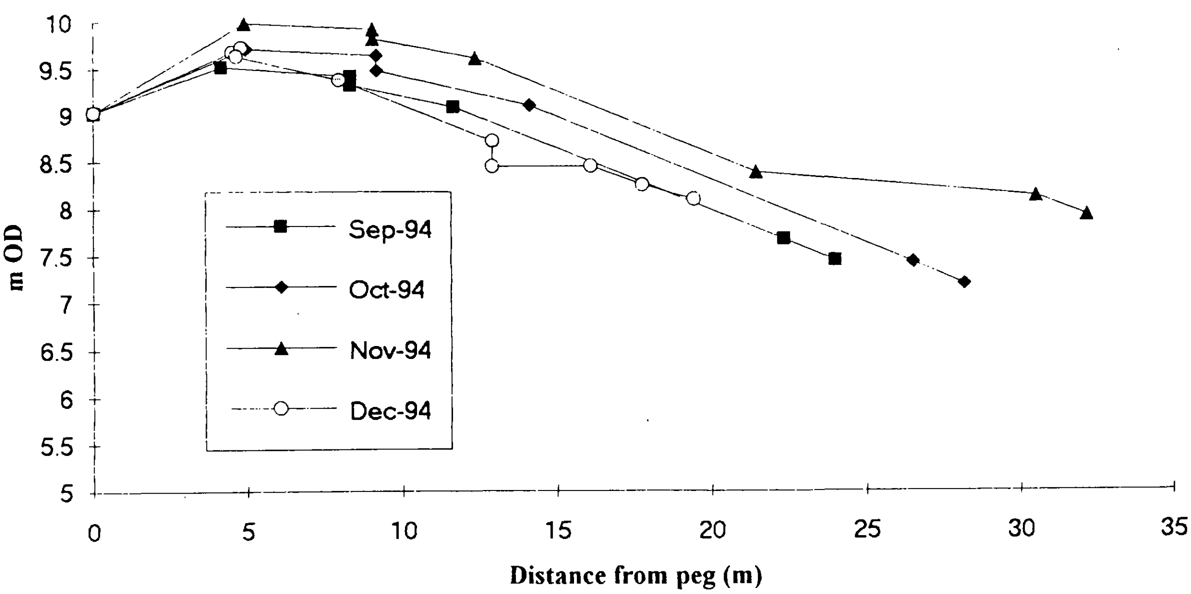
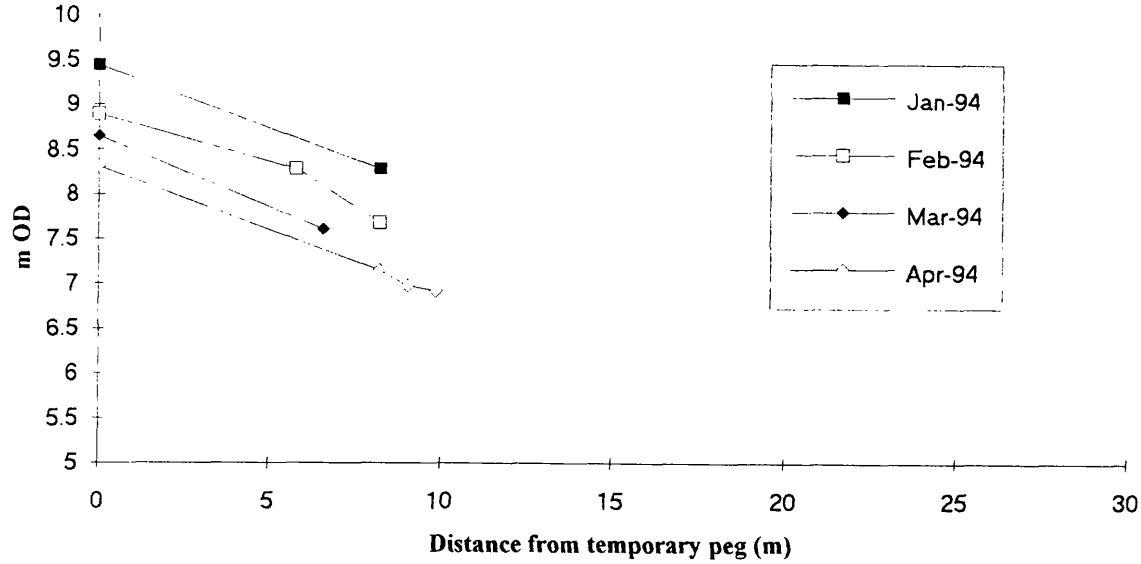
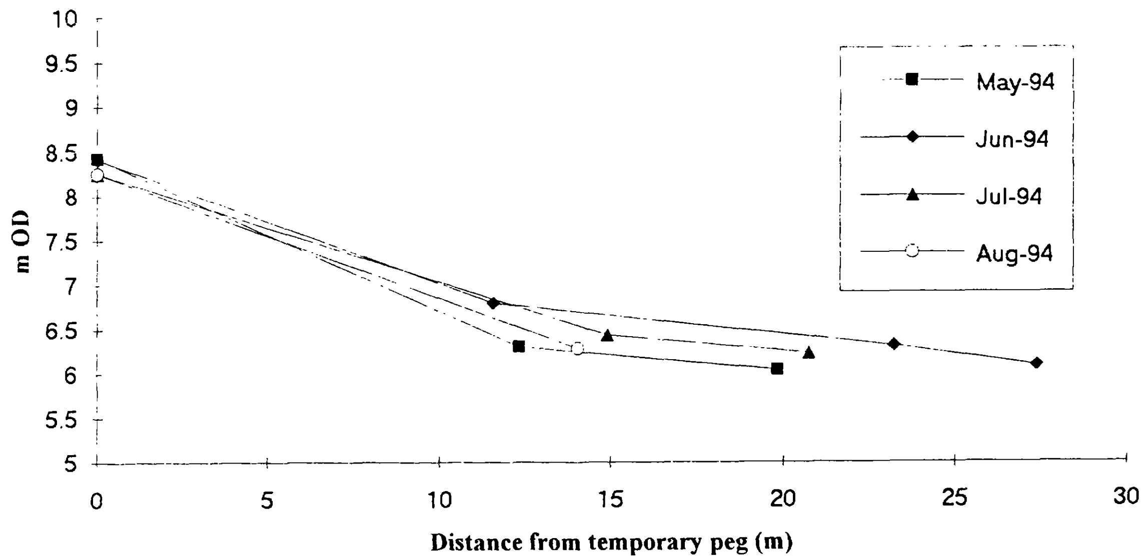


Fig. 5.10 Beach profile variability at Profile 2, Milarrochy.
Surveyed lengths of profile are shown. Profile length was dictated by water levels.





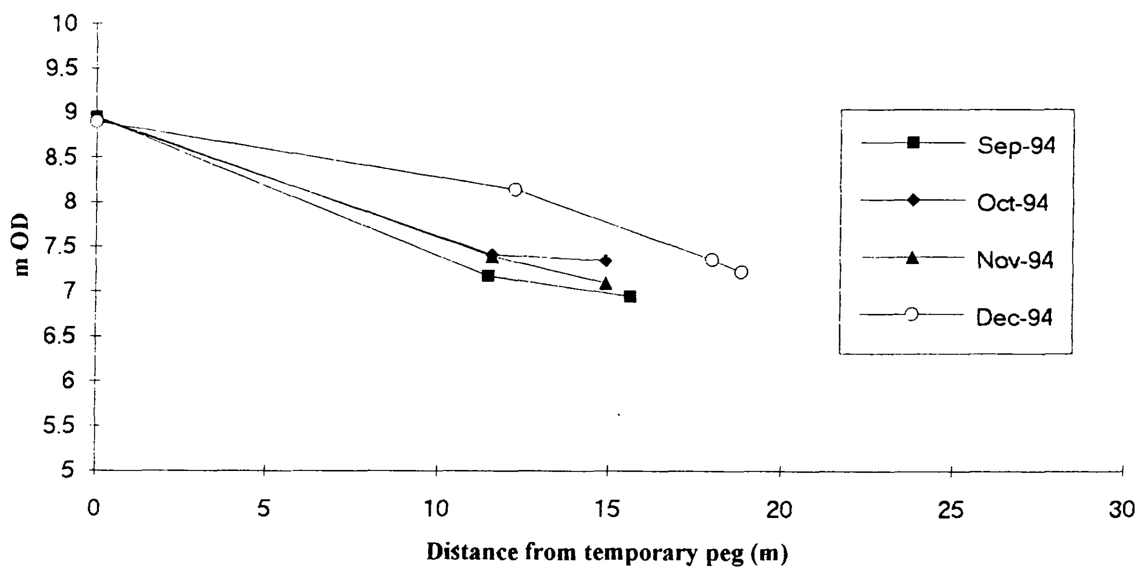


Fig. 5.11 Beach profile variability at Profile 6, Milarrochy.
Surveyed lengths of profile are shown. Profile lengths are dictated by water levels.
Varying peg altitude reflects cliff falls and sediment removal by waves.

5.3.1.2 *Beach volumetric change*

Monthly variation in beach volume is presented in this section (Figs.5.12a-1, 5.13a-f). The volumetric change between surveys (section 3.3.3.2) calculated from the profile results summarises net sediment flux at each profile. The calculation methods are described in section 3.3.3.2. and represent beach volume at the profile line.

The *Cashel* results at profile A, B and C are characterised by small largely alternate net changes in sediment volume from month to month: net gains followed by net losses of relatively small volumes (Figs. 5.12a-c). Adjacent profiles show gains and losses which may reflect longshore as well as cross-beach sediment transport. Profiles D to I (Figs. 5.12d-i) show much greater variability with larger volumes of sediment being moved, especially profiles E1-I which are in the more exposed sections of beach. Profile E shows the greatest annual change for 1994 with a gain of 31.5 m^3. Profile D shows the greatest loss of 16.8 m^3 (Fig. 5.12d). Profile A shows relatively small volumetric change over the year, being in a more sheltered position close to the headlands.

At *Milarrochy*, there is a general trend of negative sediment change from north to south (Figs. 5.13a-f). Profiles 1 and 6 (Figs. 5.13a and f) show relatively little variation over 1994 being in the less exposed areas of beach and partly sheltered by headland. Profile 5 (Fig.5.13e) has the highest net volumetric change, with a loss of 50.4m^3. This is most probably attributable to the nearby stream exit which transports sediment offshore to the delta. Profiles 3 and 4 (Figs. 5.13c and d) show months of sediment gain followed by periods of loss throughout the year, the changes at profile 4 being especially low between May to September.

The volumetric beach change findings are important because they highlight the magnitude of beach variability during 1994. Overall volumetric change alongshore is shown in Figs. 5.14 and 5.15. There is greater volumetric variation in the more exposed sections of beach and those close to the stream exits, revealing clearer trends than the measurements of profile form. These figures are based on the strips of beach at each profile and are indicative of alongshore pattern of change rather than absolute volumes. Absolute rates are used later in the sediment budget calculations.

For both beaches net annual changes in sediment volume for each profile are relatively small, although the monthly variation is greater. Over 1994 from the profile surveys alone Cashel shows an annual gain of 27.6 m^3 and Milarrochy a loss of 123 m^3. These figures are subject to possible surveying errors and the use of closure depths means that extrapolation of data were used, which can also incorporate error into the calculations (section 6.2.1). Sections 4.5 and 4.6 however have highlighted the nearshore and alongshore limits to coarse sediment transport,

Fig. 5.12a

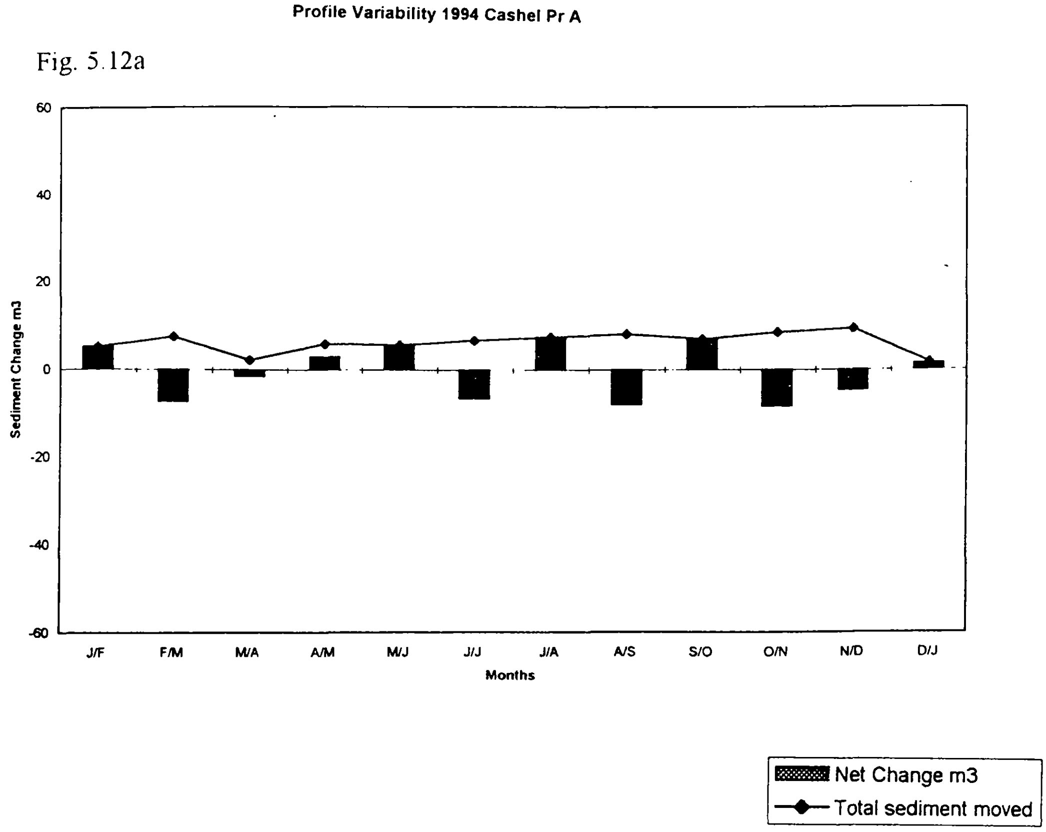
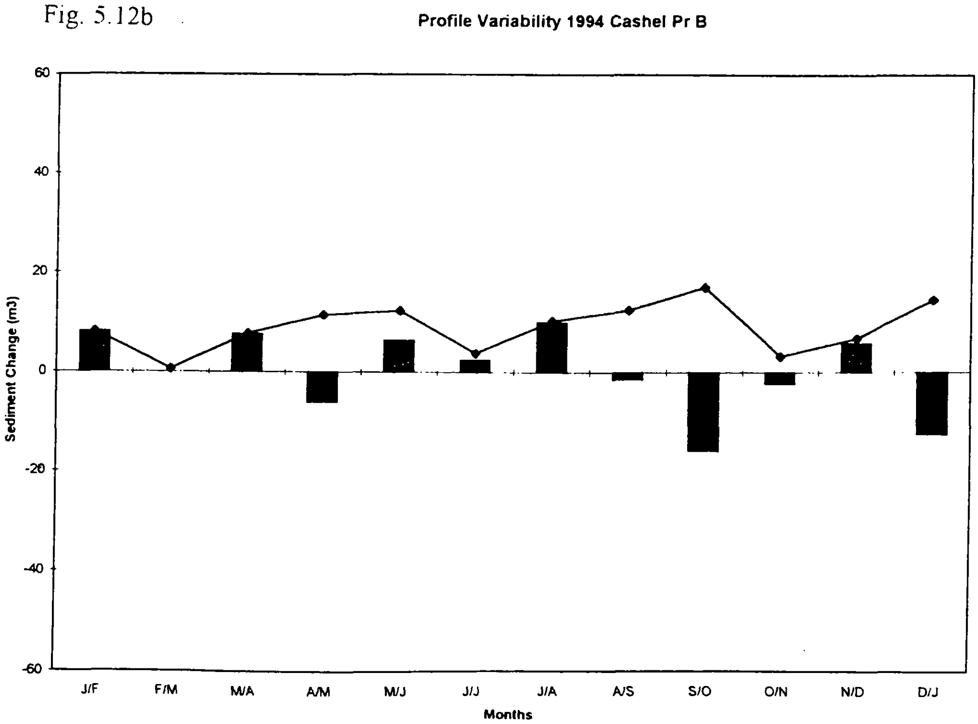


Fig. 5.12b



Figs. 5.12a-i Beach volumetric change at Cashel profiles:
Net change (m^3) is net gain or loss of sediment at each profile (i.e. ε erosion + ε deposition); Total sediment moved (m^3) is the sum of volumes of sediment moved whether lost or gained.

Fig. 5.12c

Profile Variability 1994 Cashel Pr C

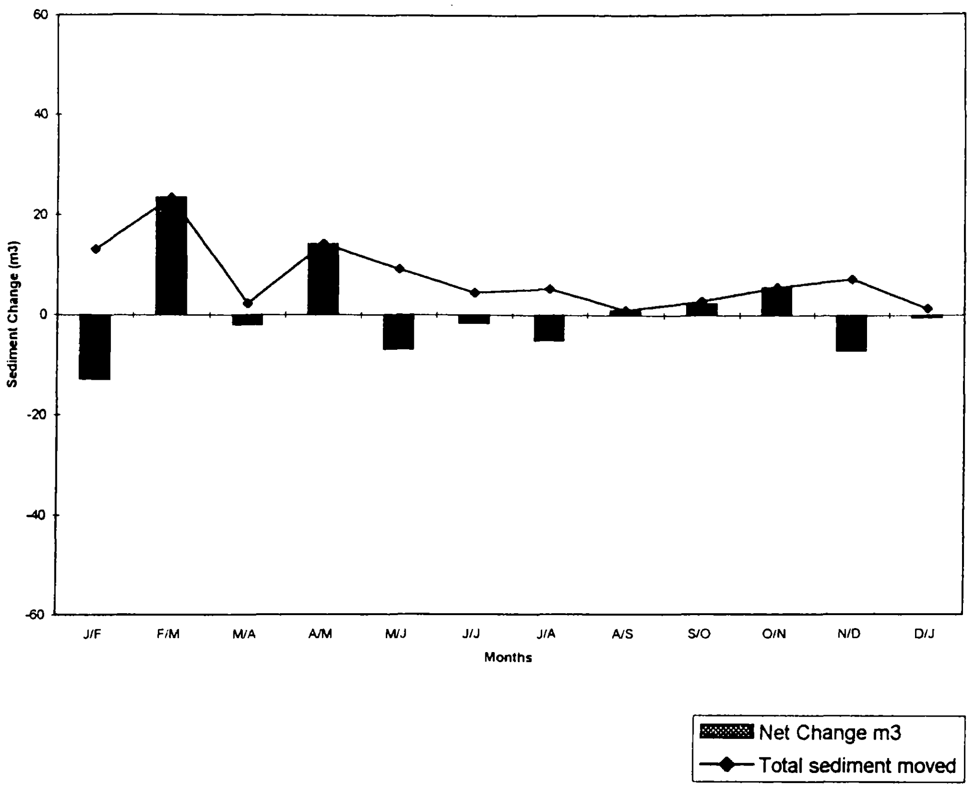


Fig. 5.12 d

Profile Variability 1994 Cashel Pr D

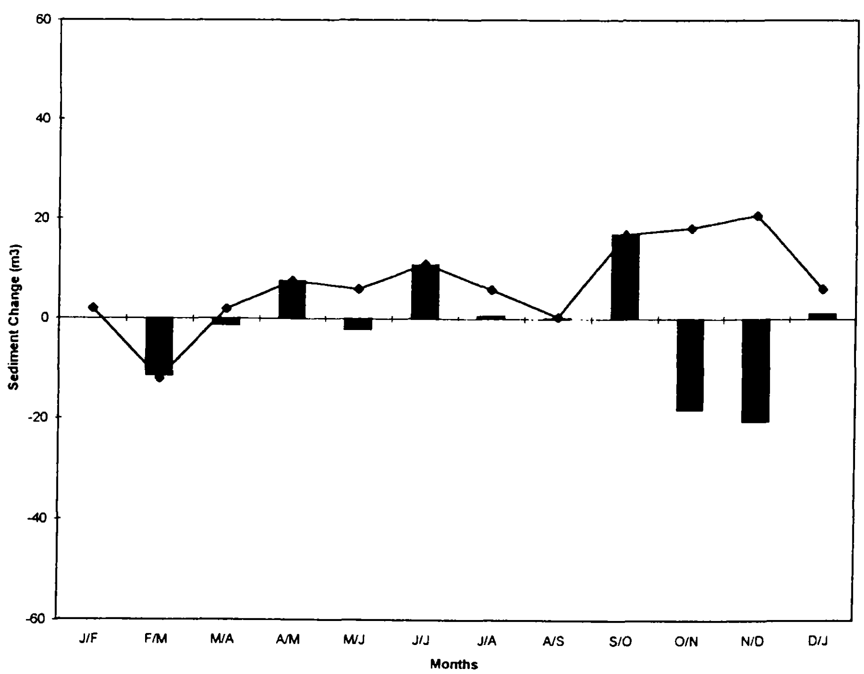


Fig. 5.12e

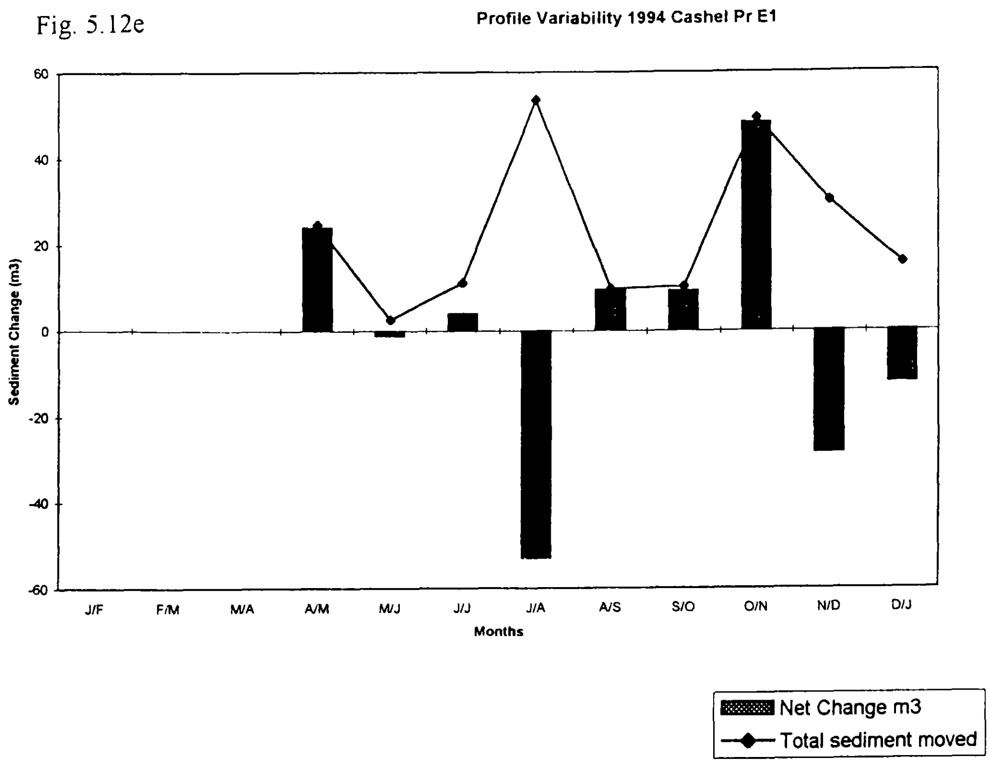


Fig. 5.12f

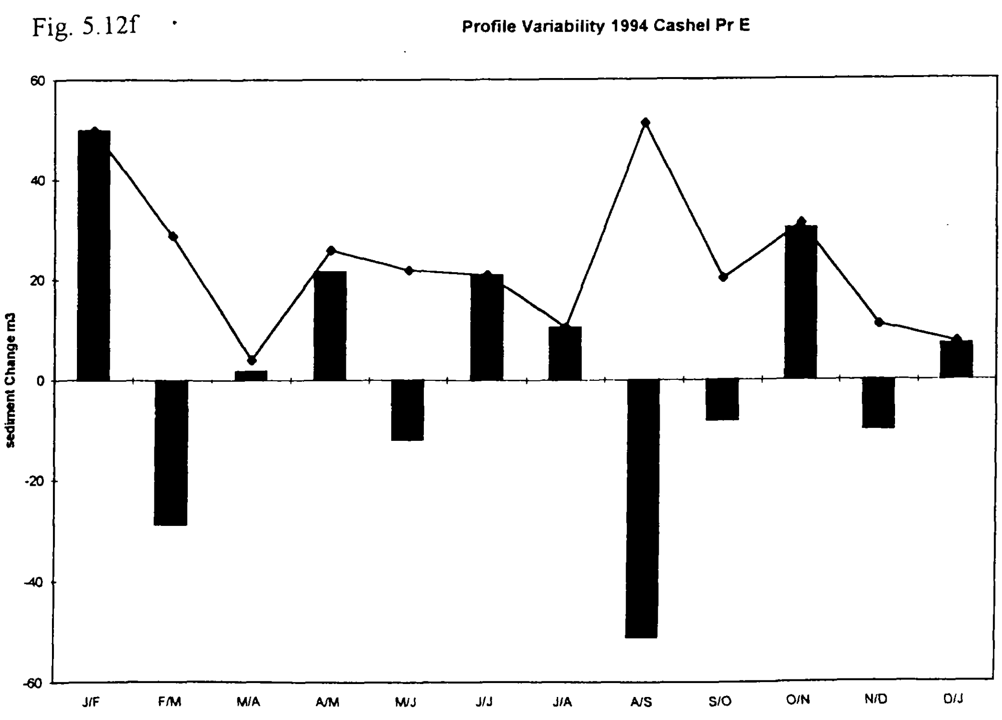


Fig. 5.12g

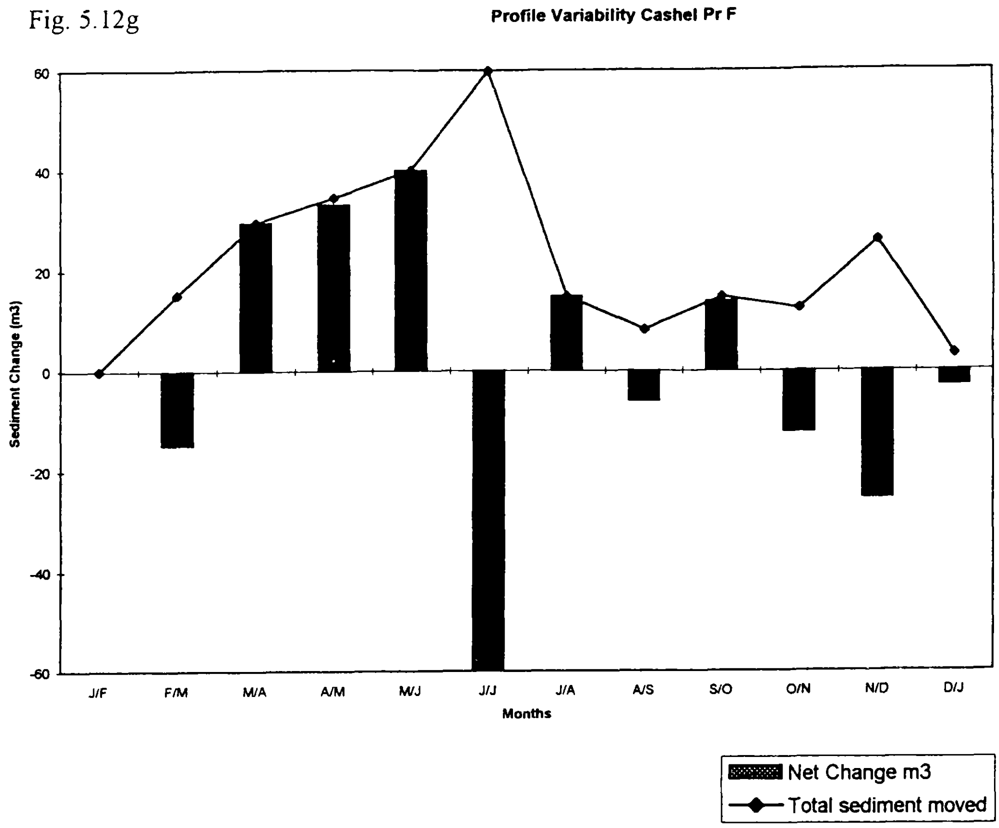


Fig. 5.12h

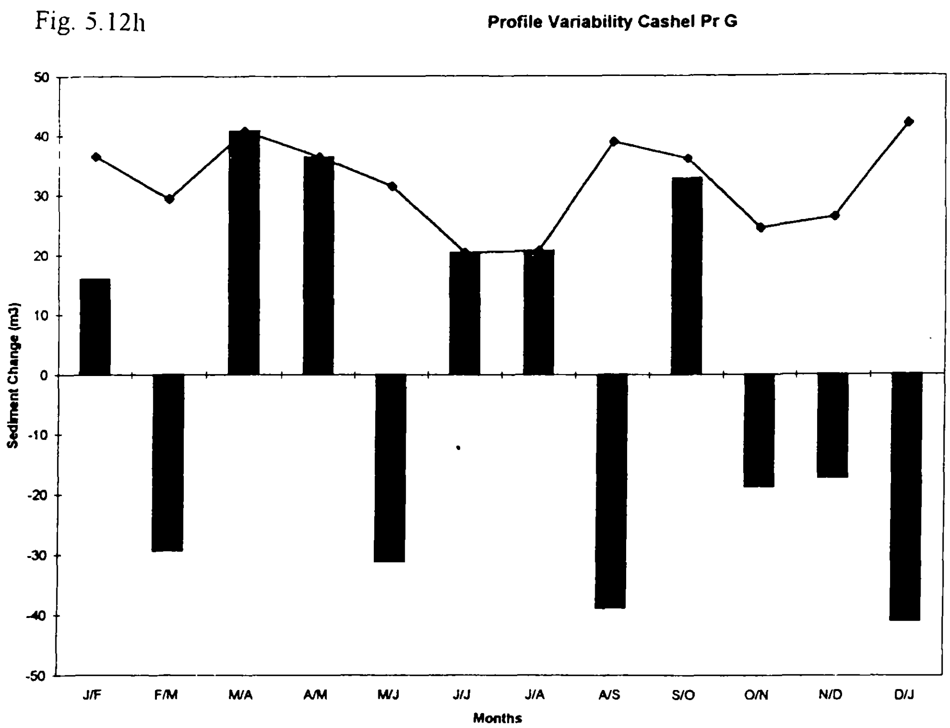


Fig. 5.12i

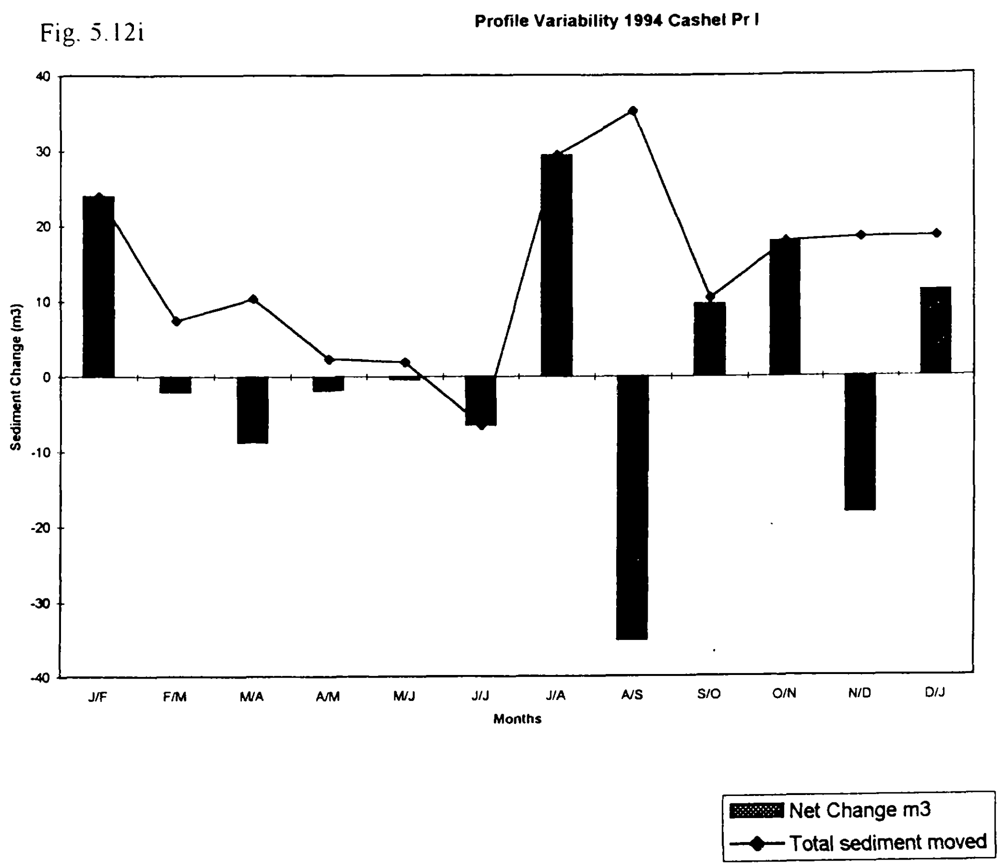

Profile Variability 1994 Cashel Pr I
Sediment Change (m3)
40
30
20
10
0
-10
-20
-30
-40
J/F
F/M
M/A
A/M
M/J
J/J
J/A
A/S
S/O
O/N
N/D
D/J
Months
Net Change m3
Total sediment moved

Fig. 5.13a

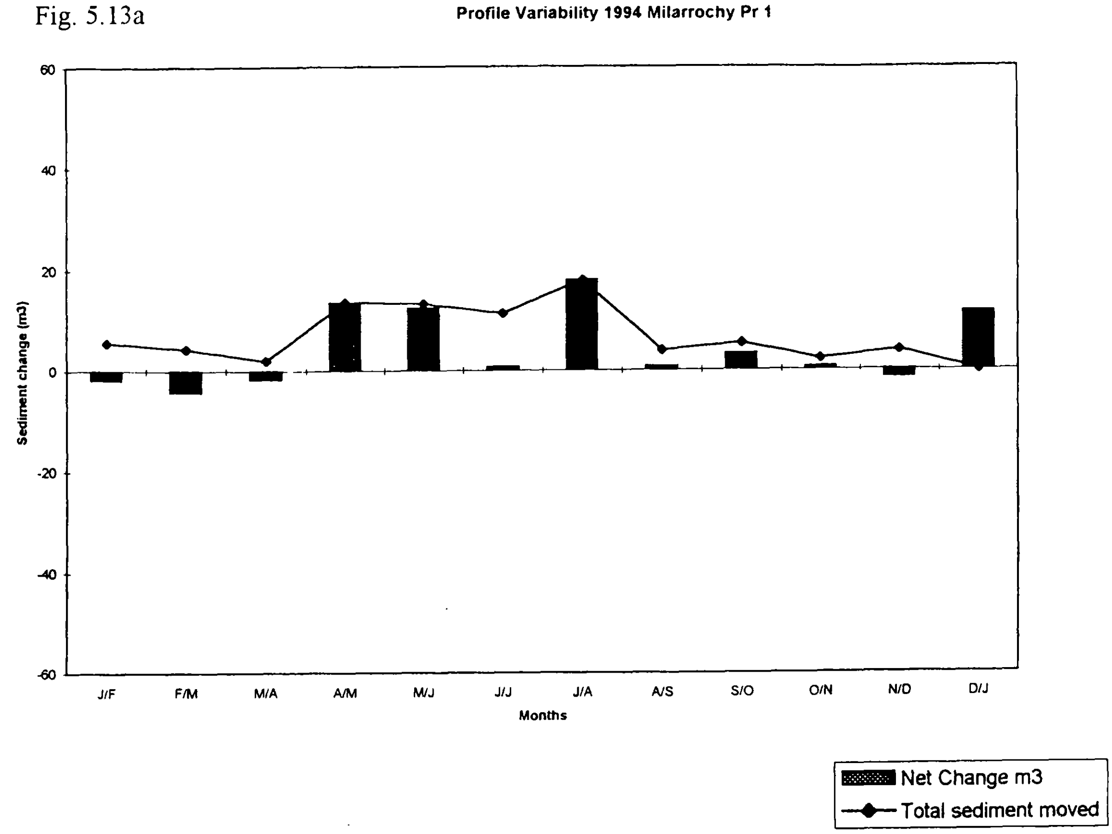
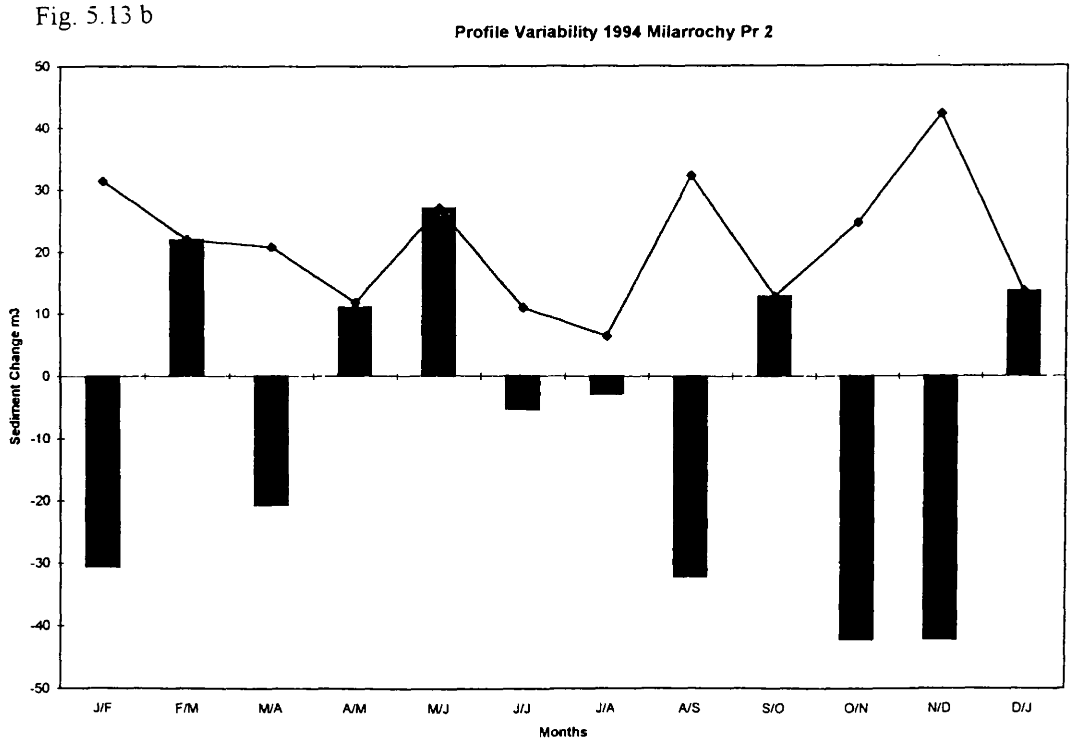


Fig. 5.13 b



Figs. 5.13a-f Beach volumetric change at Milarrochy profiles
Net change (m^3) is net gain or loss of sediment at each profile (i.e. ε erosion + ε deposition); Total sediment moved (m^3) is the sum of volumes of sediment moved whether lost or gained.

Fig. 5.13c

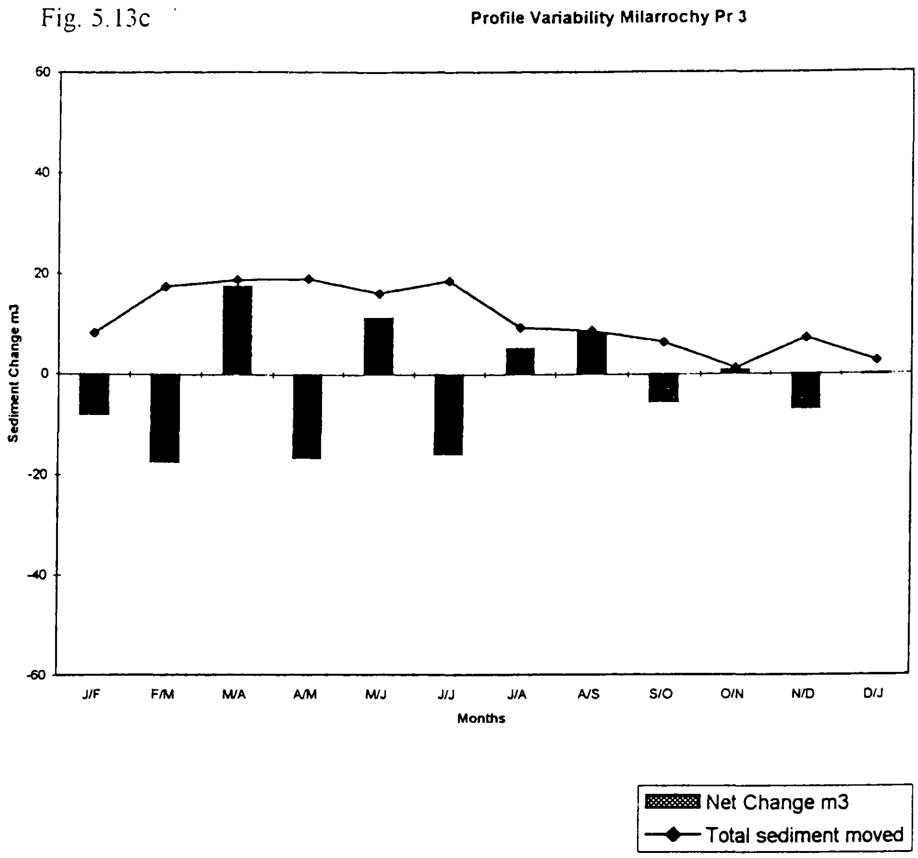


Fig. 5.13d

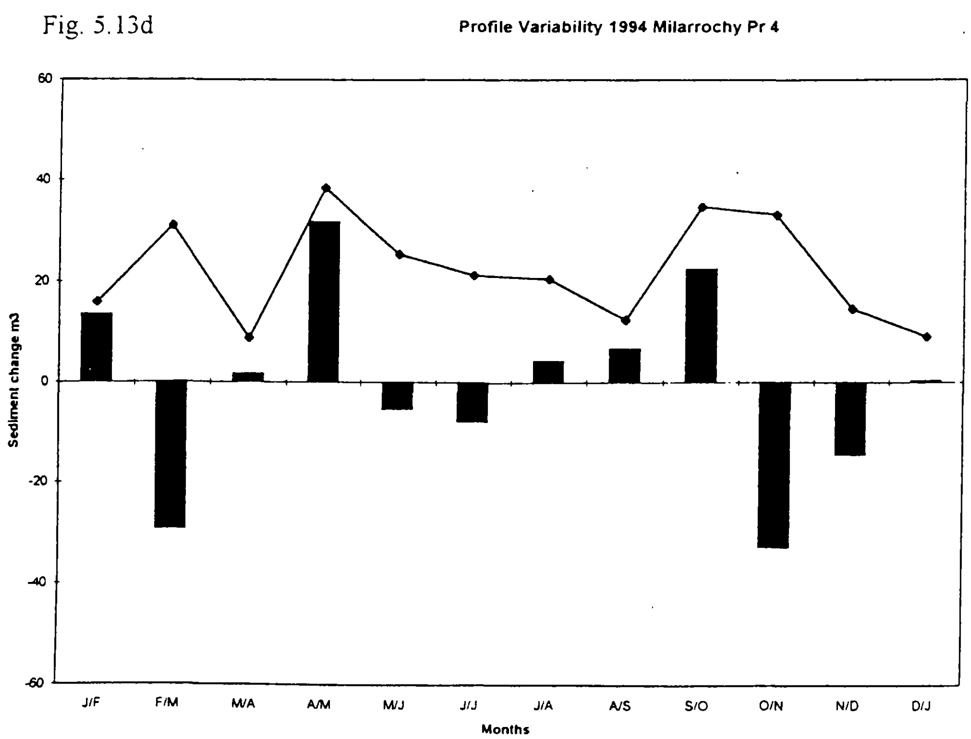


Fig. 5.13e

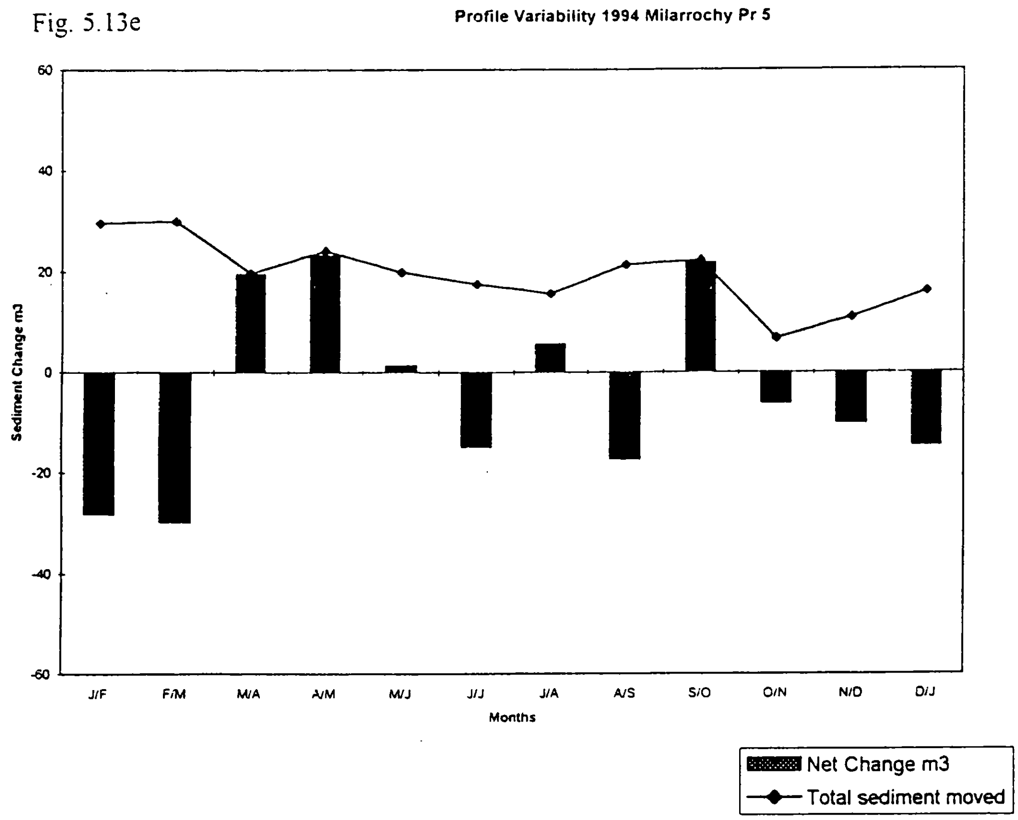
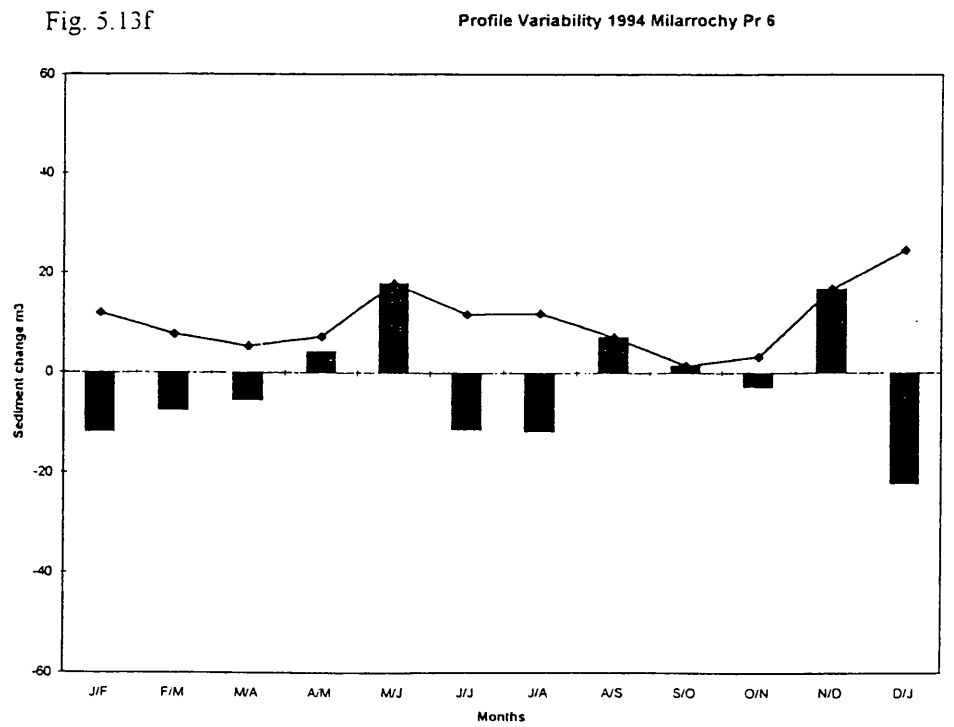


Fig. 5.13f



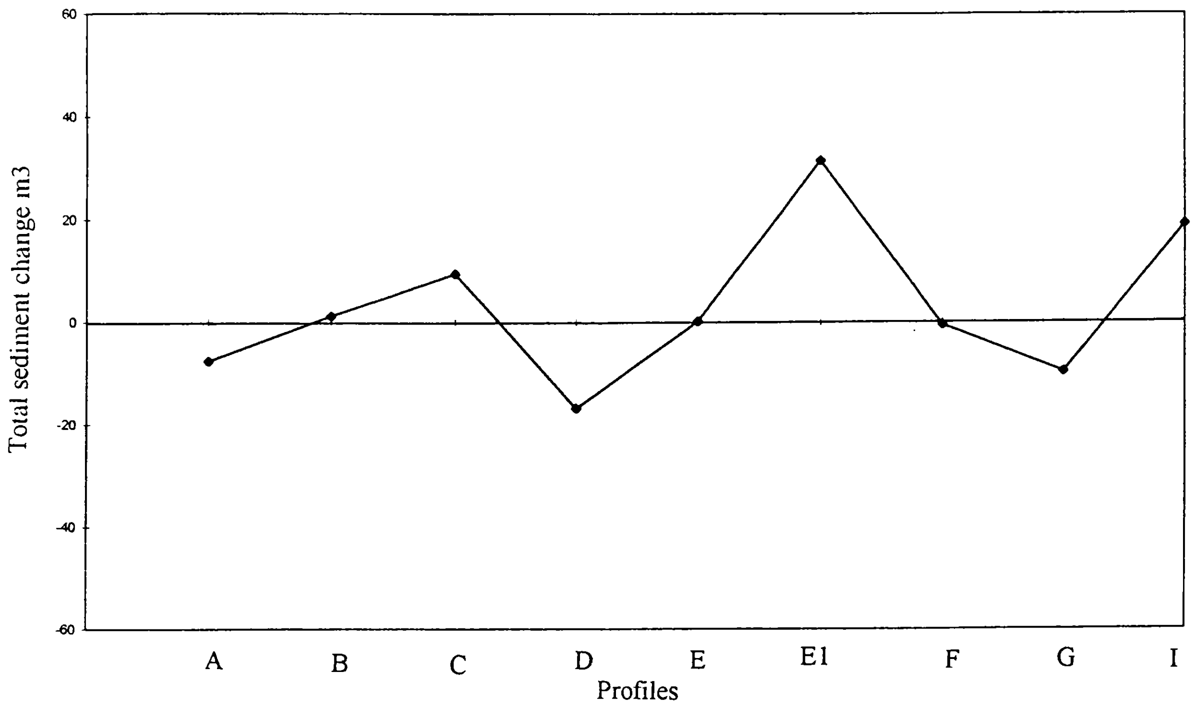


Fig. 5.14 Alongshore beach volumetric change at Cashel in 1994

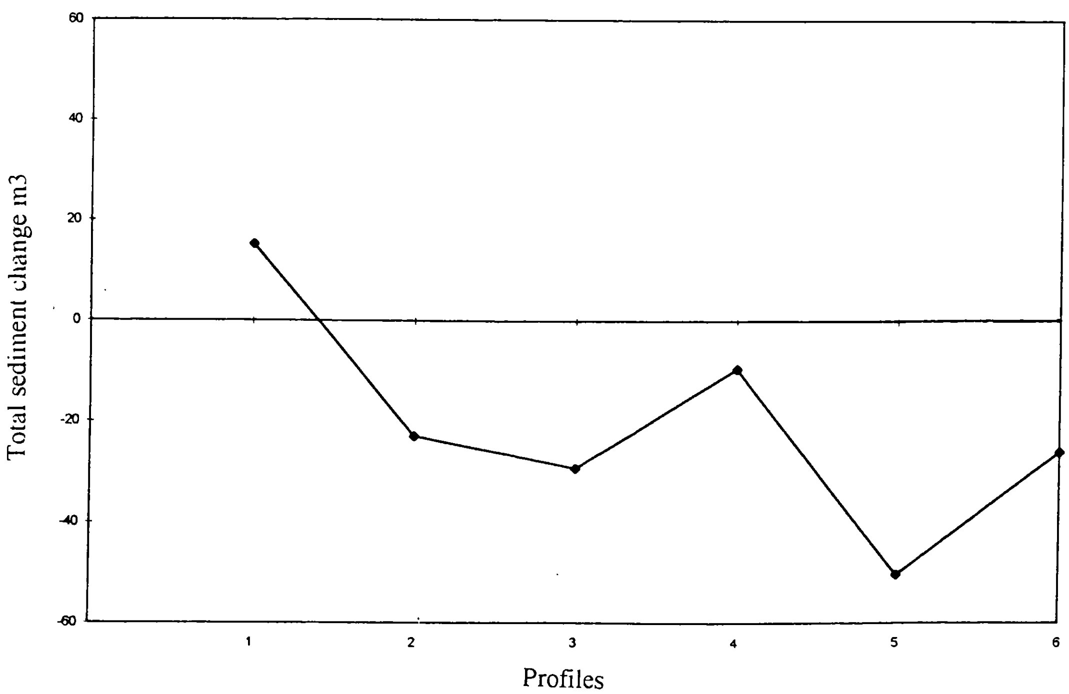


Fig. 5.15 Alongshore beach volumetric change at Milarrochy in 1994

showing that sediment remains within the cells defined by the bay headlands. Thus sediment losses (at Milarrochy) cannot be attributed to offshore or alongshore transport. The Milarrochy beach is affected by compaction especially at profiles 4 and 5 where vehicles are allowed on the beach. This could account for some of the apparent sediment losses (by volume). Further sediment storage is accounted for in the deltas and small scale forms such as ridges, bars and spits. If these fall outwith the beach profile sampling frame, their storage role may be missed (sections 5.3.2 and 5.3.3). Further quantification of the sediment budget is given later in this chapter. Overall, annual volumetric change is relatively small at both beaches, but month-month change is much more marked.

5.3.1.3 Controls over beach morphological changes

Beach morphological changes are particularly significant in helping to identify the various controls that may influence beach profile changes. Variables in the Loch Lomond coastal system have been measured at scales defined in sections 2.3 and 3.1.1 and the interrelationships of these variables with respect to beach morphological change are identified here.

There are many reasons why profiles show different forms. These include variation in beach orientation and exposure to waves, water levels, sediment supply, and different sedimentology. To try to determine links with generating processes, variables were compared at the monthly scale (meso-scale) used for profile measurements. Any such comparison presents difficulties within the coastal system because of the interaction of several variables, and the temporal and spatial scales of sensitivity and change are variable.

Tables of beach change variables were constructed. Examples of these for Cashel, profiles D, E and G and Milarrochy, profiles 2 and 4 are shown in Tables 5.3 -5.7. Each of the profile types was compared to waves (modal and maximum significant wave heights), number of storms, mean water levels, fluvial sediment delivery (section 5.4) and sedimentology of surface sediments (section 5.4) at the meso- (monthly) scale of the morphological change measurements. The net monthly sediment change at each profile and the volume of sediment moved between surveys were also plotted.

Examination of Tables 5.3-5.8 shows complex relationships between profile form and processes. Few clear relationships are immediately apparent at the monthly scale. Some links between sediment delivery and volumetric change and beach variability can be identified at the adjacent profiles but there are no strong correlations. When the profile results are viewed spatially on a bay scale, the presence of streams contributes to the complexity of results in terms of profile form. The headlands also exert a control in that they shelter some sections of beach from wave activity. The areas where the beach shows more change are those which are more exposed (section 4.1).

Section 5.3.1.1 identified two main periods of profile type change, in May and September. This follows the pattern of Loch levels which are significantly lower in the Summer months. A rapidly increasing or rapidly decreasing water level and therefore a moving wave and swash base may cause greater instability leading to changes in profile form. This is shown in both the sedimentological and morphological transitions in April/May and September/October and suggests that seasonal water level changes exert a significant control on beach form.

Volumetric changes show that exposed sections of beach (such as profile E at Cashel and profile 2 at Milarrochy) have greater net sediment flux than more sheltered sections of beach (such as profiles 1 and 6 at Milarrochy and profile A at Cashel). This suggests that macro-scale morphology, and thus exposure (section 4.1.1), exert a strong control on potential volumetric change. Whilst there is considerable variation on a monthly basis, annual volumetric change is relatively small.

When comparing and identifying links between variables, micro-scale links (e.g. daily sediment transport) can be relatively straightforward to interpret as the causal relationship is clear. At the meso-scale (monthly) process response links are more complex, although some trends can be observed at this scale. At the macro-scale (years) other trends may be much more apparent. These ideas are discussed further in Chapter 6.

In summary, the changes in beach morphology suggest that:

1. longshore beach morphological variability is relatively high, but is related to beach exposure as profiles close to headlands show less variability than those which are more exposed. This suggests that macro-scale morphological influences are significant;

2. adjacent profiles, with similar exposure do not necessarily exhibit similar profile types or transitions. Under similar conditions, different profiles may show different responses. This is often related to supplies of sediment (e.g. from streams);

3. individual profiles may exhibit a range of types although one type tends to be dominant. The presence of a cliff seems to restrict profile development. The most frequently occurring profile type at both Cashel and Milarrochy is a straight form (type a1);

Beach Behaviour vs Variables												
Pr D												
	J	F	M	A	M	J	J	A	S	O	N	D
Profile type	h1	h1	e1	e1	a1	b1	a1	a1	a1	c1	a1	h1
Sediment classification (lower)	Y		W	W	W	W	W	W	W	W	W	W
Sediment classification (mid)	Y		W	W	W	X	X	W	X	W	W	X
Net sediment change m3	0.04	-11.53	-1.45	7.45	-2.28	10.76	0.59	0.2	16.94	-18.16	-20.49	1.07
Volume sediment moved m3	2	12.03	1.87	7.58	5.88	10.96	5.85	0.38	16.94	18.16	20.75	5.95
Mean water level m OD	8.41	8.34	8.68	8.46	7.79	7.64	7.81	7.87	7.88	7.87	8.27	8.68
Vol. of sediment delivered (at E1)m3/m	No data				4.28	0	0	0	1.43	8.24	308.16	374.4
Maximum significant wave height (m)	0.1	0.4	0.25	0.25	0.6	0.5	0.45	0.65	0.45	0.35	0.45	0.35
Modal significant wave height (m)	0.05	0.05	calm	0.05	calm	0.2	0.05	0.05	0	0.05	0.05	calm
No. of storms >10m/s (6 hr sample)	5	1	9	1	no data	3	no data	1	2	0	2	3
No. of storms >10m/s (1 hr sample)	79	7	113	14	no data	3	no data	3	14	0	18	29

Table 5.3 Cashel beach behaviour variables. Profile D.

Beach Behaviour vs Variables												
Cashel Pr E												
	J	F	M	A	M	J	J	A	S	O	N	D
Profile type	a2	f2	b2	b2	b1	b1	b1	b1	b1	a5	b2	b2
Sediment classification (lower)	Z		Z	Z	Z	Z	Z	ZY	Z	ZU	ZU	ZU
Sediment classification (mid)	W	W	Z	Z	ZU	ZY	Z	ZY	Z	Z	Z	Z
Net sediment change m3	49.79	-28.8	1.8	21.63	-12.05	20.94	10.4	-51.22	-8.26	30.2	-9.99	7.09
Volume sediment moved m3	49.79	28.8	3.96	25.97	21.89	20.94	10.4	51.22	20.28	31.2	10.89	7.51
Mean water level m OD	8.41	8.34	8.68	8.46	7.79	7.64	7.81	7.87	7.88	7.87	8.27	8.68
Vol. of sediment delivered (at E1)m3/m	No data				4.28	0	0	0	1.43	8.24	308.16	374.4
Maximum significant wave height (m)	0.1	0.4	0.25	0.25	0.6	0.5	0.45	0.65	0.45	0.35	0.45	0.35
Modal significant wave height (m)	0.05	0.05	calm	0.05	calm	0.2	0.05	0.05	0	0.05	0.05	calm
No. of storms >10m/s (6 hr sample)	5	1	9	1	no data	3	no data	1	2	0	2	3
No. of storms >10m/s (1 hr sample)	79	7	113	14	no data	3	no data	3	14	0	18	29

Table 5.4 Cashel beach behaviour variables. Profile E.

Beach Behaviour vs Variables												
Cashel Pr G												
	J	F	M	A	M	J	J	A	S	O	N	D
Profile type	b1	e1	a3	d1	a1	h1	h1	h1	b2	h2	b2	e3
Sediment classification (lower)	Y		XZ	XY	Y	Z	X	X	X	X	Y	X
Sediment classification (mid)	Y		Y	Y	Y	Z	Y	Z	Z	Y	Z	Z
Net sediment change m3	15.97	-29.38	40.8	36.41	-31.13	20.43	20.76	-38.91	32.71	-18.86	-17.37	-41.05
Volume sediment moved m3	16.5	29.38	40.8	36.41	33.09	20.43	20.76	38.91	36.07	24.47	26.33	41.99
Mean water level m OD	8.41	8.34	8.68	8.46	7.79	7.64	7.81	7.87	7.88	7.87	8.27	8.68
Vol. of sediment delivered (Stream 1)m3/m	No data				1.23	7.6	6.16	53.28	70.56	107.64	128.88	126.36
Maximum significant wave height (m)	0.1	0.4	0.25	0.25	0.6	0.5	0.45	0.65	0.45	0.35	0.45	0.35
Modal significant wave height (m)	0.05	0.05	calm	0.05	calm	0.2	0.05	0.05	0	0.05	0.05	calm
No. of storms >10m/s (6 hr sample)	5	1	9	1	no data	3	no data	1	2	0	2	3
No. of storms >10m/s (1 hr sample)	79	7	113	14	no data	3	no data	3	14	0	18	29

Table 5.5 Cashel beach behaviour variables. Profile G.

Beach Behaviour vs Variables												
Milarrochy Pr 2												
	J	F	M	A	M	J	J	A	S	O	N	D
Profile type	f1	c1	a1	h1	e1	a1	e1	h1	c1	e3	h1	e3
Sediment classification (lower)	U		ZT	U	U	T	WT	ZT	YT	Y	UT	Y
Sediment classification (mid)	X		X	X	UZT	UZT	UZT	W	X	W	X	W
Net sediment change m3	-30.71	22.04	-20.79	11.07	27.06	-5.4	-2.94	-32.26	12.83	24.69	-42.69	13.6
Volume sediment moved m3	31.39	22.04	20.79	11.85	27.06	10.96	6.42	32.26	12.83	24.69	42.21	13.6
Mean water level m OD	8.41	8.34	8.68	8.46	7.79	7.64	7.81	7.87	7.88	7.87	8.27	8.68
Vol. of sediment delivered m3/m	No data				4.28	0	0	0	1.43	8.24	308.16	374.4
Maximum significant wave height (m)	0.1	0.4	0.25	0.25	0.6	0.5	0.45	0.65	0.45	0.35	0.45	0.35
Modal significant wave height (m)	0.05	0.05	calm	0.05	calm	0.2	0.05	0.05	0	0.05	0.05	calm
No. of storms >10m/s (6 hr sample)	5	1	9	1	no data	3	no data	1	2	0	2	3
No. of storms >10m/s (1 hr sample)	79	7	113	14	no data	3	no data	3	14	0	18	29

Table 5.6 Milarrochy beach behaviour variables. Profile 2.

Beach Behaviour vs Variables												
Milarrochy Pr 4												
	J	F	M	A	M	J	J	A	S	O	N	D
Profile type	e3	a1	h2	b1	h1	h1	a1	b1	a1	c1	c1	a1
Sediment classification (lower)	Y		ZT	U	Y	Z	Y	Y	Y	Y	Y	Y
Sediment classification (mid)	Y		WT	W	Y	Y	X	Y	Y	X	Y	Y
Net sediment change m3	-30.71	22.04	-20.79	11.07	27.06	-5.4	-2.94	-32.26	12.83	24.69	-42.69	13.6
Volume sediment moved m3	31.39	22.04	20.79	11.85	27.06	10.96	6.42	32.26	12.83	24.69	42.21	13.6
Mean water level m OD	8.41	8.34	8.68	8.46	7.79	7.64	7.81	7.87	7.88	7.87	8.27	8.68
Maximum significant wave height (m)	0.1	0.4	0.25	0.25	0.6	0.5	0.45	0.65	0.45	0.35	0.45	0.35
Modal significant wave height (m)	0.05	0.05	calm	0.05	calm	0.2	0.05	0.05	0	0.05	0.05	calm
No. of storms >10m/s (6 hr sample)	5	1	9	1	no data	3	no data	1	2	0	2	3
No. of storms >10m/s (1 hr sample)	79	7	113	14	no data	3	no data	3	14	0	18	29

Table 5.7 Milarrochy beach behaviour variables. Profile 4.

4. profiles adjacent to streams, and therefore a sediment supply, show greater volumetric variability. Profiles which are most exposed to wind/wave activity also show greater volumetric change; and

5. a rapidly rising or falling water level (as in April/May or September/October) is associated with a high probability of profile type change i.e. a change in beach macro-form. This is a significant influence of beach variability.

Section 5.3.1 has identified from the profile surveys an annual sediment deficit at Milarrochy and the previous chapter has established that coarse sediment is recirculated within the bays. There is some landward transfer "rollover' of sediment beyond the back beach at both Cashel and Milarrochy, however this is unlikely to account for all the sediment deficit reported from the 1994 Milarrochy surveys (section 5.3.1). Thus sediment losses to the budget need to be more closely investigated and accounted for.

5.3.2. Role of the deltas in sediment storage

The bathymetric surveys (section 4.5) and the beach morphological surveys (section 5.1) have identified deltas at the stream exits of both beaches. Detailed monitoring of deltas was outside the aims of this research, and their role as sediment stores has emerged during the field work period.

Cashel Burn (stream 1) has the largest and most complex delta development, (Plate 5.1) and this is highly mobile. The Summer (May-September) delta has distributary channels. These features are modified by wave action and water levels. Fluvial sediment yield is greater during the wetter winter months (October- April; section 5.4.1) causing significant delta growth.

At Cashel profile E1 (stream 2; plate 5.2), the delta is considerably smaller with a lobate pro-delta zone. The stream exit at Profile E1 is an area of frequent development of spits and barrier beaches (section 5.3.3) and therefore accounts for considerable transient beach sediment storage.

All three streams at *Milarrochy* have deltas which are frequently modified by wave activity. The smallest delta (stream 3) at the most northerly stream (close to profile 1), has a simple lobate form and its' sediments are frequently dispersed alongshore under wave activity. Both the profile 2 (stream 4) and profile 5 (stream 5) deltas are larger, although typically lobate with a shifting position, modified by prevailing wave direction. The position of the stream 5 exit varied over a 40 m stretch of beach during the fieldwork period.

These deltas are important in understanding beach dynamics because they are significant areas of sediment storage. Sediment not otherwise accounted for within the beach surveys is stored within the deltas or other small scale forms. To account for such volumes of sediment, the deltas were surveyed during the bathymetric survey and further land survey measurements were made. A mean sediment depth of 0.15 m over the whole delta area was used to estimate delta volumes (Table 5.8). These sediment volumes incorporate all grain sizes.

Table 5. 8 Delta sediment storage. For delta locations see Figs. 5.1 and 5.2.

Delta location	Area (m^2)	Volume (m^3)
Stream 1 (Cashel Burn)	914	137
Stream 2 (Cashel pr E1)	343	51
Stream 3 (Milarrochy N of Pr 1)	16	2
Stream 4 (Milarrochy pr 2)	256	38
Stream 5 (Milarrochy pr 5)	240	36

From these results, approximately 188 m^3 of sediment is stored within Cashel deltas and approximately 76 m^3 at Milarrochy. Whilst quantities of deltaic sediment vary under differing fluvial sediment yields, and nearshore processes modify sediment distribution, lake wave energy is such that deltas are never completely removed and under some conditions become well developed. They are therefore significant areas of storage, particularly in relation to the net sediment budgets for the two beaches.

5.3.3 Small scale forms

Some additional beach processes and micro-forms observed during fieldwork also contribute to understanding beach dynamics (aims 2 and 3).

Small offshore bars, spits, deltas and barrier beaches are frequently found on the Loch Lomond beaches. A typical spit extends for 9.1 m and the recurve is 3.3 m long. Spits occur frequently at stream exits where there is often a change in shoreline direction and an additional sediment supply. Such forms are transitory in nature rarely lasting for more than 7 days. They are areas of sediment storage within the beach system and also indicate process and magnitudes of alongshore sediment transport. The development of shore-parallel sediment ridges in the nearshore zone is also common. These tend to occur below the water surface close to the wave breaking point. Such ridges can extend up to 40 m alongshore, broken only by a change in shore orientation, the presence of boulders, or a stream exit. These features are only a ≤ 0.1 m high and are break-point bars. These constitute a further location of sediment storage, although they are accounted for in the profile surveys.

In summary, these forms also identify scales of alongshore sediment transport and some beach sediment storage can be accounted for in various small scale and transitory forms found on the Loch Lomond beaches.

5.4 Beach Sediment Supply

Quantifying beach sediment supply and characterising the nature of beach sediments is important for understanding beach dynamics and sediment budget operation. Sedimentological analysis is necessary where a wide range of sediment sizes are available such that spatial and temporal sorting of sediment can occur. This section presents the results of the investigations into quantities of sediment supplied to the beaches and the results of measurements designed to describe the nature, composition and behaviour of beach sediment.

5.4.1 Sediment delivery

The main sources of sediment supply to the coastal areas are terrestrial (rivers and cliffs), from alongshore and from offshore. Nearshore/offshore sediment sampling (section 4.5.1) showed that there are no sources of coarse clastic material in the offshore zone which could be delivered to the beach. This sampling, together with wave refraction (section 4.4) identified virtually no around headland transport, suggesting that the bays operate as discrete units, ruling out significant onshore and alongshore transport from other bays. This means that sediment delivery to the profiles at Cashel and Milarrochy is primarily from terrestrial sources together with minor redistribution of sediments already on the beach. This section is therefore divided into three parts: fluvial sediment supply, cliff sediment supply and artificial sources of sediment.

5.4.1.1 Fluvial sediment supply

The main hydrological characteristics of the two streams at Cashel and three at Milarrochy (section 3.3.3.1) are given in Table 5.9 overleaf.

The second set of results (Table 5.10) gives the summary recorded peak stage for each month at each stream, all of which have flashy hydrological regimes. The estimated maximum sediment delivery (m^3 m^{-1} s^{-1}) allows for inter-site comparison of peak rates and the maximum total sediment delivery (m^3 per 15 minute flow) provides estimates of total supply. These results are for bedload sediment delivery (> 2mm/<-1ϕ).

Table 5.9 Stream hydraulic characteristics

Stream	Catchment Area (km^2)	Length (km)	Catchment slope	Slope at gauge (long bed profile)	Bedload Size D50 (phi)	Particle D84 (phi)	Channel (Bed) (m)	Width (Bankful) (m)
Stream 1 (Cashel Burn)	9.2	22.8	0.18	0.0227	-6.38	-5.57	5.8	9.1
Stream2 (Pr E1, Cashel)	0.42	0.48	0.12	0.051	-6.52	-5.49	1.6	4.7
Stream 3 (Pr 1 Mil.)	0.9	0.78	0.12	0.020	N/A	N/A	2.15	3.15
Stream 4 (Pr 2 Mil)	0.98	1.33	0.11	0.009	0.013	-5.81	6.68	11.42
Stream 5 (Pr 5 Mil.)	12	10.95	0.11	0.020	-6.41	-5.64	22.6	5.0

As described in chapter 3, the peak flow was estimated from peak stage readings, and other hydraulic characteristics. Peak flow represents the conditions under which sediment is most likely to be entrained and transported and is therefore of most significance for estimating sediment delivery. These results show similar overall trends, peaking in November/December 1994.

In order to reconstruct sediment delivery from peak stage, flow duration and peak frequency need to be established. When the peak stage trends are compared with the those of the River Falloch (Figs. 5.16, 5.17), similar patterns occurs showing similar trends of wet and dry months are found, in particular the peak rainfall in November/December 1994. This finding supports using monthly peak stages to calculate sediment budget estimates. It also suggests that it is reasonable to use the Falloch data (for which stage is recorded every 15 minutes) as a surrogate to determine an appropriate frequency of high flows for use in the field site stream reconstruction calculations. To determine the frequency of high flows in any one month, a threshold stage for the Falloch of 1.3 m was selected, to include about 5% of flows. Using a different threshold would produce the same monthly pattern although total sediment transported would be different. This is an arbitary

Fluvial Sediment Delivery results

Streams		1994 May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	1995 Jan	Feb	Mar	Apr	TOTAL
Stream 1	Max stage (m)	0.92	0.28	0.25	0.74	0.86	1.09	1.25	1.24	0.65	0.75	0.68	0.7	
	delivery/m3/m/900s	0.31	1.9	1.54	13.32	17.64	26.91	32.22	31.72	10.25	13.59	11.25	68.9	
	delivery/m3/900s/m x ch width	1.78	11.02	8.93	77.26	102.31	156.1	25.78	183.98	59.45	78.82	45	399.6	1150.03
Stream 2	Max stage (m)	0.07	0	0	0	0.02	0.1	0.65	0.72	0.25	0.22	0.27	0.2	
	delivery/m3/m/900s	1.05	0	0	0	0.36	2.06	77.04	93.6	11.88	9.36	13.68	0.29	
	delivery/m3/900s/m x ch width	6.09	0	0	0	0.58	3.3	123.26	149.76	19.08	14.98	21.89	0.47	339.41
Stream 3	Max stage (m)	0.02	0.02	0.03	0.12	0.22	0.25	0.29	0.29	0.24	0.55	0.26	0.38	
	delivery/m3/m/900s	0	0	0	0	0.05	0.09	0.16	0.16	0.75	1.23	0.15	0.42	
	delivery/m3/900s/m x ch width	0	0	0	0	0.1	0.19	0.35	0.35	0.11	2.16	0.31	0.19	3.76
Stream 4	Max stage (m)	0.11	0.1	0.1	0.16	0.18	0.6	0.62	0.67	0.04	0.17	0.12	0.08	
	delivery/m3/m/900s	0	0	0	0	0	1.17	1.32	1.74	0.23	0	0.002	0.001	
	delivery/m3/900s/m x ch width	0	0	0	0	0	7.81	8.81	11.66	1.52	0	0.02	0.008	29.828
Stream 5	Max stage (m)	0.14	0.21	0.19	0.36	0.29	0.41	0.78	0.76	0.39	0.7	0.42	0.61	
	delivery/m3/m/900s	0.025	0.16	0.11	1.07	0.51	1.74	12.69	11.88	1.45	9.99	1.9	6.42	
	delivery/m3/900s/m x ch width	0.065	0.42	0.27	2.78	1.32	4.5	32.99	30.89	3.77	29.97	4.94	16.69	128.605

Table 5.10 Fluvial sediment delivery results:
The reconstructed sediment delivery results for streams 1 and 2 (Cashel) and 3, 4 and 5 (Milarrochy) are given in above table. For each stream:-
row 1 = peak stage for each month
row 2 = volume transport rate per 15 minutes for 1 m width
row 3 = total volume transport rate over the entire channel

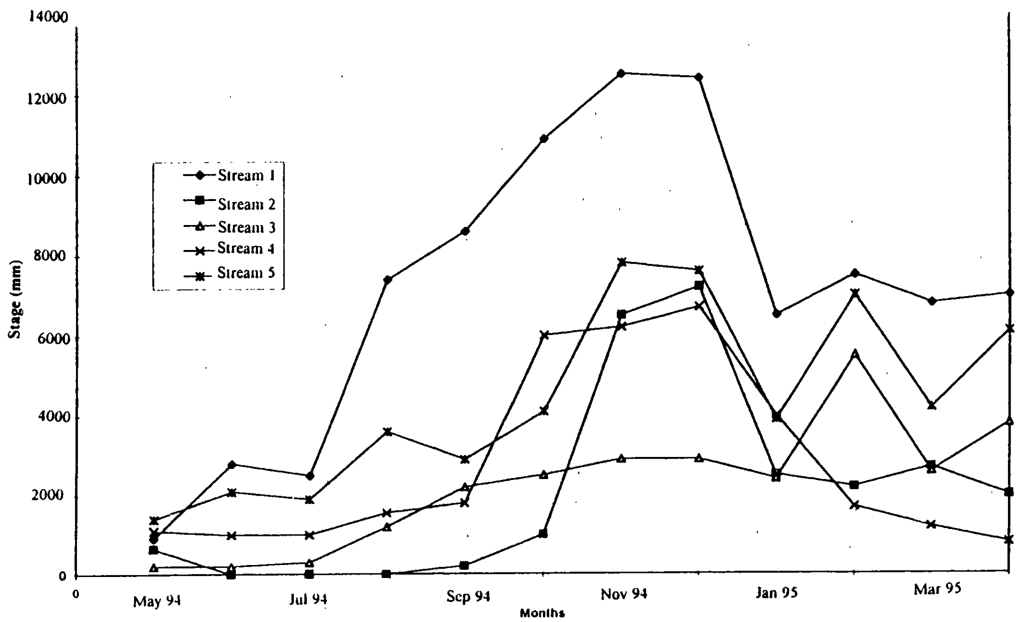


Fig. 5.16 Maximum stage per month: Cashel and Milarrochy streams.

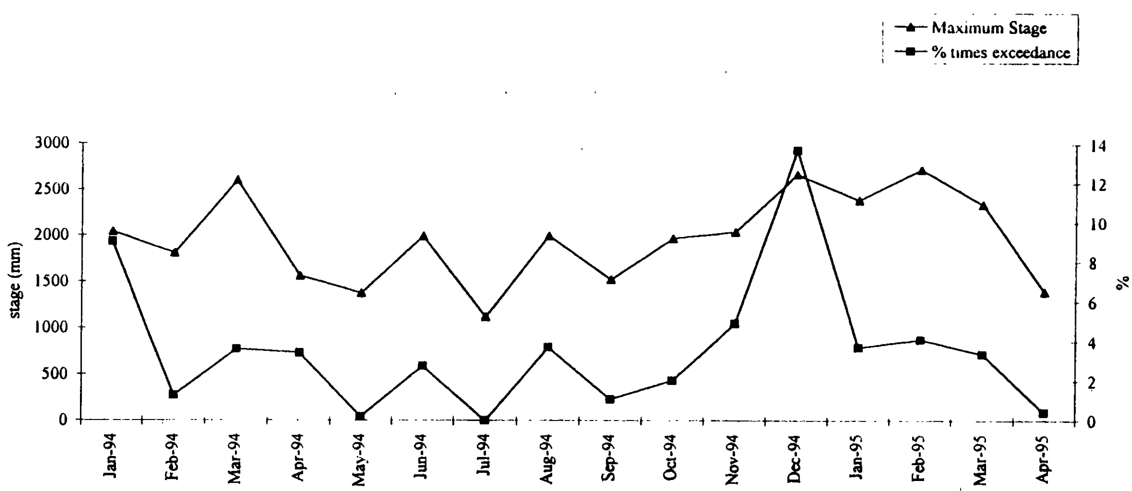


Fig. 5.17 Maximum stage per month: River Falloch.
Percentage exceedance denotes percentage time an arbitary threshold (1300mm) was exceeded.

choice and is not meant as a surrogate transport threshold. The number of times in any month that flow exceeded this gives a generalised index of how long high flows persisted. The frequency of high flows is similar to the trend of maximum stage (Fig. 5.17). It is also assumed that high stage, and high frequency of high stage events, relate to periods of high sediment entrainment and yield. Thus the number of events exceeding the threshold for each month was multiplied by the duration of flow events. The 15 minute duration used was determined by the observation that few consecutive readings from the Falloch maintained a peak value i.e. the highest flows rarely lasted longer than 15 minutes. The yields calculated by multiplying the number of high stage events for each month, gave such high delivery rates (e.g. 179435 m^3 per annum) that it was decided to use estimates assuming one high event per month. Although different thresholds for defining high events were experimented with, the results given are regarded as the best estimate using this method, accepting its' limitations.

Having established the peak flows for the 5 streams, the sediment yield (delivery) for each month was calculated using the roughness estimates, hydrological characteristics and bedload calculations as described in section 3.3.3.1. Thus for each stream, the sediment delivery estimates were calculated (Table 5.8) based on 1 peak flow of 15 minutes duration per month. These results were totalled for Cashel and Milarrochy to give the 1994 fluvial sediment delivery estimates.

Total fluvial sediment delivery estimates for 1994

Using these estimates (Table 5.8), the total fluvial sediment delivery to *Cashel* beach from two streams (May to December 1994) is 850 m^3. If the Jan-Apr 1995 estimates are used as a surrogate for Jan to Apr. 1994, this gives an alternative budget of 850 + 639 = 1489 m^3.

At *Milarrochy* the 1994 fluvial sediment delivery estimate from 3 streams is 103m^3. The alternative estimate incorporating the 1995 data is 103+ 57= 163 m^3.

These results show the temporal variability of potential sediment input, high in winter and low in summer. The sediment supply may however be a limiting factor. These data are used in the construction of the sediment budget in section 5.5.

5.4.1.2 Sediment supply from the cliffs

Cliff recession rates varied spatially at both sites, with vegetated cliffs more resistant to recession as is reflected in their embayed nature (section 5.1). The most significant cliff falls were associated with vegetation failure such as tree falls (only at Milarrochy) during high winds, as in

March 1994 where two trees fell causing cliff top recession and cliff falls (approx. 15 m^3 of sediment).

Recession tended to be episodic and occurred under both high and low water levels, and varying wave conditions. Observations suggest that recession was predominantly related to precipitation and cliff saturation resulting in cliff failure, rather than to the direct action of waves. When water levels were high, the cliff foot was subject to direct wave action and undercutting which left cliff material vulnerable to collapse. As the cliff foot altitude is generally lower at Cashel (e.g. 8.3 m at Profile F) compared with the more variable cliff foot height at Milarrochy (e.g. 8.4-9.5 m OD at Profile 6), the Cashel cliff tends to receive more wave action when water levels are high. The Milarrochy cliff is higher (Figs. 5.2 and 5.3) and the variable cliff foot altitude is mostly attributable to cliff falls. During 1994, the mean loch level was higher than 8.3 m for 6 months (January to April, November and December), so that the cliff foot at Cashel and to a lesser extent at Milarrochy were subject to direct wave activity for about half of the year.

There is an overall trend of cliff recession at both Cashel and Milarrochy. At Cashel, between October 1993 and April 1995 the mean cliff retreat rate was 0.81 m yr^{-1}. At Milarrochy the overall retreat rate between May 1993 and April 1995 was 0.54 m yr^{-1}. To calculate the volume of sediment eroded from the cliffs for input into the sediment budget calculations, the following equation was used:

$$V = [H \times R \times L] + SP \qquad (5.1)$$

where V = volume of sediment supply (m^3); H = mean cliff height (m); R = mean retreat (m); L = cliff length (m); SP = volume from shore platform erosion (m^3).
SP was calculated from survey data.

At *Cashel*, from field surveys, it has been established that the area of the cliff face is 27 m^2 With a retreat rate of 0.54 m yr^{-1} in 1994, over 71 m of cliff length, this represents a contribution to the sediment budget of 14.3 m^3 of cliff material (most of which is fine sediment (< 2mm/>-1 ϕ). At Cashel, the field surveys reveal a steepening in shore platform angle of 3^0 during the year. With a mean length of 9 metres offshore over 70.9 metres alongshore the maximum contribution of eroded till from the shore platform would be 147 m^3. Thus at Cashel sediment delivered to the beach from cliff recession and from the lowering of the shore platform is 162 m^3.

Over the 214 m length of the *Milarrochy* cliff, recession rates varied. During 1994, the lowest mean rates were 0.1 m yr^{-1} at the low northern end of the cliff, 0.2 m yr^{-1} close to the southern headland and 0.46 m yr^{-1} at profile 6. These recession rates combine to give a total of 77 m^3 of cliff sediment to the 1994 beach sediment budget.

At Cashel with approximately 2% of the cliff material being coarse (> 2mm/< 1ϕ) (section 5.1), the total contribution to the beach sediment budget is 0.3m^3 of coarse sediment and approximately 162 m^3 of fine sediment. At Milarrochy where approximately 10% of the cliff material is coarse, and approximately 69.5 m^3 is fine and 7.2 m^3 of coarse sediment delivered to the beach sediment budget.

5.4.1.3 Artificial sources of sediment

As part of shore protection measures, at *Milarrochy*, 200 tonnes or 111 m^3 of coarse sediment were introduced during 1994 and 20 tonnes or 11.1 m^3 of fine sediment (< 2mm) (between profile 1 and the northern headland). Approximately 75 m^3 of mixed grades of sediment was introduced adjacent to profile 5 in March 1994. These constitute part of the input sediment budget calculations.

5.5 Beach sediment analysis

Having established the primary sources of sediment in the previous sections, the beach sediment samples were analysed to determine sedimentological characteristics. These are important both in determining the nature of the shore zone and variability within that zone (aim 2) and where possible for identifying relationships between nearshore and shore process (aim 3). In this section, the particle size and shape analysis findings are presented.

5.5.1. Particle size analysis (extractive sampling)

The results from the surface particle size analysis are presented in Tables 5.11 and 5.12 and the sub-surface results in Appendix F. The discussion in this section focuses on the main trends of variability of beach sediments, including any alongshore or cross-beach trends. As few separate trends emerged from the sub-surface sediments, the focus is on the surface sediments.

Cashel: Surface particle size analysis.

The particle size analysis of the all the Cashel surface sediments (Table 5.11) shows variation in beach sediments. Examination of the median particle size (Fig. 5.18a) illustrates both alongshore and cross-beach variation in particle sizes. The *upper beach* results varies markedly from the

Summary Particle Size Analysis: Cashel, Surface Samples.										
Upper Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-3.74	-1.85	-3.07	-1.07	-4.42	-5.58	-6.27	-6.26	-6.08	-5.47
Sorting	0.71	0.85	1.12	2.07	0.58	0.79	0.48	0.62	0.68	0.33
Skewness	0.14	0.62	-0.09	0.12	0.09	-0.43	-0.11	-0.46	-0.23	-0.02
Median	-3.7	-1.49	-3.07	-1.07	-4.38	-5.78	-6.3	-6.45	-6.17	-5.46
D 16	-3.11	-1.14	-2.01	0.78	-3.82	-4.67	-5.73	-5.5	-5.33	-5.11
D84	-4.42	-2.29	-4.13	-3.95	-5.05	-6.3	-6.78	-6.83	-6.31	-5.83
Mid Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-2.11	-6.24	-6.46	-5.71	-3.83	-4.37	-3.68	-3.55	-5.75	-5.25
Sorting	0.77	0.16	0.45	0.24	0.81	0.92	0.86	0.6	0.64	0.44
Skewness	-0.01	0	-0.33	-0.23	-0.04	-0.34	-0.09	-0.07	0	-0.07
Median	-2.16	-6.24	-6.52	-5.71	-3.79	-5.25	-3.71	-3.56	-5.75	-5.27
D16	-1.27	-6.07	-6.02	-5.52	-3	-3.29	-2.73	-2.95	-5.09	-4.81
D84	-2.9	-6.42	-6.85	-5.91	-4.69	-5.42	-4.49	-4.16	-6.41	-5.69
Lower Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-5.9	-4.73	-5.11	-5.37	-5.31	-3.5	-3.5	-5.12	5.92	-2.08
Sorting	0.4	0.67	0.38	0.6	1	0.98	0.39	0.4	0.3	1.13
Skewness	-0.08	-0.41	-0.06	-0.56	-0.53	0.06	-0.3	0.05	0.22	-0.2
Median	-5.9	-4.87	-5.14	-5.57	-5.66	-3.47	-3.56	-5.13	-5.88	-2.27
D16	-5.49	-4.02	-4.71	-4.72	-4.09	-2.62	-3.08	-1.23	-5.62	-0.85
D84	-6.31	-5.3	-5.46	-5.86	-6.16	-4.42	-3.86	-3.2	-6.26	-3.12

Table 5.11 Cashel surface particle sizes

Summary Particle Size Analysis: Milarrochy Surface Samples						
Upper Beach						
Profiles	1	2	3	4	5	6
mean	-0.49	-4.45	-3.78	-4.36	-5.25	-5.13
sorting	0.79	0.7	0.86	0.8	0.44	0.78
Skewness	0.11	-0.26	-0.08	-0.2	-0.07	0.22
Median	0.57	-4.57	-3.78	-4.44	-5.27	-4.99
D16	1.25	-3.67	-3.06	-3.51	-4.81	-4.34
D84	-0.36	-5.1	-4.48	-5.13	-5.69	-6.06
Mid Beach						
profiles	1	2	3	4	5	6
mean	-1.98	-3.65	-3.43	-5.66	-2.33	-5.56
sorting	1.08	1.04	0.68	0.45	2.07	0.53
skewness	0.52	-0.16	-0.24	-0.13	-0.41	-0.04
median	-1.47	-3.7	-3.52	-5.7	-2.65	-5.56
D16	-1.1	-2.54	-2.73	-5.2	-0.34	-5.05
D84	-3.37	-4.7	-4.04	-6.09	-4.01	-6.37
Lower Beach						
Profiles	1	2	3	4	5	6
mean	-2.33	-0.92	-0.66	-5.5	-5.93	-6.39
sorting	0.71	2.31	2.39	0.32	0.37	0.56
skewness	-0.18	-0.09	0.2	-0.07	-0.04	-0.51
median	-2.39	-1.09	-0.22	-5.51	-5.92	-6.55
D16	-1.16	1.88	1.99	-5.13	-5.57	-5.76
D84	-2.98	-3.55	-3.73	-5.84	-6.31	-6.85

Table 5.12 Milarrochy surface particle sizes

mid and lower beach results. The trend is for a general increase in median grain size southwards. Sediment sizes from profiles E1 to A are significantly coarser than from profiles I to E, with profile C (-6.45 ϕ) having the coarsest sediment followed by a trend of fining towards profile A. Upper beach samples at profiles in the vicinity of the Cashel Burn (I, H, G) show finer median grain sizes than found elsewhere (other than at F). This may be attributable to the mixed fluvial sediment supply.

The *mid- beach* median samples alongshore are much more varied. Profiles H, G and F have coarser sediments than the upper beach whereas profiles I and E to A have finer sediments than the upper beach. This further illustrates the different characteristics of the northern and southern sections of Cashel beach as identified in previous sections. The *lower beach* samples show a net alongshore fining towards profile A, although there are a number of fluctuations in this trend (Fig. 5.18a). At the southern section of Cashel beach (profiles A-E1), there is trend of cross-beach fining, with the upper beach sediments being significantly coarser than the mid and lower beach. This situation is largely reversed in the northern section of the beach (profiles E-I), largely due to the supply of fine materials from the cliff, shore platform and from finer fluvial sediments which feed the upper beach.

The Cashel surface sediment *sorting* shows fairly consistent alongshore trends (Fig.5.18b). On most sections of the beach, the sediments are very well sorted to moderately sorted. This indicates that selective particle transport has taken place before sediment deposition or selective deposition from transport. The *upper* beach sorting between profiles D and B is better than the lower beach. This section of beach was not affected by waves in 1994 and sorting trends will be from waves at high water levels occurring prior to this. Of note is the unusually poor sorting (2.07 ϕ) on the upper beach at profile F, where fine cliff sediments combine with the coarser gravels to give a large range of sediment sizes

Skewness is a good indicator of the sediment history (section 3.4.4) and shows considerable variability, both alongshore and cross-beach (Fig. 5.18c). Interpretation is not straightforward as the fluvially derived sediment complicates any pre-existing trends, but is predominantly negative due to a lack of fines. The skewness suggests a very mixed sediment history. This is consistent with the findings of chapter 4 where the offshore sediment sampling and investigations into nearshore processes show that sediment is reworked and re-distributed within the bays.

The *Cashel sub-surface* sediments results show very similar trends to the surface sediments (Appendix F). The median grain sizes tend to be slightly finer than at the surface, except at the

Fig. 5.18a

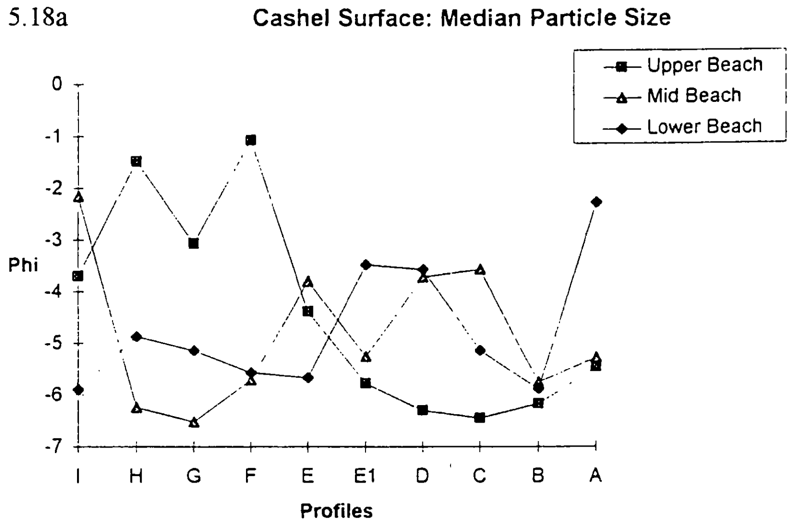


Fig. 5.18b

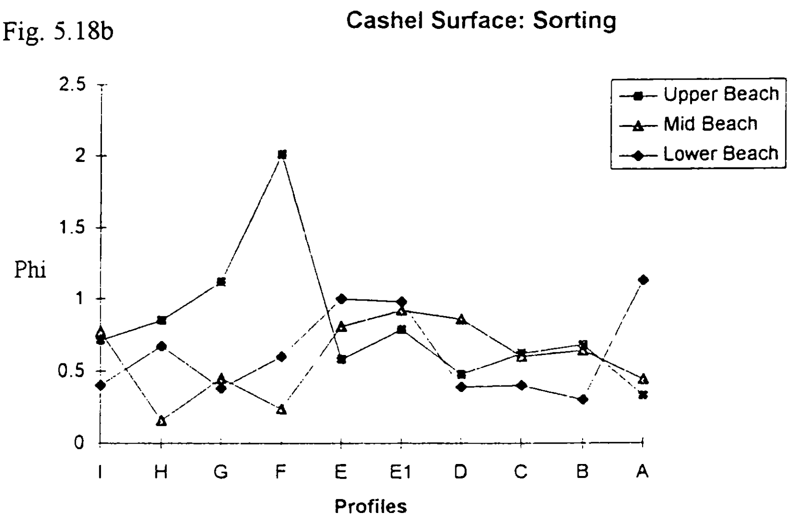


Fig. 5.18c

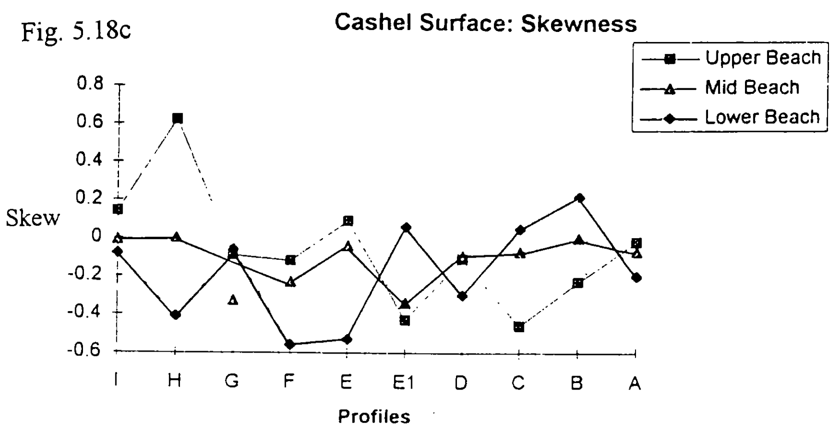


Fig. 5.18a-c Cashel Sedimentology

lower beach, where sizes are largely comparable. This is as expected as smaller particle sizes tend to fall between surface clasts to the lower levels (as shown in the stratigraphic profiles) leading to a degree of surface armouring. Sorting is less good in the sub-surface sediments. As the lower beach sediments represent the most recently deposited sediments less segregation is likely as significant vertical sorting has not yet occurred.

Milarrochy: Particle size analysis

At Milarrochy, the *median* surface size fluctuates both alongshore and cross-beach (Figs. 5.19a, Table 5.12). The *upper* beach sediments show a general trend of southward coarsening. Profile 1 shows particularly fine sediments (0.57ϕ, sands) whereas profile 6, the most southerly profile has a median size of -4.99ϕ (gravel), although the median value at profile 5 is slightly coarser (-5.27ϕ). This latter result may be affected by beach feeding (section 5.4.1.3). The *mid* and *lower* beach results show no significant alongshore trends in median size.

Cross-beach coarsening (*upper to lower*) is in evidence at profiles 1 and 6 (Fig.5.19) which are the areas of beach closest to the headlands and are less exposed. Cross-beach fining occurs at profiles 2 and 3. Profile 5 does not show a pattern, but may be this result may be affected by artificial sources of sediment.

Surface sediments are moderately *sorted* and reasonably uniform on the *upper* beach (Fig. 5.19b). On the *mid* beach the results are more mixed with considerable variation alongshore, although profile 6 sediment is significantly coarser than profile 1. The *mid* beach ranges from poorly sorted sediment at profiles 1, 2 and 5 to good at profile 4. The *lower* beach shows very poor sorting at profiles 2 and 3, and moderately to well sorted sediment elsewhere. The higher altitude upper beach sediments are on the whole better sorted than the mid and lower beach.

There is a skew towards the coarser grain sizes for almost all the samples (Fig. 5.18c). The exception is at Milarrochy profile 1 where fine sediments (sands) were found on the upper beach.

The sub-surface sediments at Milarrochy mirror the surface trends (Appendix F) although the median results show slightly finer grain sizes.

Summary trends at Cashel and Milarrochy

Although the influx of sediments from the streams complicates the results, sedimentological trends are apparent at both beaches. Both show a southwards trend of upper beach sediment coarsening. This occurs on the southern section of Cashel beach and on all of Milarrochy beach.

Fig. 5.19a

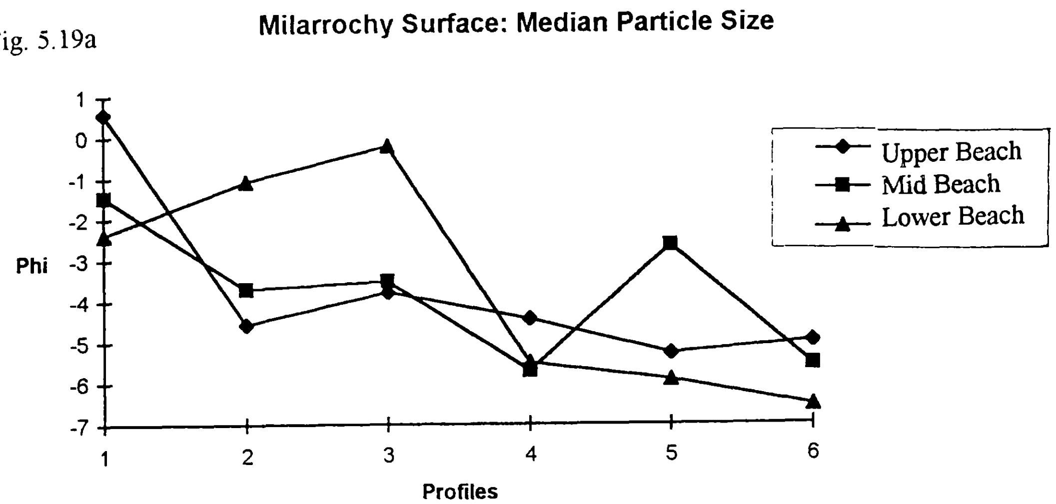


Fig. 5.19b

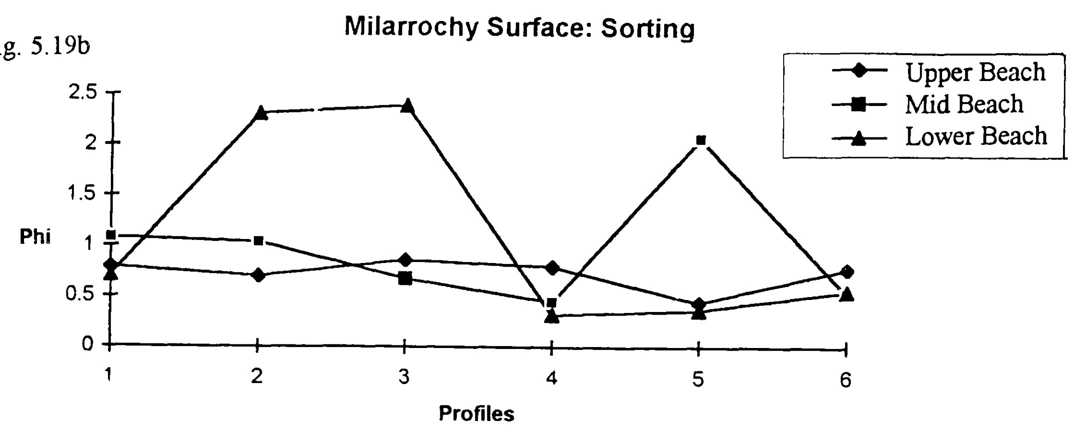


Fig. 5.19c

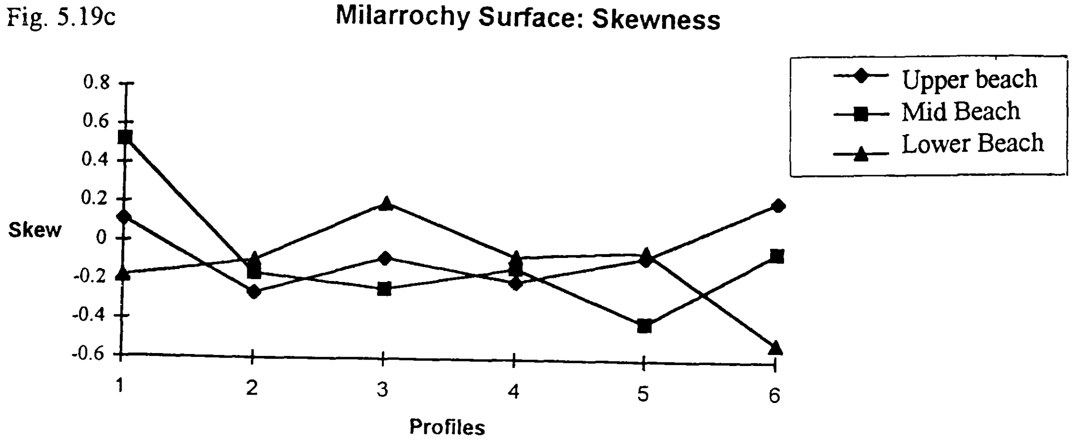


Fig. 5.19a-c Milarrochy Sedimentology

The upper beach sediments tend to be distinct from mid and lower beach sediments (surface and sub-surface). This may be a reflection of morphology and beach elevation whereby the upper beach tends to be affected by high water levels and higher energy waves, causing distinct sedimentological characteristics. Trends of cross-beach fining (upper to lower) are noted at some profiles, generally in the more exposed parts of the bays. At the headlands, cross-beach coarsening (upper-lower) on these less exposed sections of beach was observed.

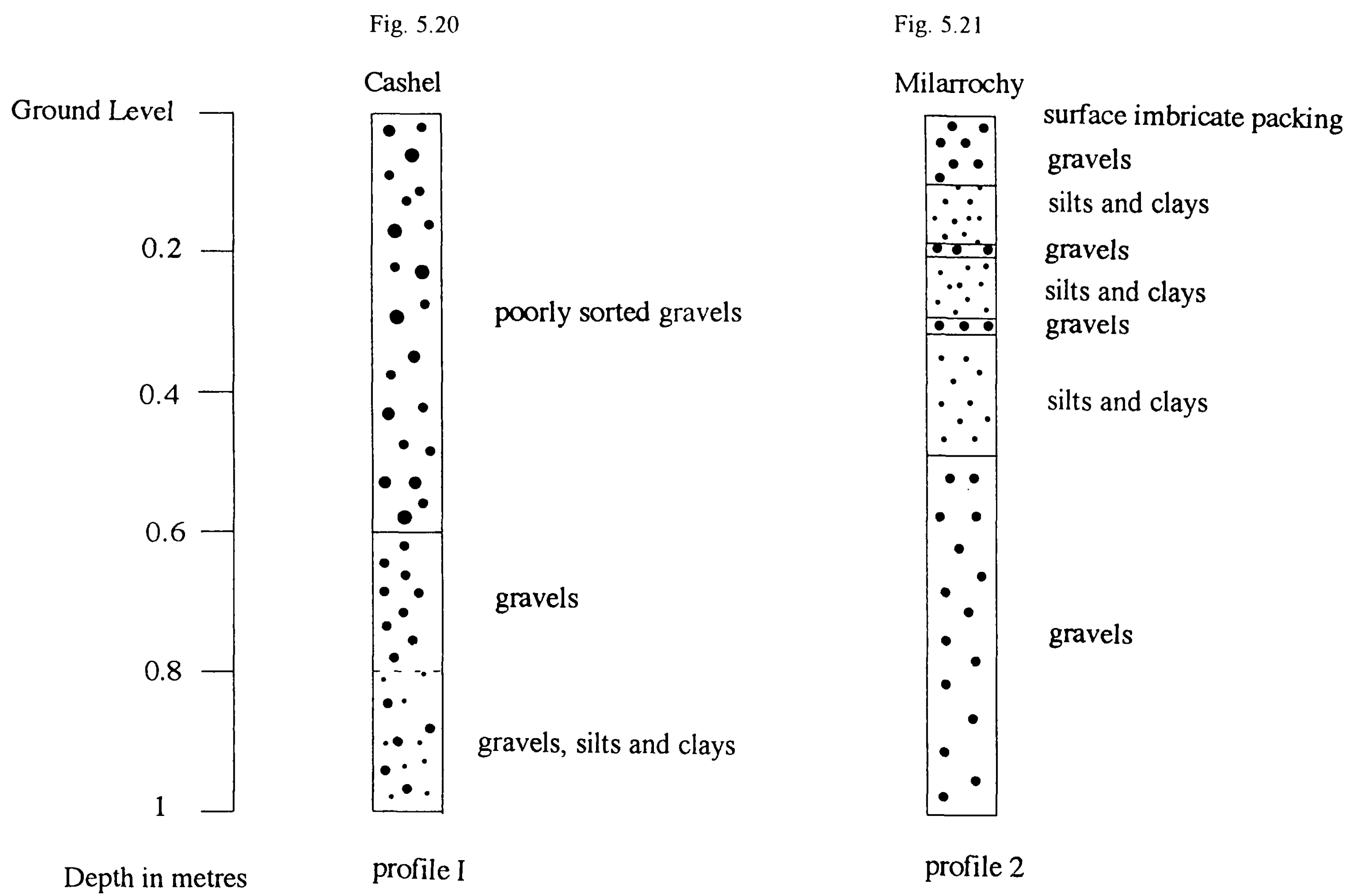
5.5.2 Beach sub-surface stratigraphic profiles

Two 1 m deep pits were dug as described in section 3.4.4.1, from which sub-surface stratigraphic profiles were drawn (Figs. 5.20 and 5.21). The profile sections were taken adjacent to profile I at Cashel, and profile 2 at Milarrochy. Both showed uniformity in sedimentological composition along the length of the pit/trench. The sub-surface stratigraphic analysis enabled identification of beach sediment facies, sub-surface sorting and sediment packing, giving an indication of 3-dimensional beach composition and the depth of sediment disturbance.

At *Cashel* the sub-surface profile reveals loosely packed poorly sorted gravels (approx. -7 to -2 ϕ) to a depth of approximately 0.6 m. Beneath this lie better sorted and finer sized gravels (approx. -4 to -1 ϕ). At a depth of approximately 0.8 m these gravels are interspersed with silts and clays, the finer particles having fallen through pore spaces to the lower levels.

The *Milarrochy* 'ground level' taken for the profile was marked by a layer of grass on the upper sediments. Above this however, were recently deposited sediments, comprising a 0.1 m layer of poorly sorted gravels (-6 to -1ϕ). The sub-surface profile shows evidence of horizontally bedded lithofacies. The upper sediments (to a depth of 0.08 m) have a top layer of imbricately packed gravels (-4 to -1 ϕ) and generally well packed gravels below. Beneath this there was a laminated layer of sands and silts to 0.18 m depth, followed by a 0.03 m layer of gravels, further laminated sands and silts and another layer (approx. 0.03m) of gravels. At approximately 0.48 m deep the sediments were gravels (-4 to -1ϕ) which were densely packed.

The profiles suggest that the beach at Cashel adjacent to profile I is disturbed to a much greater depth by wave activity than the beach at Milarrochy Profile 2. At Milarrochy the packing and distinct stratification of sub-surface sediments suggests a less mobile upper layer of beach, and a higher percentage of finer grained sediment. This profile indicates a better sorted, packed and generally more stable section of beach than at Cashel. The sedimentological composition at Milarrochy is more mixed, but the profile lies close to a fluvial sediment source. The



Figs. 5.20 and 5.21 Sub-surface stratigraphic profiles at Cashel profile I and Milarrochy profile 2. Sediment sorting was good except where indicated.

stratification may represent pulses of fluvially derived fine sediment overlain with beach gravels from on-shore wave activity and deposition, a pattern which the section suggests is repeated.

5.5.3 Particle shape analysis

Particle shape is important for describing the beach sediment characteristics (aim 2), but also for identifying sediment provenance (and as environmental discriminators in the reconstruction of palaeoenvironments from sedimentary evidence). As described in section 3.4.4.3, particle shape was assessed from the coarser sediment fractions (>2mm/< -1ϕ). The results are presented in a series of Zingg plots and Powers roundness tables (Appendices G and H) from which environmental discrimination is attempted.

The Zingg plots from the *upper beach at Cashel* (profiles A, B and D) show almost entirely discs and blades. These particles are predominantly 'well rounded' sediments which have been subject to high energy or prolonged moderate energy environments. The *mid beach* at *Cashel* at profiles (C, E1 and I) has largely discs and blades, although profiles I and C have a proportion of rollers. These are mainly the more resistant quartz-rich clasts. Of these 40 % - 58%, were rounded and 32 % were sub-rounded.

At *Milarrochy*, profiles 1, 3 and 6 show predominantly discs and blades, although the spread of b/a to c/b ratios at profile 6 is more centralised, with particles showing forms closer to the spherical and roller shapes. This could be attributable to a higher percentage of quartz clasts. Between 48 and 52 % were rounded and 15-24% sub-rounded.

Overall, there are approximately equal proportions of disc and blade shaped particles on both beaches. There is a variety of roundness, but the dominant shape is rounded. These results are consistent with marine beach sediments. This could be derived from both the cliffs found on the beach or sediment transported by the streams from higher in the catchment.

5.5.4 Clast Fabric analysis of the field ridge at Cashel

The fabric (100 clasts) of an exposure of the field ridge 30 m behind the present day beach was analysed to establish the nature of the landform. This ridge has an elevation approximately 3 m higher than the maximum elevation of the contemporary highest back beach ridge. The clasts are oriented (long axis) in two predominant directions, approximately 90^0 and 180^0. The upper section of the exposure shows greater uniformity about the two directions than the lower. The modal dip is 0-5^0 (80 clasts), 13 clasts are in the range 6-10^0. Mostly disc and blade shaped clasts were found. These factors, coupled with morphology suggest that the feature is a relict beach ridge which shows many similarities with the contemporary ridge. This result is important as it suggests previously higher water levels and a beach location further inland than the current location. The implications of this are discussed in chapter 6.

5.6 Sedimentological change

5.6.1 Temporal and spatial sedimentological change.

Repeat vertical photograph sediment sampling enables description of temporal and spatial sedimentological change. The data collection technique and classification is described in section 3.4.4.2 and the summary results are in Tables 5.13 and 5.14.

The *Cashel* results (Table 5.13) show a stable upper beach for profiles A to E1, all exhibiting sediment type Y. In these locations, individual clasts can often be identified from month to month. This section of the beach is between 8.9 m and 9.47 m in altitude, and mostly above 1994 levels of water fluctuation.

The upper beach results at profiles E to I is more varied. Profile E exhibits sediment of types Y, W and X, with finer sediments tending to be deposited further up the beach in stormy conditions. When the surface layer of sediment is disturbed exposure of the sub-surface reveals finer particles. The upper beach at profile F is of particular interest. It is at the foot of a recessional cliff and on a sometimes exposed shore platform. The sediment found on this platform is variable and at times the gravel beach layer is completely absent, exposing the fine-grained shore platform. There is no apparent pattern to this, which may be related to sediment supply as field observations show both gravel deposition and gravel removal under similar wave conditions. The upper beach at profile G shows mostly sediment types W and X, although type Y was recorded in January 1995 following severe weather conditions. At profile H upper beach, adjacent to Cashel Burn, there is a great variety in sediment type, a reflection of stream flow levels, sediment supply and deposition. Profile I again shows some variation between sediment types Y, W and X.

The *middle* and *lower* beach sites are subject to inundation and wave action. The results reveal a highly variable pattern although the steeper beach (Southern Cashel) shows largely Types W and Y, except in the vicinity of profiles A and B where type Z occurs. The results further north reflect a coarsening of sediment The more frequent occurence of type Z at Profile E is due to the addition of finer sediment which is deposited and then removed again from the relatively immobile coarse sediment. During the Summer months (May to September), with the exception of profile I, there is less sediment change, particularly in the mid beach. Throughout the period, the loch

BEACH SEDIMENT CLASSIFICATION. CASHEL																
	1994												1995			
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A
Cashel A, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	Y		Y	Y	W	Y	Y	ZX	Y	X	Y	Y	Y	Y	Y	Y
lower	Y		Y		Y	ZT	ZX	Y	Y	Y	Y	Y	W	Z	Y	ZX
Cashel B, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	Y		X	Y	W	Y	X	Y	Y	Y	Y	Y	Y	Y	Y	Y
lower	Y		X	Y		Y	Z	Y	Y	Y	X	Y	X	Y	ZU	W
Cashel C, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	X		Y	Y	X	X	Y	X	X	X	X	Y	Y	Y	Y	[illegible]
lower	Y		Y	Y	Z	Y	X	Y	Y	W	X	Y	W	Y	W	W
Cashel D, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	Y		W	W	W	X	W	X	X	W	W	X	W	Y		W
lower	Y		W	W	W	W	W	W	W	W	W		W	Y	W	W
Cashel E1, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	Y		W	W	W	X	X	V	W	U	W	WX	Y	W	X	W
lower	W		W	W	W	W	W	X	WX	X	W		Y	Y	W	W
Cashel E, upper	X		Y	W	W	X	Y	X	W	W	X	X	X	X	X	WX
mid	Y		W	W	Z	Z	ZU	ZY	Z	Z	Z	X	X	W	W	W
lower	Z		Z	Z	Z	Z	Z	ZY	Z	ZU	ZU	ZU	YU	X	ZU	Z
Cashel F, upper	Y		Y	YS	ZU	SY	SY	SY	SY	SY	SY	SY	SU	X	Z	X
mid	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	FLOODED	W	X	X
lower	FLOODED		Y	Y	Y	Y	SZ	Y	Y	Y	Y	Y	FLOODED	X	X	Y
Cashel G, upper	X		W	X	W	W	W	W	W	X	X	W	Y	X	X	W
mid	Y		Y	Y	Y	Z	Y	Z	Z	Y	Z	Z	W	W	W	X
lower	Y		XZ	XY	Y	Z	X	X	X	X	Y	X	Y	Y	Z	X
Cashel H, upper	W		X	W	U	ZU	ZU	ZU	ZY	Z	W	X	X	X	W	V
mid	ZU		Y	ZT	YU	X	Y	Y	YS	ZS	Z	YS	Z	Z	Z	Z
lower	FLOODED		YS	W	Y	X	X	X	FLOODED	FLOODED	W	W	X	X	Y	W
Cashel I, upper	Y		W	W	Y	X	X	X	X	X	X	X	X	X	W	W
mid	W		X	X	W	W	YU	W	W	YU	W	X	X	W	X	Y
lower	W		X	W	TU	ZS	W	Y	Y	V	Y	Y	W	Y	Y	YU

Table 5.13 Temporal and spatial sedimentological change at Cashel (Jan. 1994-April 1995). Letters denote sedimentological classification. see text for details.

BEACH SEDIMENT CLASSIFICATION MILARROCHY																
	1994												1995			
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A
Mil 1, upper	W		WT	X	XT	W	W	WT	W	W	W	W	W	W	W	W
mid	W		XT	W	W	U	V	W	W	W	XT	W	YT	ZT	W	W
lower	Z		ZT	U	VW	ZT	V	WT	VY	Y	WV	X	YT	XW	W	TX
Mil 2, upper	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
mid	X		X	X	UZT	UZT	UZT	W	X	W	X	W	X	X	X	X
lower	U		ZT	U	U	T	WT	ZT	YT	Y	UT	Y	U	W	W	TW
Mil 3, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	V		V	T	W	W	W	W	X	W	W	W	TZ	Y	W	T
lower	T		TZ	T	Y	SZ	YZ	W	WV	YW	TV	Z	U	Y	U	W
Mil 4, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
mid	Y		WT	W	Y	Y	X	Y	Y	X	Y	Y	X	Y	Y	X
lower	Y		ZT	U	Y	Z	Y	Y	Y	Y	Y	Y	Y	Y	Y	Z
Mil 5, upper	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	X	Y	W	W	W
mid	Z		Z	U	ZUS	Z	Y	Y	Y	Z	Y	Y	Y	Y	Y	Y
lower	Z		Z	Z	Z	Z	Z	Z	Z	Z	ZT	Z	Z	Z	Z	Z
Mil 6, upper	YS		W	X	Y	Y	Y	Z	Y	Y	Y	Y	Y	YS	S	YS
mid	Y		Y	Y	ZS	ZS	Z	Z	YS	ZS	Z	Y	Y	Y	Y	Z
lower	Z		Z	Y	ZT	ZT	T	TS	ZT	ZT	T	YT	Y	W	Z	Z

Table 5.14 Temporal and spatial sedimentological change at Milarrochy (Jan. 1994-April 1995). Letters denote sedimentological classification. see text for details.

edge samples show the greatest degree of variation as they are exposed to daily fluctuation in wave conditions. On the foreshore, imbrication of sediment on deposition has been noted.

At *Cashel* the temporal analysis of the surface sediments reveals that Types W, X and Y occur most frequently, and Type Z fairly frequently. Occasionally mixed types are found and are mostly Types ZU or Type YS, where the fines infill spaces between the coarser sediment particles.

At *Milarrochy* (Table 5.14) there is more sedimentological change, and at times the results show complex depositional patterns (e.g. downslope fining around beach ridges, Fig. 5.22). The upper beach is unstable in contrast to Cashel. The altitude of the *upper* beach is between 9.3 m and 10.7 m OD such that only high water levels affect this section of the beach. The most stable parts of the beach sedimentologically are the upper beach at Profile 2 (at 9.9 m OD and largely unaffected by fluvial sediments) and Profile 4 (at 9.08 m OD). The sediment at profile 4 is compacted by vehicle traffic. Profile 5 upper beach is also relatively stable with sediment types persisting for several months. The upper beach at profile 6 is rarely under water. The most significant reason for sediment variation is deposition from the slumping cliffs (type S) particularly after high winter rainfall.

The *mid* beach results show more complex patterns with the occurrence of several sediment types in one location, frequently occurring in 'sediment stripes' parallel to the waters' edge which display evidence of fining away from small ridge crests (Fig. 5.22). Such patterns reflect differing water levels and wave energies affecting sediment transport and deposition. The *lower* beach in the vicinity of profiles 5 and 6 shows the coarsest sediments (type Z) which appear to be less mobile with infills of different sediment grades. Type U sediment (fine gravels) is only found in the vicinity of the stream exits at profiles 2 and 5.

At Milarrochy, temporal sediment trends are more complex than at Cashel. Types Y, X , Z and W occurred most commonly, but mixed sediment types were also more frequent. This reflects a more mixed sedimentological composition than at Cashel with more fine particles (sands, silts clays) found at the surface. This is related to fluvial sediments directly affecting more of the beach than at Cashel because of the spatial distribution of streams (section 5.4.1.1). The sub-surface composition is also more mixed than at Cashel (section 5.5.2), such that supplies of finer sediments are available. Overall, Profile 6 exhibited the most variation in mixed sediment types because of the supply of fines from the receding cliff.

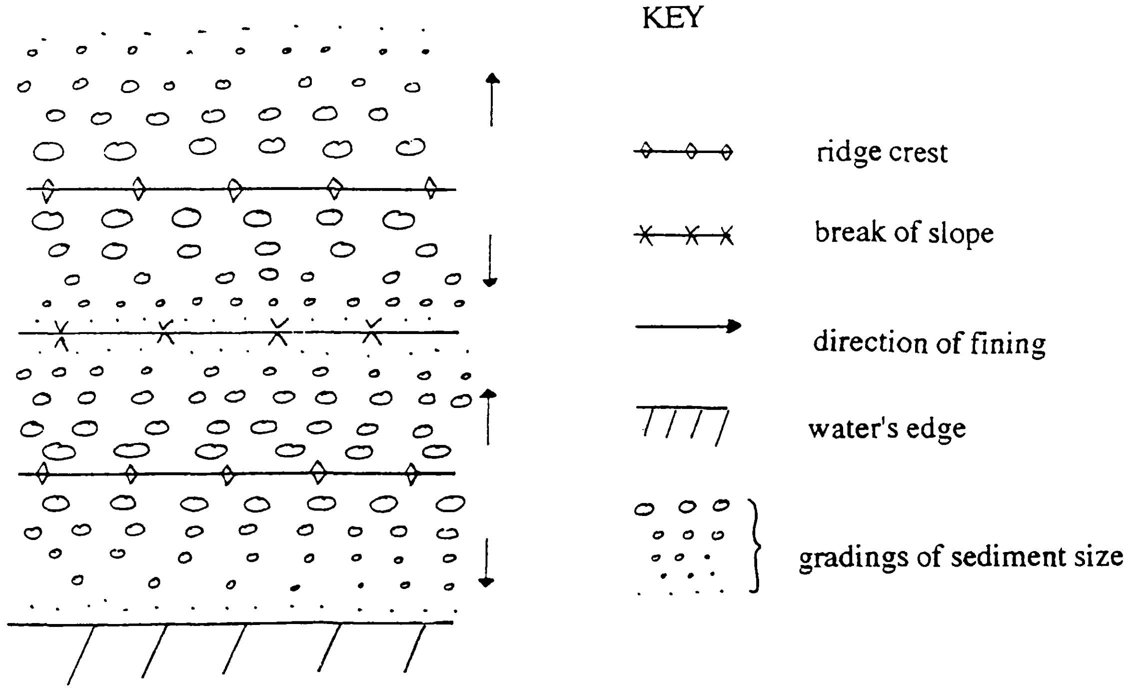


Fig. 5.22 Gravel fining around a suite of parallel beach ridges.

In summary, both beaches exhibit a high degree of monthly variation in sediment type. Mostly the sediment is in the gravel/cobble range with occasional occurrence of fines. This is in contrast to the nearshore beach as described in the previous chapter, where the gravel is abruptly succeeded by into fine sediments offshore. The higher altitude upper beach locations at Cashel remain largely unaffected by contemporary wave conditions. The sediment found here is of type Y. Thus altitude and position on the beach has been shown to be a significant control on beach sedimentologcial stability.

5.6.2 Controls on beach sedimentological change

The sedimentology (sections 5.4.2 and 5.4.3) shows that the upper beach generally exhibits different trends from the mid and lower beach. Beach elevation emerges as a clear control on sedimentological stability. The higher elevation sections of beach (e.g. Cashel profiles A-E1) show stability in sediment type, because they are less affected by wave activity, only being subject to wave action during periods of high water levels.

Sediment supply affects the sedimentological variability. Direct comparison at the monthly scale between variables such as volumes of sediment supply and sediment type (Tables 5.3-5.7, section 5.3.1) shows no clear relationships, but the sedimentological analysis reveals more complex relationships. Spatial and temporal complexity of sediment type particularly at Milarrochy is attributable to the range of sediment sizes available for entrainment and deposition. The sub-surface sedimentology (section 5.4.2) reveals potential sources of fine sediment within 0.01 m of ground level. The spatial distribution of streams and longer length of cliff means that sources of fine sediment are more readily available to all sections of Milarrochy beach. As sediments are reworked and distributed within the bays, this means that there is greater potential for a more complex depositional pattern.

Both beaches show an upper beach general trend of southwards sediment coarsening during 1994. The dominant wind/wave directions were westerly and north-easterly trends (section 4.3.3). No clear evidence linking wave direction with longshore sediment coarsening emerges from the monthly scale 1994 data (section 5.3.1.3), but the upper beach results may reflect longer term trends which are discussed in chapter 6. When the sedimentological results are compared with other variables such as wave heights, storm incidence, profile type, and sediment supply volumes (section 5.3.1.3), no clear controls on sedimentological pattern are discernable at the monthly scale.

Both beaches show cross-beach fining towards the sub-aerial upper beach at the headlands, which suggests that macro-scale beach planimetry (section 5.1) exerts controls on sediment deposition with the headlands providing more sheltered depositionary environments. Cross-beach coarsening (lower to upper) is in evidence elsewhere, in the more exposed sections of beach.

5.7 Sediment Budgets of Cashel and Milarrochy

Sediment budgets are a means of quantifying the various sources and sinks of sediment within the coastal system, as presented in Chapters 4 and 5. Fig. 5.23 shows the primary components of the beach sediment budget which are presented for Cashel and Milarrochy. Each component of the budgets is presented below, together with a summary of the underlying assumptions and uncertainties in determination. The morphological sediment budgets for the two beaches (aim 4) are presented at the end of this section.

Fig. 5.23 The Sediment Budget

Alongshore inputs →	Beach sediment store	→ Alongshore outputs
Fluvial sediment inputs →		→ Offshore sediment loss
Cliff sediment inputs →		→ Sediment extraction (human)
Shore platform inputs →		→ Rollover (shorewards sediment transfer)
Beach feeding (human) →		

5.7.1 Fluvial sediment input

The fluvial sediment input was calculated from records of maximum stage, flow reconstruction and sediment transport estimates of coarse sediment (> 2mm /-1ϕ), (section 5.4.1). At Cashel, the sediment estimates are used from the two incoming streams (1 and 2, Table 5.8), and at Milarrochy from the three incoming streams (3, 4 and 5, Table 5.8). The underlying assumptions are:

1. one peak flow at maximum recorded stage of 15 minutes duration per stream per month;
2. unlimited sediment supply for that 15 minutes peak flow (i.e. bedload transport is at capacity and is not supply limited);
3. the entire channel width at the gauging site is active;
4. peak stage from Jan-Apr 1995 can be used as a surrogate data set for missing Jan-Apr 1994 data; and

5. only coarse sediment (> 2 mm/<-1ϕ) is accounted for. Any fine material is assumed to be lost offshore and not part of the budget.

The total fluvial sediment delivery to Cashel beach from May 1994 to April 1995 was 1489 m^3. At Milarrochy, the total fluvial sediment delivery over the same period was 163m^3.

5.7.2 Cliff and shore platform sediment input

Cliff sediment input is calculated from field shore recession surveys (section 5.4.1.2) and the shore platform input at Cashel from profile surveys during 1994. Sediment delivery from these sources is quantified in section 5.4.1.2. The underlying assumption is that recession rates are uniform between survey points for both the cliff and the shore platform.

The sediment contribution from the cliffs at Cashel is 14.3 m^3 and 147.4 m^3 from the shore platform. Of the 14.3 m^3 of cliff sediment, 0.3m^3 is coarse sediment (included in the budget) the rest being fines (sands/silts/clays). This means the cliff and shore platform contribute 161.4 m^3 of fine sediment.

At Milarrochy the sediment contribution from the cliff is 77.2 m^3. At Milarrochy with approximately 10% of the cliff material being coarse sediment, the total contribution is 69.5 m^3 of fine and 7.2 m^3 of coarse sediment delivered to the beach sediment budget. The latter is included in the budget.

5.7.3 Beach feeding (human)

At Milarrochy, 200 tonnes or about 111 m^3 of coarse sediment were introduced and 20 tonnes or 11 m^3 of fine sediment (< 2mm) (stream 3) as described in section 5.4.1.3. Approximately 75 m^3 of mixed grades of sediment was also introduced adjacent to profile 5. The underlying assumptions for redistribution of this material are that

1. fine material is lost offshore; and
2. assessing the contribution of the Milarrochy mixed grades of sediment (by profile 5) to the budget is difficult, so it is to assume that half (37.5 m^3) was coarse sediment contributing to the budget.

5.7.4 Sediment extraction (human)

No sediment removal from the beaches is authorised, but sediment is removed unofficially from Cashel beach (between profiles I to E1) to provide a gravel base for caravans. This is estimated to be in the order of 10-15 m^3 (eg. 30 caravans x (gravel area of 7 x 3 x depth of 0.02 m = 0.42) = 12.6 m^3) in 1994.

5.7.5 Alongshore sediment supply

From the offshore and nearshore sediment sampling results and the wave refraction results (sections 4.3 and 4.5) the headlands were found to prevent alongshore sediment transport. Therefore no sediment is supplied to either Cashel or Milarrochy sediment budgets from alongshore sediment transport.

5.7.6 Alongshore sediment loss

Alongshore sediment loss to adjacent beaches is assumed to be negligible for the reasons cited in sections 4.4, 4.5, and 5.5.

5.7.7 Offshore sediment loss

The offshore/nearshore sediment sampling and wave results (sections 4.5 and 4.3) have shown fine sediment loss to the offshore zone, but coarse sediment remains within the sub-aerial or sub-aqueous beach. Thus for this budget, the offshore sediment loss figures for Cashel and Milarrochy are zero. The underlying assumption is:

1. as the profile surveys in the immediate vicinity of the cliffs (profile F at Cashel and profile 6 at Milarrochy) have shown that most fine sediment is lost offshore, fine material inputs are assumed to be lost offshore.

5.7.8 Volume of sediment in the beach store

Calculating the variation in volume of sediment stored within the beach store is difficult, and there is no completely reliable way of calculating this from the data collected. An estimate can be derived from the maximum and minimum sweep zones from the survey data for 1994 at each profile, extrapolated to the offshore closure depth (the nearshore limit of the coarse sediment). However, such a figure may considerably overestimate the volume of sediment on the beach. This is because maximum differences in sweep zones for each profile occur at different times, and may represent alongshore movement of the same sediment. Thus sediment is accounted for on several occasions. Whilst a beach store volume would be desirable, calculating one in this way may introduce errors since determining depth of scour, or beach activity is difficult. Whilst there are indications of this from the surveys, the tracer experiments and the sub-surface stratigraphic logs, there is no clear across beach depth of active beach. Using scour chains (e.g. Laronne and Duncan 1992) is one method, but these would have been impractical on the study beaches given human activity around the sites.

Spatial analysis of changes in beach morphology is helpful (sections 5.1.2; 5.2; 5.3) as it shows in detail zones of accretion and depletion. Using the field survey data the beach volumetric change between profiles is computed and this comprises the morphological sediment budget.

5.7.9 The sediment budget

This section compiles the overall morphological budget using results from chapters 4 and 5. This gives detail of gains and losses in beach sediment between profiles. Tables 5.13 and 5.14 below show the construction of the budgets at Cashel and Milarrochy. The tables show a breakdown of the volume change calculated between profiles from the survey results. These figures include any overall gain or loss calculated from inputs/outputs to the budget (e.g sediment from streams or cliffs).

Table 5.15 Cashel morphological sediment budget showing alongshore beach change in 1994

Profiles	*head-land-I*	*I-H*	*H-G*	*G-F*	*F-E*	*E-E1*	*E1-D*	*D-C*	*C-B*	*B-A*	*A-head-land*
Volume change between profiles	+1228	+1233	-187	-41	+167	+3040	-889	-1224	+437	-194	-1032

The Cashel total = + 4031 m^3 (sediment gain)

Table 5.16 Milarrochy morphological sediment budget showing alongshore beach change in 1994

Profiles	*headland-1*	*1-2*	*2-3*	*3-4*	*4-5*	*5-6*	*6-headland*
Volume change between profiles	+2753	-413.4	-1921	-2184	-2250	-5109	3774

The Milarrochy total = - 5351 m^3 (sediment loss)

Thus the results show that Cashel has a positive sediment budget, a small overall net gain and Milarrochy a negative budget, a relatively small overall net loss. The distribution of this is lost and gained from different areas alongshore.

From the sediment volumes of each budget component (section 5.7.1-5.7.7) the sediment accounted for in 1994 at *Cashel* (using the surrogate 1995 data) is + 1474 m ^{3} assuming that fines from cliff are lost offshore. At *Milarrochy* in 1994 this is +318.7 m^3 (using the surrogate 1995 data) assuming fines from cliff are lost offshore. Unaccounted for beach change is +2557

m^3 at Cashel and -5357 m^3 at Milarrochy. The differences between these estimates and the total sediment budgets constitute areas of uncertainty, in particular the fluvial sediment delivery estimates and landward 'rollover' of sediment. Uncertainty also exists in the morphological calculations of closure depth, although this may be zero. The uncertainty of these budgets is discussed in Chapter 6.

5.9 Chapter summary

This chapter has presented the results of the shore zone sub-system of the coastal zone and identified linkages within the coastal zone. The shore zone undergoes change at a range of scales. There is a long-term trend of beach recession, supported by historical and contemporary evidence, and recession rates in recent years are higher than longer term averages. The northern section of Cashel beach and all of Milarrochy are recessional, being particulaly exposed to westerly winds and waves. The southern section of Cashel beach is largely stable.

Beach morphology varies both spatially and temporally. Areas of beach protected by headland are less variable than those which are more exposed to prevailing waves. The most commonly occurring profile type on both beaches is straight. Areas of beach adjacent to incoming streams exhibit more volumetric change although their profile form may persist. Seasonal water level fluctuation is seen to exert a significant control on beach profile form and beach elevation is a key factor in beach stability. The times of greatest change in water level are the times of greatest instability highlighting the significance of bi-annual water level changes on beach variability. Attempts to link the process variables, at the meso-scale (monthly) were made but few clear relationships emerged, although exposed areas and those by the incoming streams showed higher variability.

Trends of annual volumetric change were calculated for both beaches, whilst there is a relatively large monthly variation, the total annual changes are small. The alongshore volumetric change results (for the sediment budget) show a clear beach response to the processes affecting it. Exposed areas and those adjacent to deltas show the greatest volumetric change. The deltas are significant areas of sediment storage within the beach system.

The streams feeding the two beaches were gauged and estimates of sediment delivery calculated. All five streams had fairly similar hydrological regimes with seasonally variable flows.

The beach sediments show some trends of cross-beach fining into the nearshore. Profiles near headlands exhibited different trends on the sub-aerial beach from more exposed sections of beach.

The sediments adjacent to the waters' edge were very mixed in composition. Upper beach sediments showed different trends from mid and lower beach sediments. The Cashel sediments contained less fine material than those at Milarrochy, which had more silts and clays in the sub-surface. Particle shapes are mostly discs and blades.

Sediment budgets for the coarse (> 2mm/ < -1ϕ) fractions at the two beaches were constructed to show a positive budget at Cashel and a negative budget at Milarrochy. Chapters 4 and 5 complete the results from the nearshore and shore investigations.

Chapter 6 DISCUSSION

6.0 Introduction

This chapter aims to interpret and synthesise the results described in chapters 4 and 5, with reference to existing literature in the broader geomorphological context of open coast processes and shore zone modification. Interpretation is aided by establishing a conceptual framework for the lake coastal zone (refer to Fig 2.1). Understanding lake response to various forms of physical forcing functions (Fig. 6.1) sets the overall perspective of this chapter within the broader context of temporal and spatial scales. At Loch Lomond, the most significant forcing functions are wind (waves) and river inflow/outflow (affecting water levels).

The chapter begins with a discussion of nearshore zone processes: Loch levels, waves and nearshore sediment transport. Discussion is then devoted to shore zone and whole coast processes: beach morphological variation, sedimentology, shore erosion and sediment budgets. The main findings and implications of the research in the context of broader scales and further research are discussed in the final sections.

6.1 Nearshore variability

6.1.1 Water levels

The water balance of the lake catchment is reflected in water level, and this is a significant factor affecting the lake coastal zone. The water level range during 1994 was 1.76 m, and the changing water levels produces high variability in the position and extent of the sub-aerial beach by controlling the extent and location of the surf zone. Water level provides a fundamental control over the spatial extent of wave activity. During high water levels the shore is directly affected by flooding and vegetation submergence and damage.

The effects of wind and waves are controlled by water level and together these determine relationships between nearshore and shore processes and forms. When the water level is high, there is an increased potential for waves to affect the upper beach, cliff and human structures. This gives rise to the most destructive conditions at the shore, since run-up distances may exceed the available upper beach length. Under these conditions higher elevation beaches such as at the southern section of Cashel beach are afforded greater protection. High elevation water levels affect beaches in different ways depending on beach elevation and characteristics.

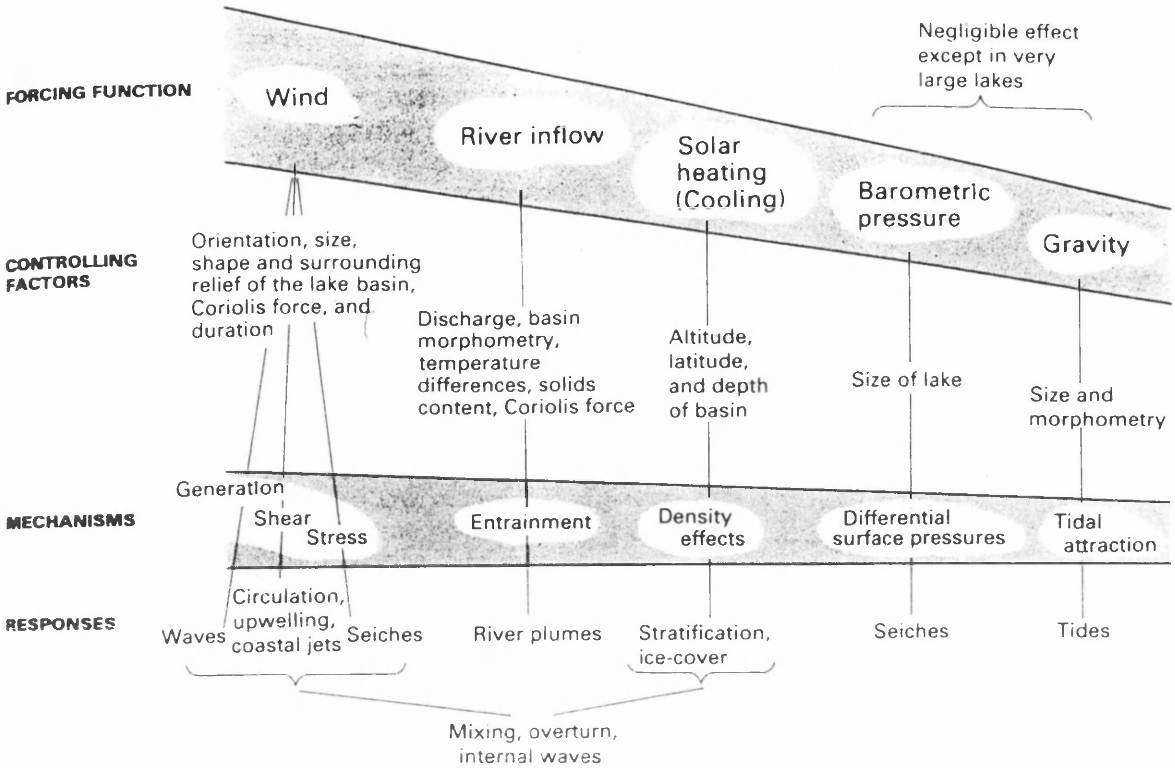


Fig. 6.1 Lake response to various forms of physical forcing functions (after Sly 1978; 1995). The wedge shape illustrates decreasing importance of particular controls.

During 1994 there were high winter water levels and low summer levels with a rapid fall in April/ May and a rapid rise in September/October (Fig. 4.5) a trend observed every year between 1992-1996. Incoming stream discharge reveals a similar seasonal pattern (Fig. 5.16) as do the long term Loch Lomond water level records (Fig. 6.2). In individual years rises and falls are rapid although average values (shown here) are smoother. The effects of this seasonal pattern are discussed further in relation to different variables throughout this chapter.

Ventura (1995) has demonstrated a mean 76 % increase in annual and winter precipitation for the whole Loch Lomond basin over 23 years (1970-1992) using moving means and polynomial curve fitting for annual and seasonal (half year) trends. These results suggest evidence of longer term change in weather patterns. Increased precipitation also explains the trend of increased water levels at Loch Lomond (Fig. 6.2). Longer term stream inflow records form the R. Endrick from 1969-1990 (Curran and Poodle 1995) show a 36% (± 11%) increase in flow rates ($p< 0.01$).

At Loch Lomond, increased water levels have been locally attributed to the building of a barrage in 1974 across the River Leven (the only outflow river) by the then Central Scotland Water Development Board (CCS 1979; Dickinson and Pender 1990, Curran and Poodle 1995). The effect is no greater than a mean increase of 0.1 m (Curran and Poodle 1995). Water levels are maintained artificially high if the water level falls below 7.925 m (as in the 1984 drought) and the barrage gates are elevated. The barrage gates are rarely in operation in the winter months, so outflow via the River Leven is 'natural'. Poodle (1979) described an increase of mean monthly levels between 1947-1970 and 1973-1978 of approximately 1 foot (0.3 m) attributed it directly to the Leven barrage. However, this period was affected by a rise in precipitation as noted above.

Evidence from 100 years of records from the Great Lakes of N. America and Canada suggest a 30-40 year cycle of levels (Carter 1988) added to which are non cyclic changes which are attributed to human activity within the catchments (e.g. deforestation, land use change, dam construction). Water level rise has been correlated with shore recession at Lake Michigan (Hands 1980, 1983). Slow water level rises are associated with landward movement of nearshore bars (and also at Loch Lomond, section 5.3) but no converse offshore movement occurs when water level falls (Hands 1980). Lake Michigan shore retreat data (1976-86) suggest that shore response lags several years behind water level stabilisation after a rapid rise in water levels (Hands 1979) i.e. a longer temporal scale is required to detect beach response. At Loch Lomond, longer term data sets, particularly of beach profiles, are needed to establish if such relationships exist.

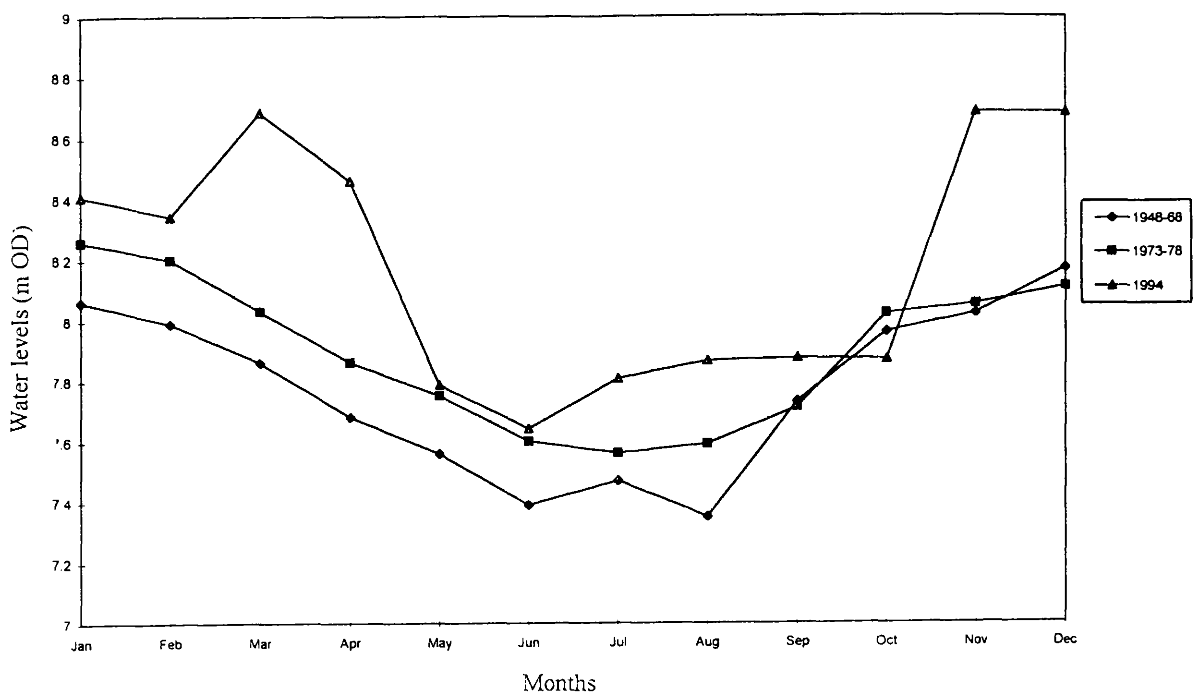


Fig. 6.2 Long term mean monthly water levels for Loch Lomond. (measured at Ross Priory by CPRB). Averages for 1948-68 and 1973-78 from Poodle (1979). Note the increase in mean levels between these two periods, particularly in the first eight months of the year.

Despite Hands' results, the influence of water level on erosion is far from clear. Davidson-Arnott (1979) argues that Great Lakes shore erosion rates are independent of water level fluctuation. His argument is that most shore erosion occurs where two particular types of shore exist and that these are related to local beach sediment budgets. Areas of shore with sediment inputs that increase the width of the beach (usually downdrift of a littoral cell) have a natural protection against cliff-toe erosion, as wave energy is dissipated by the wider beach. Where beaches are sediment-poor and narrow, cliff-toe protection is not provided as there is insufficient beach sediment to dissipate wave energy before it reaches the cliff. Over time, even at low water levels a deepening profile will lead to beach erosion, reduction in beach width and cliff-toe recession being re-established. His conclusion is that a stabilisation of lake levels would bring about an immediate but temporary halt in recession rates. Despite the lack of data, this argument is applicable to Loch Lomond where water level effects have been associated with beach elevation and sediment supply (section 5.3.1.3). The southern section of Cashel beach is relatively unaffected by fluctuating water levels as a high elevation, sediment-rich beach provides adequate wave energy dissipation. Milarrochy beach and the northern section of Cashel are much more severely affected by water level and wave activity at particular water levels because of their lower elevation. The findings also show how sediment supply and distribution are critical, independent of water levels (see sections 6.2 and 6.3.2).

There is evidence that water levels have fluctuated to a significantly greater degree during the Quaternary (section 2.5.3). Such evidence sets the present processes and change in a longer term context of environmental change. Stratigraphical and geomorphological evidence for the fluctuating water levels, and marine transgression and regression, suggests that water levels have been both higher and lower than at present.

Evidence for higher levels includes the morphology and stratigraphy of the field ridge at Cashel (section 5.4.4) which suggests a former beach berm. Assuming similar processes to contemporary processes the elevation suggests mean water levels 3 m or so higher than present day. Former lower levels are indicated by archaeological evidence. The southern headland at Cashel is the site of an Iron Age Fort, but much of the area is currently flooded. The earliest iron appears in Europe around 1100 BC (3100 BP). Iron Age forts were built in natural positions such as hilltops, promontories and ridges, including lake shores (Coles and Harding 1979). They were usually 250 m in diameter with smaller ones being about 100m. This suggests, even for a small fort, an areal extent much greater than the archaeological site exposed today, and this in turn suggests water levels 4-5 m lower than present. On the southern shore of the Loch (Gartocharn) is the flooded port of Aber which was a ferry port in 1816 (Macleod 1889) and still operational in 1840 (Thomas 1971). This also supports the idea of lower Loch levels in the past (perhaps 2 m).

Fig. 6.3 is a tentative relative sea level/Loch level curve constructed using estimates from published data and from the findings of this research to show long term water level change.

As described in Chapter 2 there is some variation in estimated altitudes from different boreholes, sediments and shoreline features. Such discrepancies are likely as water level (tidal) ranges at any point in time are unknown. Shoreline features (e.g. Clyde beds; shore platforms; beach gravels) are relatively good indicators of former water levels, despite wave energies for each time period being unknown.

Recent water level trends may be part of a cycle of rising and falling levels. This change is relatively small when set in the context of the Holocene during which water levels have been influenced by sea level change as well as lake level change. However while the gross morphology of the shore is related to long-term water level changes, at the scale of this research the range of water level change in 1994 is important as demonstrated by the high variability in the shore zone.

Isolating the full extent of water level influence at the annual scale is not possible. The complexity of water level, waves, and sediment transport interactions is evident and identifying the precise influence of each variable is difficult. The effect of water levels on beaches depends primarily on beach elevation, and therefore beaches of differing elevations respond differently to similar water levels (all other variables aside). The lag times for beach response to differing water levels would become clearer with long-term data sets of beach morphology to match those of water level. Mean water levels have increased significantly in the past 50 years and these increases, in conjunction with other variables, are modifying the shore zone. At a long temporal scale, present water level fluctuation is not unusual in magnitude and current changes may indicate a phase of higher levels or represent a relatively short-lived cyclic trend from which levels will fall again.

In summary, water level variation is significant as it determines the area and location of submerged beach. It determines the location of fluvial deposition on entering the lake and affects delta development. During periods of wave activity it determines the position of the surf zone, affects run-up and therefore exerts a control on potential sediment movement and beach morphodynamics. Water level variation is significant in setting a context within which other variables operate, and as these are discussed in the following sections of this chapter water level

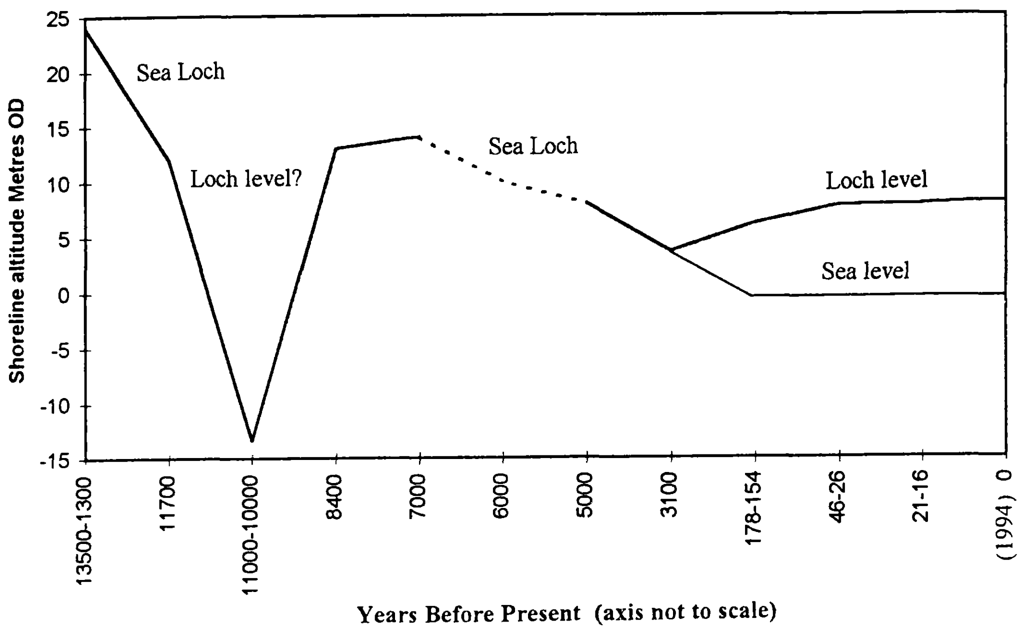


Fig. 6.3 Relative sea level/water level curve for Loch Lomond area showing long-term variable water levels.

A variety of Holocene shoreline estimates have been suggested in the area, this curve uses the more conservative estimates from sites closest to Loch Lomond and includes periods of marine incursion. Marine limits at deglaciation vary from e.g. +36 m OD (Brown 1980), + 34 m OD (Rose 1975), +31 m OD Robertson 1879) and + 25 (Sissons 1974). The dotted line denotes uncertainty over the age of raised shorelines at Ross priory, associated with the Flandrian marine transgression following low sea level at the time of the Loch Lomond stadial (Dickson *et al.* 1980; Jardine 1980; Rose 1980). Archaeological evidence allows water level reconstruction (e.g. Coles and Harding 1979; Macleod 1889; Thomas 1971). Recent water levels are from Poodle (1995) and the CPRB (pers com.). Refer to section 2.5 for further details.

will be further referred to.

6.1.2 Wave Climate

The wave results and analysis (section 4.3) constitute the only wave records derived from Loch Lomond and are one of very few sets of lake wave records in the UK. These results contain a high volume of consistent high quality data allowing confidence to be placed in these results. This is a result of the method of reliable wave recording, calibration and wave time-series checks before spectral analysis.

The relatively long term records obtained are unusual in a UK context and reveal a number of important patterns, particularly in identifying the nature of high frequency, short period, fetch limited waves. These have important geomorphological and lake coastal management implications. The mean significant wave height is relatively low (0.11 m), but the modal frequency is high (0.6-1.8 s) and calm conditions alternate with periods of considerable wave activity. The short period waves shown in Chapter 4 illustrate the distinctive wave climate. The impact of waves on the shore is governed by the water level. Low water levels mean that even when very high waves occur, as in August 1994, they have a limited affect on the upper beach (e.g. back berm and vegetation). Thus high amplitude waves at low water levels are of much less significance than somewhat smaller waves at high water levels, where the full force of the waves affects the upper beach. Where artificial landward limits to the beach are imposed (e.g. at Milarrochy by the road), these contribute to environmental degradation as the dynamic beach cannot naturally readjust to changing water levels and waves, and naturally re-form the back shore defences.

Significant wave heights which are small in international terms must viewed in the context of wave frequency, whereby higher total energy reaches the shore than is suggested by significant wave height alone. Thus the detail of zero-crossing period, crest frequency and wave heights from the analysis are particularly important. At the shore, the rapid succession of breaking waves means that wave backwash is frequently interrupted by incoming swash, limiting the depositional area. This results in some of the complicated sedimentation patterns described in Chapter 5, which will be discussed later in this chapter.

The 1994 results typify the dominance of westerly winds and waves, which affected the eastern shoreline. Under different prevailing conditions, beach modification at Cashel and Milarrochy would be likely to be less pronounced. Both wind velocities and directions vary rapidly over time and it would seem within the basin. Of particular interest is that persistent winds from the same direction, over the longer fetches, caused some of the largest waves to develop, even with velocities just below 10 m s^{-1} (measured at 5 m above water level, section 4.3.3: storminess). Short duration, high velocity winds, did not cause particularly large waves. Thus the size, shape and orientation of the lake (affecting fetch) exerts a control over the development of the wave climate coupled with the duration of wind from particular directions. The sampling was such that full details on wind-wave response times are not available. Field observations suggest that waves develop from a calm lake within ten minutes, and that storms can develop in less than an hour (although unless wind duration is long, these waves are not particularly large). It is clear that lake response times are very rapid in comparison with marine environments, as recognised by Sly (1994).

The wave energy spectrum provides a different way of describing the wave field, emphasising frequency. Spectra have been produced for each of the wave records in 1994 and have been combined to form a summary spectrum for the wave climate (Fig. 6.4). This shows the dominance of high frequency, relatively low energy waves with a low modal spectral density.

When the wave climate spectrum is placed in the broader context of the coastal literature (Fig. 6.5 the Loch Lomond data falls towards the extreme of the wave records. Composite spectra which have been derived from field measurement are published as generalised models (e.g. Bretschneider 1959; Hasselmann *et al.* 1973; Inoue 1967; CERC 1977; Pierson and Moskowitz 1964), to which the Loch Lomond results can be compared. The Loch Lomond spectra (highest recorded spectral densities of 0.15 m^2 s^{-1}) fall at the high frequency/low energy extremes of the Pierson and Moskowitz data and the JONSWAP (Hasselmann *et al.* 1973) spectra (Fig. 6.6). The JONSWAP spectra are important because they provide a close marine analogy to restricted fetch waves and show similar trends in spectral shape to the Loch Lomond spectra. Overall, the Loch Lomond spectra are consistent with other spectra, but close to the low energy extremes.

Most published spectra have been derived from tank experiments with sinusoidal waves, or from wave theory (e.g. reported in Chakrabati 1987). The amount of field data in the literature remains relatively small, although Goda (1979) shows wave height distributions from Nagoya Port, Japan with a modal wave height of just below 1 m. Sampling rates were between 3.5 and 6 Hz, frequencies not appropriate for the Loch Lomond wave climate. Another example is from a shingle beach at Elmer, East Sussex (Chadwick *et. al.* 1995), where 112 waves measured at a frequency of 4 Hz were analysed. The waves had a mean H_s of 1.75 m and H_{max} of 2.43 m, with

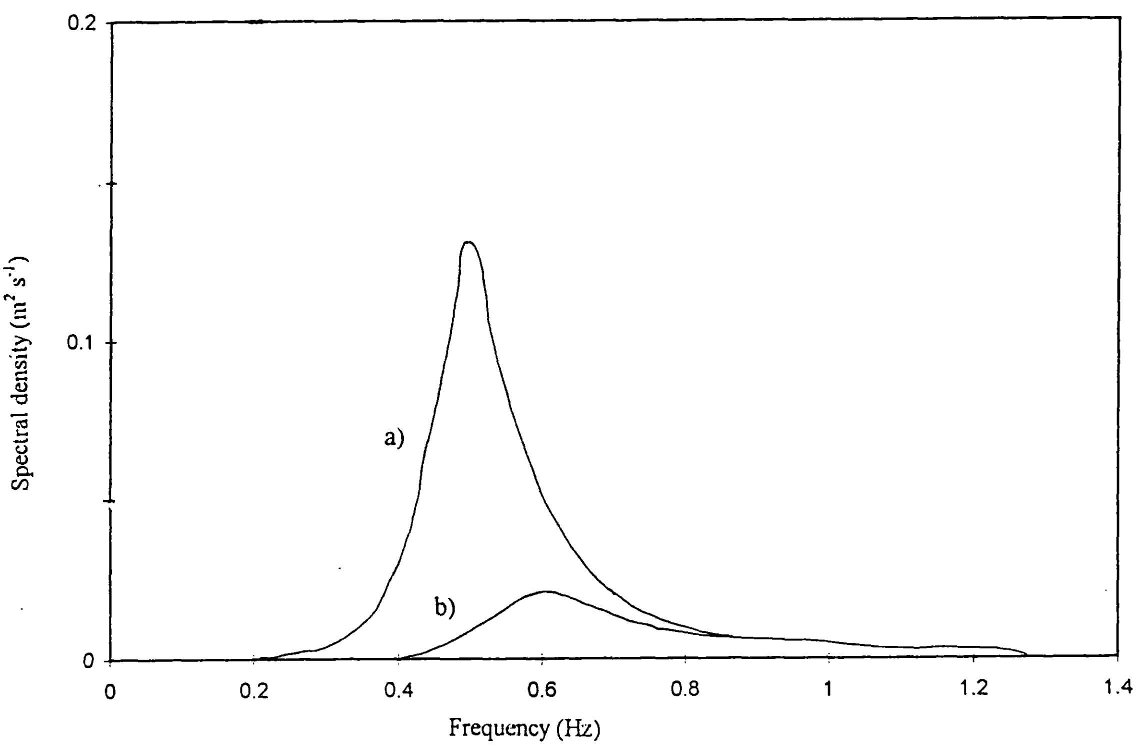


Fig. 6.4 Summary wave climate spectra for Loch Lomond (1994).
Spectrum a) shows the highest energy wave conditions; spectrum b) shows the modal wave conditions.

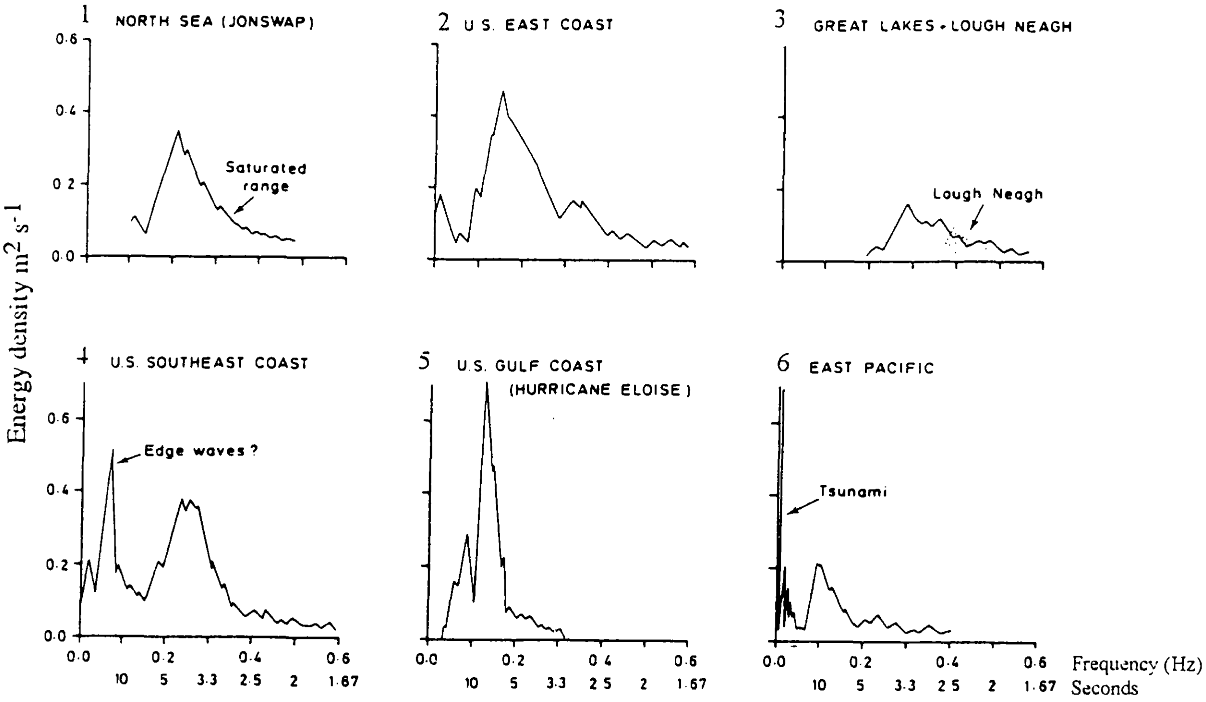


Fig. 6.5 A selection of wave spectra from different environments. 1 and 2 are sea wave spectra; 3 shows two lake spectra where development is fetch limited; 4 shows a double peaked spectrum, possibly indicating low-frequency edge or standing waves (at 20s periods) as well as higher frequency incident waves; 5 is a spectrum from hurricane waves; while 6 is from a tsunami record, showing the high concentration into a narrow low-frequency bandwidth; (after Carter 1988).

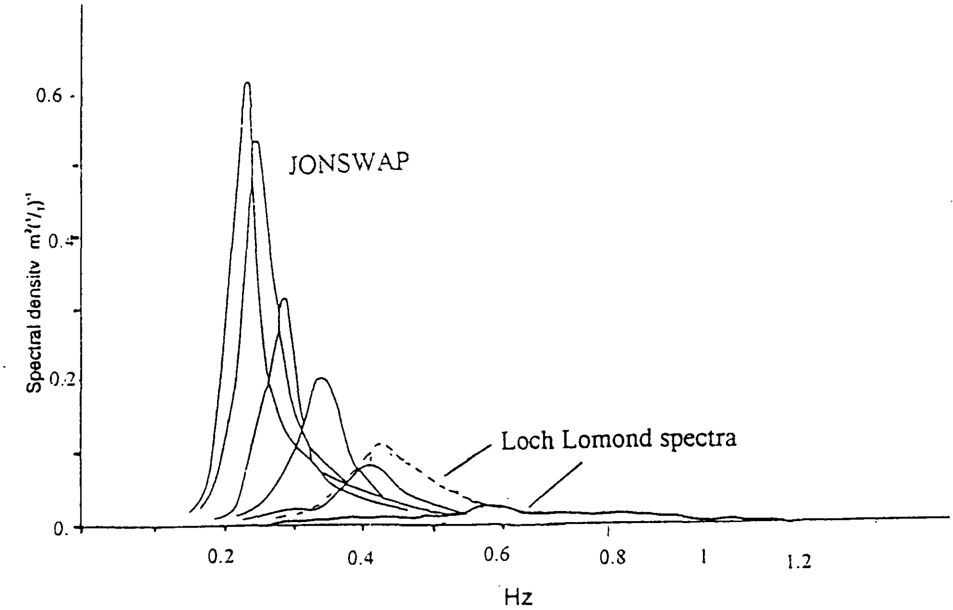


Fig. 6.6 Loch Lomond wave spectra (1994) and JONSWAP spectra (Hasselman *et. al.* 1973).
The series of JONSWAP spectra represent the progressive downward shift to lower frequencies (longer frequencies). The Loch Lomond spectrum (dashed line) shows the extremes of high energy conditions recorded during 1994. The lower energy Loch Lomond spectrum (solid line) summarises the modal conditions.

a peak frequency of 0.1 Hz, much greater than the Loch Lomond waves. Davidson-Arnott and Pollard (1980) describe indirectly derived (SMB technique, e.g. CERC 1984) lake wave records at Nottawasaga Bay, Lake Ontario, using remote wind records of above 6 hourly duration and 10 m s^{-1} . They estimated waves greater than 0.5 m to occur less than 16 % of the time over a 5 year period. Because L. Ontario is a much larger lake (surface area 1900 km^2) than Loch Lomond, its' wave records are closer to marine types. Figure 6.5 shows a selection of spectra from different environments, which serve to illustrate the marine/lake wave climate differences. Such comparisons highlight basin size (which affects fetch) as important in determining the wave characteristics, in particular trends for lower wave frequencies in bigger basins, whether lacustrine or marine. In summary the wave climate has low significant wave heights, and high frequency, and this has implications for wave refraction and sediment transport.

6.1.3 Wave- shore interaction and sediment transport

An important reason for wave recording on Loch Lomond was to define the nature of the wave climate and identify the way in which it affects beach variation and shore erosion. The recorded waves are deep-water waves which undergo modification as they approach the shore before breaking. The wave refraction calculations have highlighted how little refraction takes place because of the high frequency, low amplitude waves breaking on steep beaches. Trends of wave-sediment interaction have been shown both directly and indirectly in Chapters 4 and 5. In this section the results presented in Chapter 4 are used to establish the rates and extent of sediment transport in the nearshore and shore systems of the Loch Lomond beaches. Understanding the rates of sediment transport also helps to explain beach variability, and the relationships between nearshore and shore processes. Identification of boundaries of sediment circulation is essential in the definition and construction of a sediment budget. It is helpful to consider nearshore processes and therefore sediment transport in two groups (Hardisty 1995): 1) orthogonal processes which operate approximately normal to the shoreline; and 2) longshore processes which operate in a shore parallel direction.

Direct sediment transport measurements in the surf zone are difficult. Broadly speaking, shore normal processes (and sediment transport) are primarily responsible for beach profile change and longshore processes (and sediment transport) for beach plan change. In addition to these are small scale features such as longshore bars or spits which also provide indications of sediment transport processes in operation.

6.1.3.1 Indirect estimates of sediment transport

Rates and patterns of sediment transport can be estimated using: 1) wave refraction patterns and drift trends; 2) headland and cell boundaries; 3) beach morphology, and small scale processes and forms; and 4) fluvial influences. Both Cashel and Milarrochy are most affected by north-westerly, westerly and south-westerly winds and waves. Winds from other directions have little effect, because of protection afforded by either the headlands or the macro-scale shoreline plan (section 5.1). In 1994 the predominant winds and waves were westerly. Under these conditions, with limited refraction, waves are shore-normal thus shore-normal processes would be expected to dominate, changing the beach form (sections 4.3 and 6.2). Refraction-driven longshore sediment transport is limited (section 4.4) even though the calculated potential longshore sediment transport rates (P_L) are based on calibrations with sand of 1 mm (Komar 1977) and are thus overestimates.

However, where incident waves approach the shore obliquely, longshore processes dominate and longshore drift systems can develop. Changes in beach volumes demonstrate evidence of longshore sediment transport, with adjacent profiles gaining and losing sediment in successive surveys, described in section 5.3. Under some conditions, local longshore drift systems operate. For example, on the southern section of Cashel beach, a S-N sediment transport drift occurs under south-westerly waves and under north-westerly winds, a longshore drift system from N to S operates. The wave refraction results also highlight, sections of beach which are likely to experience limited longshore sediment transport. At Cashel, the main sediment supply from Cashel Burn, tends to accumulate in a delta as it is sheltered from long-fetch northerly winds by the shore orientation (Fig 4.1). The delta is more exposed to south-westerly winds and sediment volumetric changes suggest sediment transport northwards towards profile I (N-NW).

Coarse sediment was not found offshore from the headlands which suggests that sediment transport is limited to within bays, and does not pass headlands from bay to bay. Both the wave refraction and offshore sediment sorting point towards cells of sediment transport determined by the macro-morphology of bays and headlands. The headlands therefore provide barriers to alongshore sediment transport and form 'fixed' rather than 'free' cell boundaries (Lowry and Carter 1982). As coarse sediment remains within the individual bays, it is reworked and redistributed when transported by waves and currents. It follows that the only sediment sources are terrestrial and derived from rivers input and erosion, of cliffs and shore platform (section 5.4 and 6.2.2).

A clear nearshore limit of the coarse sediments indicates a relatively limited extent of orthogonal sediment transport, but it also suggests that there is no onshore input of coarse sediment. On a higher energy shore, typical of most marine environments, coarse sediments would extend further offshore, and the margin between coarse and fine sediments would be less clear (this is further discussed in section 6.2.1.1). At Loch Lomond there is a clearly defined limit to the occurrence of coarse (>2 mm/<-1 ϕ) sediment fractions (sections 4.5; 4.6). This suggests there is no significant transport of sediments coarser than 2 mm/-1ϕ and that there is a recognisable closure depth (sections 4.5 and 6.2.1.1). Thus the sedimentology suggests that the high energy hydraulic regime with the capacity to transport coarse sediment fractions is limited to the nearshore. Evidence of prevalent shore-normal processes is suggested by the cross-beach fining from beach to the offshore zone. The limited wave refraction results also highlight these shore-normal processes.

The beach morphology and beach volumetric change are fully discussed in sections 6.2.1. However, whilst the findings reported in section 5.3 show variable beach morphology, they also indicate indirectly that, whilst sediment transport occurs, it is restricted. Some alongshore and cross-beach movement at both beaches is suggested by the results.

The occurrence of several small scale beach forms indicate longshore sediment transport. Some of the most significant and dominant transport patterns occur close to stream mouths where deltas and other small scale forms develop. Small scale spits at the stream mouths indicate the dominance of fluvial hydraulic energy under relatively calm lake conditions (section 5.3.3). The hydraulic importance of river inflow into lakes has been recognised by Hakanson and Jansson (1983). Sediment is transported to deltas which occur in the nearshore zone and alongshore by fluvial processes. Transport distances of up to 70 m (over 3 days) have been observed at the field sites (sections 4.5.2.2, 4.5.2.3, 5.3.3).

In spite of such local fluvial influences, the overall finding from indirect sources is that both orthogonal and longshore sediment transport is relatively limited on these beaches. This is demonstrated by the wave refraction based sediment transport calculations, the nearshore limit to coarse sediment, suggesting the on/off transfer is limited to the coarse beach; the absence of around headland transport, suggesting discrete cells and beach morphology.

6.1.3.2 Direct sediment transport

Sediment transport was also measured directly by tracer pebbles (section 4.5.2) which show bi-directional longshore movement of sediment in response to wave conditions. The tracer experiment results should not be given undue importance because the conditions were calm and therefore sediment transport will be under represented. At Profile D, Cashel, for example, sediment grades from -2 to -4 ϕ were transported up to 4 m distances alongshore, under 0.02-0.03 m waves over 48 hours. However, progress was hampered by changes in shore orientation or burial. Where there is oblique wave breaking, individual tracers were observed to move up to 70 m alongshore. Overall the tracers showed a general trend of on-shore and alongshore movement.

Establishing the relationship between individual particle movement and large scale beach behaviour is more complicated and has been the source of much debate in the literature, (e.g Kidson and Carr 1962; Phillips 1963; Yasso 1965; Caldwell 1981). Caldwell (1981) is critical of tracer techniques and presents a comprehensive analysis of errors from a marine gravel beach in South Wales. Although for statistical reasons the tracers often fail to behave as the host population, at worst they give indications of sediment transport directions. The advantage of this technique on relatively low energy lake beaches is that tracers are not lost for some time, and most buried tracers were found. There is very little published information on lake sediment transport rates, so indications given by tracers along with the more indirect evidence is helpful.

Sediment entrainment and transport are affected by armouring, where coarse surface sediment provides a relatively immobile armoured surface layer for extended periods of time. Parker and Sutherland (1990) describe mobile and static armour layers of bedload in fluvial environments. Whilst there is no precedent for lake beach armouring, the vertical image results suggest sedimentary stability because of static armour in some areas of beach, giving a more stable section of beach. As most theoretical beach sediment transport equations are derived from experiments with sand, there are problems with these: 1) the theory needs to be developed for gravel environments and 2) armouring effects need to be considered.

Field sediment transport rates are often estimated from deficits in sediment budgets, from surveyed rates of accretion or erosion (e.g. Johnson 1956, Carr 1962) or from numerical modelling (e.g.Vincent 1979; Nummedal *et al.* 1984). All of these methods are subject to unknown errors, and are affected by the temporal period of measurement or the model assumptions. Some examples from the literature, are given here for comparison with the very low transport distances found at Loch Lomond (e.g. 3.4 m day^{-1}). Phillips (1963) found the mean transport rates at Spurn Head, UK. for particles less than 0.05 m range from 7.19- 38.77 m day^{-1} under SW winds and waves of less than 0.31 m. Under easterly winds distances of 6.31 to 16.76 m were recorded. Kidson *et. al.* (1958) describe radioactive shingle tracing at Orfordness. Distances up to 2064 m were recorded over 9 days, with northerly winds up to 20 knots. One of their conclusions was that large material moved very little under high wave conditions. Under lower energy conditions in a small lake, coarser sediment may be expected to move very little even under the highest energy wave conditions.

Apart from the early tracer studies, rates for gravel beach transport are rarely reported. It seems that for gravel beaches, and particularly these lake beaches, coarse sediment transport is restricted to the surf zone. In summary, the sediment transport conclusions are tentative, the other variables measured support there being a low sediment transport rate, limited bi-directional alongshore sediment movement with variable winds and waves, circulation cells controlled by macro-morphology, strong influences of stream hydraulic energy, sediment supply and predominantly shore normal transport processes.

6.2 Shore Zone Variability

This research set out to investigate coastal zone variation via a number of routes described in section 1.3. In the following sections beach morphological change, sedimentology, relationships between nearshore and shore processes and forms, and sediment budgets are considered.

6.2.1 Beach morphological change

Sensitivity to changes in process conditions (waves, currents and sediment supply) affect beach plan and beach profile. One of the reasons for measuring beach profiles was to establish some control on the figures for an annual sediment budget. Profile monitoring (monthly scale) also establishes the degree of shore variability, volumes of sediment moved, timescales of change and morpho-sedimentary responses to particular wave conditions. Quantification of beach variability is not easy because of the spatially varying nature of the coastal environment and difficulties in delimiting the interacting sub-systems. These are crucial in the process of defining the system boundaries and sediment flux.

6.2.1.1 Profile closure/closure depths

In order to calculate a sediment budget, closure depths were defined sedimentologically (section 4.5 and 5.3.1.2). Elsewhere in the literature closure depths for marine gravel beaches are variable: they are frequently taken to be at between 10-11 m depth from the lowest tides (e.g. Hanson and Kraus 1989), although other examples have included 6 m Comber 1994; Gemmell *et al.* 1996), or they are ignored altogether. At Loch Lomond the 10-11 m figure would be unsuitable as it extends beyond the extent of coarse sediment and offshore troughs of both beaches, so a sedimentologically defined closure depth (2.5-3.5 m) was used. This was the limit of the coarse sediment in the nearshore (section 4.5.1). This assumes that all the gravel encountered is mobile under some water level/wave conditions in the present process regime.

Three main approaches to profile analysis can be used. The first is to use only surveyed profile data which does not extend far into the Loch. This means that the profiles measured are of different lengths, usually longer in the summer, making temporal comparisons difficult. Secondly only the lengths of profiles repeatedly surveyed, are compared. This means that the shortest profile measured under highest water levels determines the profile length for comparison. This technique was rejected as much survey data is ignored. Alternatively, as adopted in this study, an offshore limit to the beach can be fixed by defining a closure depth (Fig. 6.7). This means that some profile change is assumed by extending the surveying data to the closure depth. This makes temporal and spatial comparisons much easier as profiles of equal length are compared with each other giving a more accurate analysis of profile change as sediment is not 'lost' because a surveyed profile was 'short' due to high water conditions. Errors can arise where the furthest offshore survey point in any profile is high in elevation, representing a ridge, but falls steeply in the unmeasured area beyond the survey point. Conversely, a small area of scour at the offshore limit can be magnified to suggest a highly erosional profile. Using the closure depth technique, extrapolating the actual survey data to the closure depth can lead to assumptions of large areas of sediment accumulation or large areas of erosion. Precise quantification of the error is not possible but a high degree of confidence can be placed in these results because of the relatively low energy wave climate. As the Loch Lomond beaches are steep with significant foreshore slope, error introduced by limited offshore profile surveys is likely to be small, as insufficient wave energy is available to entrain and transport gravel very far as the wave base is low.

6.2.1.2 Macro-scale geomorphology

The results herein suggest that macro- scale controls are significant in the behaviour of these lake gravel beaches. Evidence for this from this research and the available literature is discussed below noting the possible influence of the temporal duration of this study. Regional and local geology (section 5.1) controls the macro-scale geomorphology which is significant in determining both beach form (embayed beaches) and sediments (derived from parent rock). The shoreline

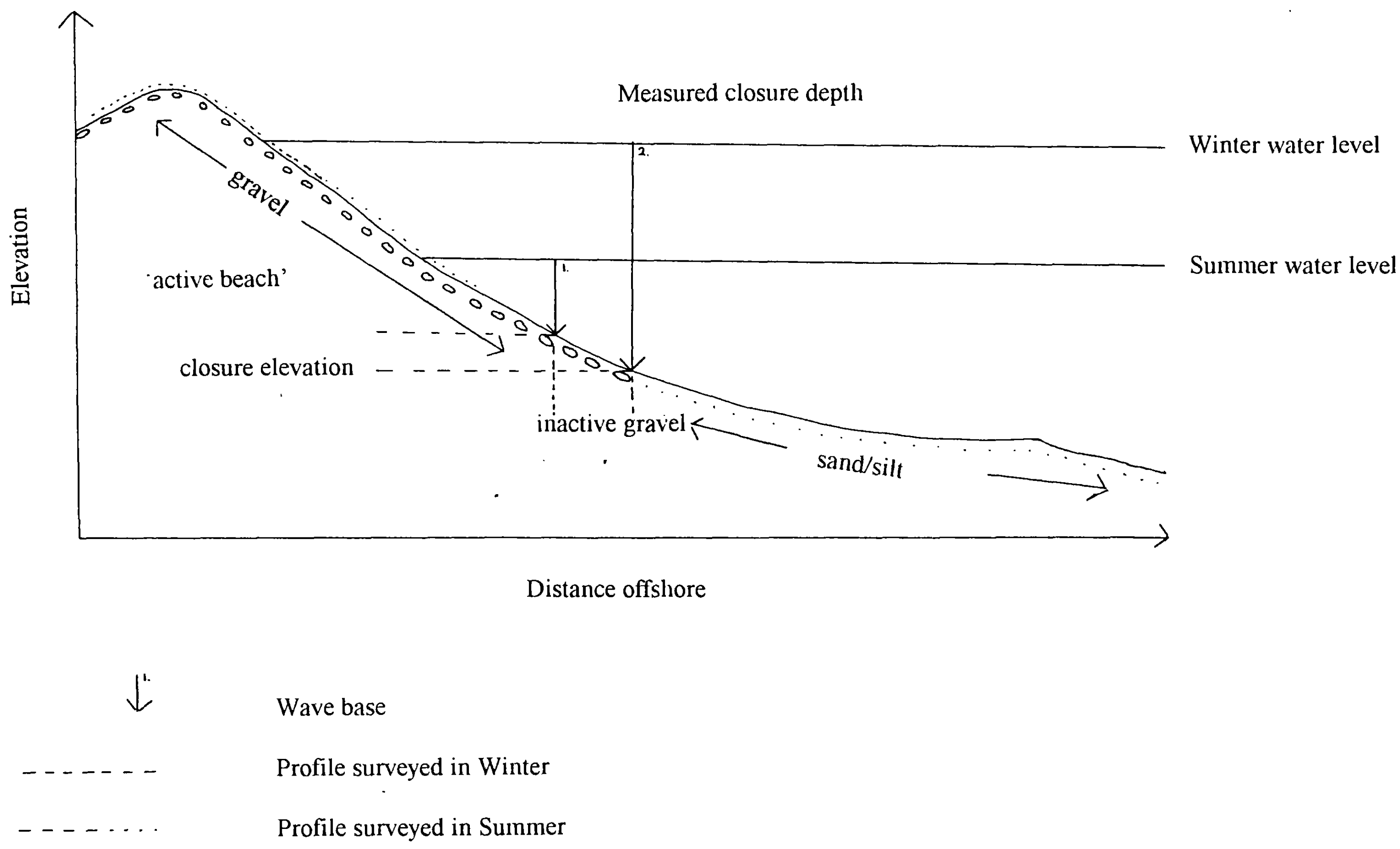


Fig. 6.7 Idealised lake beach profile showing closure elevation (depth), active and inactive beach

configuration develops in response to macro-geomorphological controls, water energy and sediment supply (Tanner 1958). Macro-scale controls on marine coarse clastic beaches have been identified by Forbes *et. al.* (1995), from Canadian and Irish examples to include sea-level change, wave climate, and sediment supply.

Despite the ongoing recession found at Cashel and Milarrochy, overall beach plan form at Cashel and Milarrochy has remained fairly constant. This can be explained by relatively low energy waves, incident wave shoaling, limited refraction, geology and fluvial sediment inputs. Of these, it is likely the local geology is most important in that it limits the scope of significant change in plan form. Spatially there is considerable variation along the length of each beach and between adjacent beaches relating to exposure to waves, altitude of the beach (water levels) and sediment availability (section 5.1 and 5.4). Adjacent sections of beach, and adjacent beaches may behave differently under similar process conditions, depending on the antecedent states of the beach.

Although water level changes temporarily affect plan form by flooding, energy in the lake beach system is insufficient to significantly change the macro-scale morphology at the scale of this study. Investigation over a longer time-scale (10^1 -10^2 years) may reveal macro-scale changes which are geologically rapid, but with low occurrence frequency. Beach plan has a much longer developmental cycle than beach profile development so any changes are more difficult to detect. Wave climate and water level variation may occur at various scales, but as long as critical thresholds in the system are not exceeded, beach plan remains constant over time.

6.2.1.3 Sediment flux

The sedimentologically defined closure depths used in this study may be relict, from when mean water levels were lower than present levels. Presently, only in coincident conditions of very low water levels and large waves would these sediments be mobilised. If the closure depths are relict this has little effect on the results (other than the interpolation problem mentioned above, which is inherent in the method wherever the closure depth is fixed). The results (long and short term) have shown a trend of landward movement of beach sediment and generally higher water levels (section 5.2 and 5.3). This suggests that the gravel found toward the offshore limit of the beach is relatively immobile, as it is too deep to be entrained under present water levels. Thus the active beach comprises the volume of sediment found onshore from this point which is affected by wave action under present Loch level ranges. At the temporal meso-scale lake water levels determine variability. The horizontal range of beach sediment mobility is determined by the vertical range of water levels over which wave action takes place. Loch level appears to be the significant underlying determinant of whether sediment is able to be entrained. The morphological response of the beach to wave energy therefore depends on not only wave heights, but the water level at which waves break. The beaches exhibit significant morphological variation at times of seasonal rapidly changing loch levels, although there is still relatively little net sediment movement.

Although month to month sediment flux is significant throughout the year as shown by the beach volume changes, the most significant factor in changing beach form or profile is the period of rapidly changing period of water levels which occurs in spring and autumn. This is illustrated by the results in section 5.3 showing the monthly variation of erosion and deposition. The stability of any profile (in terms of volume change) depends on local sediment availability. Forbes *et.al.* (1995) suggest that for coarse clastic barriers the viability of sediment pathways, in terms of sediment supply and mobilisation, affects stability. Beach volumetric change depends on the amount of sediment available. At Loch Lomond, since gravel at depth remains relatively inactive (under contemporary conditions), high water levels probably serve to reduce the availability of beach gravel for redistribution. Thus energy is available for erosion and this affects the only other available source, the cliffs, hence producing shore recession. Coarse sediment is not lost from the shore/nearshore system, but remains within the sub-aqueous beach. It is not part of the dynamic sediment system and lies unaffected at the lower beach whenever water levels are relatively high. Water levels therefore act as a further temporal control on sediment supply. Thus the shore erosion, problem identified in Chapters 1 and 2 is primarily a sediment distribution problem rather than a sediment supply shortage problem (see section 6.3.). This helps explain the paradoxical situation of a positive net sediment budget and ongoing erosion at Cashel.

Sediment distribution and supply are particularly important in this lake environment. The Bruun Rule (Bruun 1962) and its various modifications assume an equilibrium profile which is maintained with an assumed optimum depth of water in the nearshore zone. As water level rises, sediment is deposited on the sea bed to maintain equilibrium water depth. The source of this sediment is the sub-aerial beach. The beach retreats to maintain equilibrium. An equal volume of sediment constitutes the active beach. It is suggested that at Loch Lomond, as landward movement of sediment occurs with a general increase in Loch levels, insufficient wave energy is available to transport the available sediment landwards, so the volume of active beach is reduced and this consequently provides less coastal protection. There is a large sediment store which remains inactive because of the rapid increase in water level and a of the low energy wave regime unable to entrain and move onshore a sufficiently large volume of sediment. Shore retreat rates and patterns are also related to mean profile slope and to the nature of the beach sediments (so the situation is more complex than the Bruun Rule suggests). Even so, the key point at Loch Lomond is that the beach cannot keep up with the *rate* of water level change, given wave energy and sediment supply conditions. Overall in lakes of this size waves are less important in shore zone modification than they would be in a higher energy lake or marine shore environment. Water levels assume a more significant role in controlling sediment availability and therefore morphological response.

6.2.1.4 Beach form variability

There is considerable alongshore variation in beach behaviour. Changes at individual profiles include transitions between morphological states, reflecting process conditions. All profiles are subject to changes produced by erosion and deposition which can cause significant morphological variation. Ingle (1966) identifies three causes of sediment movement inside the break point on sand beaches: 1) the force of waves which move sediment on or offshore; 2) longshore currents which move sediment alongshore; and 3) an increase in beach slope which causes an increase in the effect of gravity on sediment transport. In the coastal literature, storm waves are suggested to bring about pronounced and persistent changes (e.g. Davis 1980; Fox and Davies 1973). In areas subject to frequent storms, large waves tend to destroy or limit of extent of the berm. Eroded material is frequently shifted offshore, further down the profile, where it may contribute to nearshore bar development. During periods of low energy waves, sediment moves shorewards, thus rebuilding the upper profile and sub-aerial beach. Typically storm frequency is a seasonal phenomenon, characterised by what Shepard (1950) calls a summer profile (no bars, wide berm) and a winter profile (no berm and a series of longshore bars). Where seasonal wave climates are distinctive (i.e. winter storm and summer calm), such a generalised description may be appropriate. In the UK however, storms can occur at any time of year giving changing storm and swell profiles. At Loch Lomond the complexity of the synoptic weather patterns, local topographic influences and storminess contribute to the complexity of beach profile states shown in section 5.3.1.

In this study, detailed survey results for one year were presented along with supporting evidence from four years. Particular profiles show consistent types (section 5.3) and in addition seasonal patterns were observed. Between May and September profiles tend to be concave and simpler in form with limited variation. This usually coincides with periods of lower water levels and reduced wave activity. Winter profiles (October-April) tend to exhibit gravel steps, ridges and runnels and at times more convex profiles indicative of deposition on the upper profile. Beach forms are significantly more pronounced during the winter months of increased wave activity, higher water levels and increased storminess. Events such as the storms of December and January 1992/93 cause considerable morphological adjustments on both beaches; for example, large back berms developed at Milarrochy profiles 1, 2 and 3 and at Cashel, profiles I, G, and E. These represent episodic changes which have significant prolonged effects.

Establishing the relative influence of individual variables in beach morphological modification is complicated by correlation between the variables concerned. Under different conditions, different variables exert the main influences on beach adjustment. The influence of water levels have been described earlier (6.1 and this section). The influence of waves on beach morphodynamics depends on fetch, wind duration and velocity, and still water level. Although relatively low energy wave conditions have considerably less influence on beach morphology than higher energy conditions, no clear wave-beach process responses are evident at the meso-scale. It is suggested that sediment supply is significant because the volume of sediment actually mobilised during an event depends on availability as can be seen from the profile results (section 5.3 e.g. Fig.5.12a-i and Tables 5.3-5.7). Carter and Orford (1984) and Forbes *et.al.* (1995) recognise this on marine coarse clastic beaches. Furthermore, the longer term evolution of the beaches is likely to depend on longer term sediment supply history (the macro-scale influence). This is examined further in section 6.3.1.

There appear to be longer term controls over beach morpho-sedimentary conditions, suggested by re-occurring profile types at individual profiles (section 5.3) and sedimentary types (section 5.5). Beach behaviour under differing wave conditions have usually been approached in a deterministic way (e.g. King 1972). However, some studies have identified time lags in event response (e.g. Carter 1975) and the stochastic nature of beach behaviour (e.g. Sonu and Young 1971; Mason and Hansom 1989). This approach describes the evolution of real beach states using first order Markov chains, i.e. that beach behaviour could be described by the transition matrices related to beach state at a single previous time. The Loch Lomond results suggest stochastic behaviour in that beach profile types are strongly affected by preceding beach profile types. The profile classification shows that successive profiles are developments of previous profiles (section 5.3.1). Such stochastic behaviour is complicated by different lags at low, high and meso-energy conditions related to water level and wave activity.

6.2.2 Beach sedimentology

The beach (sub-aqueous and sub-aerial) sedimentology (presented in sections 4.5 and 5.4) aimed to complement morphological data in determining the nature of shore zone variability and identifying relationships between nearshore processes and forms (section 1.3). The sub-aerial beach results in Chapter 5 showed both alongshore and cross-beach sedimentological patterns on both beaches. Analysis of samples taken from the radio echo-sounding profile extensions into the offshore zone showed clear non-linear trends of shore normal fining. The distinction between sub-aerial and sub-aqueous beach is a function of water level at any point in time, but clearly influences the location of the surf zone and data collection as explained in chapter 3.

Whilst sedimentological analysis showed complex patterns in alongshore sediment size, trends such as the median grain size coarsening southwards at Milarrochy were observed (section 5.4) suggesting a directional drift (Komar 1987). However, most of the longshore results suggest multi-directional sediment transport and redistribution within the bays.

Cross-beach sediment trends observed at both beaches were observed showing the importance of shore-normal processes. Such trends occurred at several scales. At the bay scale, the gravel beach showed evidence of down-beach fining (section 5.3) except at the headland profiles (Cashel: A and Milarrochy 1 and 6), where fining was observed up-beach (possibly indicating lower energy transport). The down-beach fining persists into the offshore zone, apart from the very mixed swash zone in the lower beach (Figs. 4.26 and 4.27). The gravel beach trends are predominantly wave dominated, whereas the continued fining beyond the abrupt change at the closure depths is dominated by below wave-base currents. These sediments also show continued fining increasing with depth. Several authors have identified such trends (e.g. Ingle 1966; Jago and Barusseau 1981; Shipp 1984; Horn 1992). Where swash/backwash processes dominate, the observed sediment size variation depends on the velocity changes in the backwash which are affected by percolation which depends on beach composition (Miller and Zeigler 1958, 1964; Swift *et. al.* 1971; Horn 1992). At Loch Lomond, the complexity of sediment sizes and sorting in the surf zone is related to variation in water levels which shifts the area of wave activity, the high frequency of waves, with incoming waves interacting with backwash, and the mixed sediment composition which gives rise to variable backwash velocities and complicated sediment transport/deposition patterns.

There are also temporal changes between sediment types at any given site. Four types of sediment which occur most frequently on both beaches (Types W, X, Y, Z; section 5.4) have been identified. At Cashel it is unusual for there to be mixed surface sediment types at any one sample, although this does occur. At Milarrochy, mixed sediment types occur much more frequently, particularly at profile 6 where there is a constant supply of fine material from the cliff into the coarse beach material. This may be related to the close proximity of streams to all the profiles at Milarrochy so that a more mixed supply of sediment is available for transport. The bulk particle size analysis also showed more variability at the stream mouths.

Different areas within the bays (represented by the different profiles) exhibit different characteristics. This variability depends on sediment supply, elevation and exposure to waves. The internal variability at profiles can obscure general relationships with the variables acting on the beach. The sediments at each profile are variable partly as a result of background controls (geology, exposure, sediment supply), and partly because of the reworking of sediment within the bays. Unlike an exposed, rectilinear beach, the headland-flanked beaches at Loch Lomond have important controls which are likely to cause variation in sedimentological patterns.

One of the main points to emerge from the results is the importance for the beaches of macro-scale controls of geology in the headlands, and beach elevation (which is closely related to water level). The sediments show a nearshore limit to the coarse sediment fraction (> 2mm/ < 1ϕ), and suggests that around headland sediment transport is negligible and thus that coarse sediment transport is within rather than between bays (section 4.5). Thus headlands act as barriers to sediment transport, which restrict both supply and loss. Their presence may restrict the development of larger scale (e.g. lake length) alongshore trends of sediment characteristics. The macro-scale geological control of beach plan (section 5.1) means that exposure to waves varies between different parts of the beach and thus explains different sedimentological trends (section 5.4).

Beach elevation is an important control on sedimentology in that the sediments show different upper beach trends from those on the mid and lower beaches where sediment is constantly being reworked by the prevailing waves. The increased variability at lower elevations is reflected in the sediments. The higher elevation sections of beach are distinctive in that the sedimentological patterns are much clearer. Higher elevation areas of beach are less frequently affected by water level and wave action, but when they are it tends to be on occasions of winter storms, therefore producing significant changes.

Clear trends emerged from the down-beach to offshore sediment sampling (section 4.5). These results show a mixed range of sediment sizes and sorting in the surf zone (a variable zone because of water level fluctuation) mostly within the cobble and gravel fractions (-6 to -2 ϕ). Beyond this there is a clear grading of gravel sediment size down-beach to the relatively abrupt nearshore limit, beyond which the finer fractions of silts and clays (>6 ϕ) grade offshore (section 4.5.1). These results have been used to delimit the beach, and identify a limit to coarse sediment transport, which was used as the closure depth. This shore normal sorting of sediment is significant, and suggests that water level variation (section 6.1) exerts an overall control on the effects of wave activity up and down beach depending on beach elevation. The beach morphology also shows a high degree of variation at each profile and throughout the year indicating a dynamic surf zone, within which wave activity redistributes sediment. The relationship between hydraulic energy and sediment transport is affected predominantly by wave height, frequency and sediment size. Beyond a certain depth (wave base) gravel sediment transport is limited. As the water deepens offshore, sediments would be expected to become finer, because wave energy is insufficient to entrain coarser sediments. This is in fact the case (section 4.5). Hakanson (1977b) identifies the occurrence of silt in the bottom sediments (> 5-10%) as an approximate guide to the limit of the high energy hydraulic regime in lakes (hence the pinch-out depth definition used herein). In lakes with a fetch of 10 km the depth is approximately 6-7 m, fairly close to the Loch Lomond figures.

Figure 6.8 shows trends of particle size against depth for selected lacustrine and marine environments which can be compared with the Loch Lomond results (Sly 1978). The Loch Lomond results (Cashel and Milarrochy offshore data combined) show a less steep curve than for most of the Great Lakes major sub-basins, and lie close to the Baltic and shallow Lake Erie sediments, the lower energy basins. A recurring theme throughout this research has been the comparability of lacustrine coastal geomorphology with marine coastal geomorphology. Sly (1978) observes that in the smaller lakes, energy levels decrease very rapidly with depth and this is reflected in sediment size at particular depths. In lakes with a fetch of 1 km this is 1-1.5 m; where the fetch is 10km the transition is 6-7 m and with 100 km fetch, the depth is 12-15 m. For much of the Great Lakes shoreline, for example, the transition occurs at 20-25 m. These figures are a guide (Hakanson 1977b; 1982) and local wind climates and local shoreline morphologies modify wave behaviour near the shore.

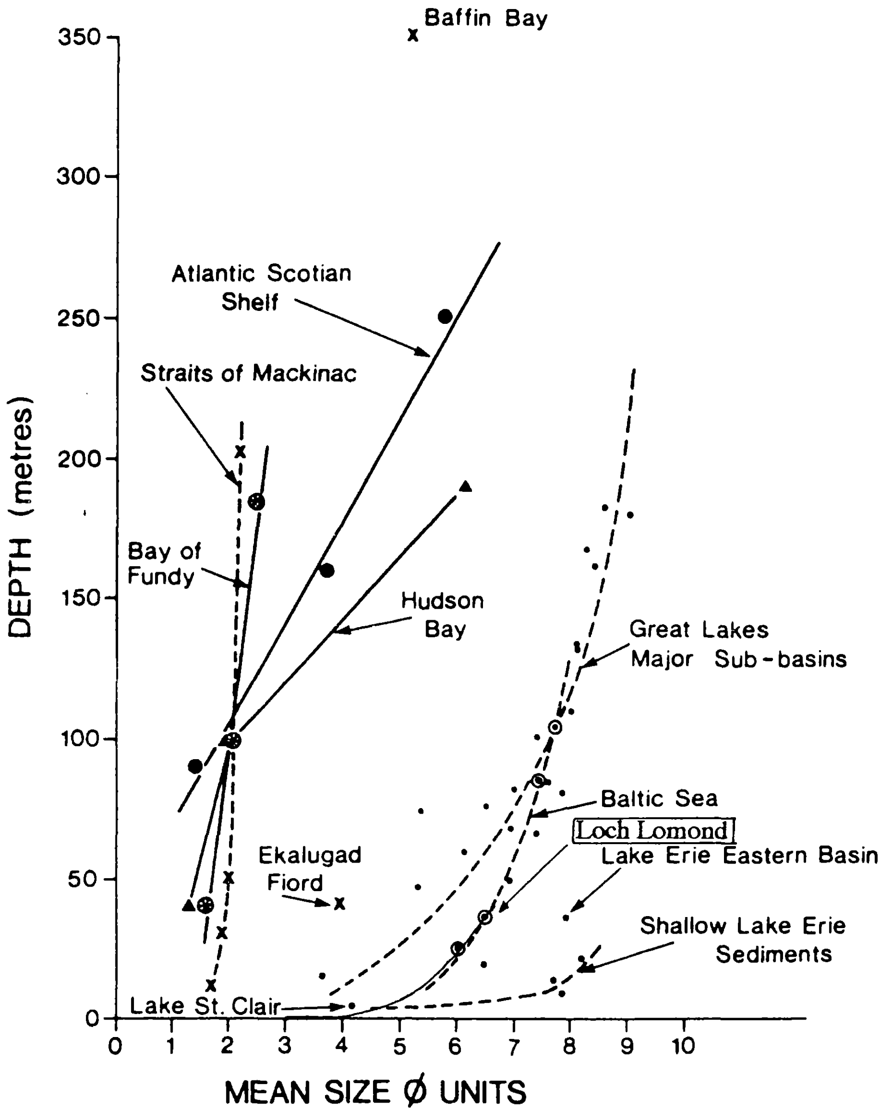


Fig. 6.8
Great lakes data from Canada centre for inland waters, Burlington Ontario; Baltic sea data from Seibold (1967), marine data from Pelletier (1973) and Straits of Mackinac data from Lauff *et. al.* Loch Lomond data from this study. (Modified from Sly 1978)

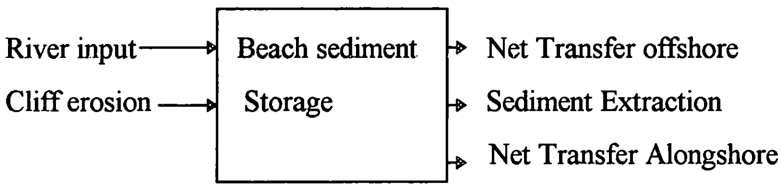
Examples of mean particle size against depth for lacustrine and marine environments.

6.3.2 *Sediment Budgets*

Sediment Supply

Sediment supply is a key factor in coastal response to changing factors (e.g. Davis 1970; Leatherman 1989). Within the beach sediment budget, if there is a deficit of sediment then shore recession or beach steepening occurs. If there is a sediment surplus, progradation and/or accretion occurs and so determining the volume of sediment supply to the Loch Lomond beaches was important (section 3.3). The main elements of the budget are shown in Fig. 6.9. The supply of fine sediment (< 2 mm/ >-1ϕ) from the cliff, the fluvial sediment yield which forms the primary source of coarse sediment, and the main budget results will be discussed.

Figure 6.9 Sediment Budget



Throughout this research, the issue of temporal and spatial scales has been revisited. The aim was to quantify an annual sediment budget (meso-temporal scale) for the two beaches (meso-spatial scale). Sediment transfer through river systems commonly occurs in pulses (Church and Jones 1982; Hoey 1992) such that sediment delivery is temporally episodic. In addition this research has shown episodic cliff erosion, consequently affecting the timescale over which a sediment budget is calculated. An annual budget is appropriate in the context of the Loch Lomond water level cycle and precipitation patterns. The results from an annual budget can be set within a broader climatic context; i.e. how representative is the year of study and time of study with reference to any secular climatic change?

6.2.3.1 Cliff recession

Cliff recession was monitored to help to quantify shore zone variation and to quantify inputs/throughputs for the sediment budget. Here, as well as the sediment budget contribution discussion, cliff recession is discussed. Map analysis shows mean long term recession in the cliffed area of Cashel of 0.22 m yr^{-1} (1918-1975). At Milarrochy surveys during this study provide the only available records averaging 0.71 m yr^{-1}, (October 1993 -April 1995). During 1994 there was a mean recessional rate of 0.54 m yr^{-1} at Cashel, and between 0.1-0.46 m yr^{-1} at Milarrochy (section 5.2). Rates of recession varied spatially, with vegetated (with trees or bushes) parts of the cliff observed to be more resistant to recession, as the root systems strengthened the cliff matrix. Sunamara (1983) noted that spatial variability in cliff recession rates is largely due to cliff material heterogenity. Recession tended to be episodic and occurred even under low water level, calm conditions. Field observations suggest that cliff recession was predominantly related to precipitation and saturation resulting in cliff collapse and rotational failure, rather than direct erosion by waves. When water levels were high, the cliff foot was liable to wave erosion. This direct undercutting left cliff material vulnerable to collapse. Eroded material was deposited at the foot of the cliff, adding both fines and some coarse material to the beach sediments. Most of the fine sediment was eventually removed offshore by wave action whereas coarse material accumulated on the beach. Material eroded during periods of low water level on the beach until water levels increased.

Differing cliff materials erode at different rates as is discussed in Chapter 2. Mean cliff erosion rates are highly variable depending on material properties, sub-aerial erosion rates and wave energy (Table 6.1).

Table 6.1 Sedimentary cliff erosion rates

Location	Material	Rate (m yr^{-1})	Reference
Cape Cod, Mass. US.	Glacial drift	0.3	Zeigler et. al. (1959)
Southern California, US.	Alluvium	0.3	Shepard and Grant (1947)
SE Lake Michigan	Glacial Diamict	0-4	Buckler (1988)
High Skirlington, Holderness UK.	Glacial Diamict	2-3	Mason (1985)
Huntcliff, Yorkshire UK.	Lower Lias clay	4.0	In King (1972)
New Jersey, US.	Sand, clay and gravel	180	Rankin (1952)

Sunamara (1983) suggests Tertiary sedimentary materials erode at rates of 1m yr^{-1} and Quaternary sedimentary deposits at 1-10 m yr^{-1}. The Loch Lomond cliff recession rates are less than these estimates, but they represent lacustrine rather than marine conditions. Sunamara (1977) describes how cliffs fronted by steep narrow beaches (as at Loch Lomond) are more likely to erode rapidly if sediments are moved more rapidly. In the context of lakes of this size the Loch Lomond rates are rapid.

6.2.3.2 Fluvial sediment supply

As fluvial sediment supply is difficult to quantify, the following discussion considers estimates of uncertainty in the presented results. The term 'sediment yield' is the quantity of sediment delivered to the beach from a specific catchment in a specified time period. Sediment yield is used as a measurement of contemporary and palaeo-hydrological and geomorphological processes (Wolman and Miller 1960; Slaymaker 1977; Walling and Webb 1983). The one year record of this study is recognised as being relatively short, although not atypically so (Owens and Slaymaker 1993). In Loch Lomond the coarse sediments are retained either in the beach, at the stream exits or in the nearshore area. This improves the accuracy of the sediment yield estimates. This small lake is different from the marine coast in terms of sedimentation and sediment transport, as the lake basin provides a tangible sediment sink. This has considerable implications in terms of shore protection schemes and catchment management (see Chapter 7).

The two primary factors affecting sediment yield from a given catchment are sediment availability and stream discharge. Three of the streams gauged are ephemeral, and their flows are dependent on recent precipitation. As a whole Loch Lomond catchment precipitation rates are high (> 1500mm yr^{-1}, and have increased significantly in the last few decades; Ventura 1995). Correspondingly higher catchment sediment yields would be expected provided that sediment was available for fluvial entrainment and delivery to the beach. This availability is unclear as catchment sediment supplies in upland Britain tend to be lower than elsewhere because most mountain sediment has already been moved and reworked during the Loch Lomond stadial, although yields may well have remained high during the early Holocene (Price 1983). Thus the amount of sediment available in the catchment is critical for determining yields and may be the overall control over shore recession. Modern sediment yields may be related to changes in land use within the catchment (e.g. Moore 1979; Dickinson 1994).

Estimates of sediment yield calculated from peak stage measurements show relatively high instananeous rates of sediment input into the lake beach systems. However, hydraulic reconstruction is an inherently uncertain procedure (Church 1978). As far as possible, best practice in methodology was used, particularly in the use of appropriate roughness measurements, emphasised as critical by Dury (1985). Two steps were used to reconstruct sediment yields; firstly hydraulic reconstruction, and secondly, bedload estimates. The use of *Acronym 1,* (Parker 1990a and b) for the bedload estimates gives a good estimate of relative stream supply enabling reliable comparison between streams. However this assumes unlimited sediment availability within the catchment. As suggested above this is unlikely to be the case and yields using every peak stage within each month are likely to overestimate yield, so the standard of 15 minutes at peak flow estimate was adopted. However good the palaeoflow reconstruction, the conditions for entrainment to occur are not totally predictable and consequently neither is the volume of sediment delivered and deposited on the beach (Reid and Frostick 1994).

Only peak stage estimates have been used in calculating the fluvial sediment input. Under conditions assumed by equilibrium formulae (e.g. Parker 1990a) are approximated most closely. The problems with recording only peak stage over a series of fixed time periods is that there is no record of frequency or duration of high flows. The duration and frequency of high flow events, were assessed by comparison with stage readings taken from the River Falloch (section 5.4.1). Although stream geometry was measured at the gauge sites, under some conditions only part of the channel width is mobile (especially E1 and Pr 2). The method assumes uniform activity across the whole channel cross-section. This could have led to an overestimation of sediment delivery during lower magnitude flood events.

There are two further indications as to the fluvial sediment delivery volumes. The first is a known minimum value of sediment delivered to the beach by Cashel Burn (stream 1), which is 240 tonnes or 133 m^3 over 8.5 years (Watson 1983, *pers. comm.*). Forest Enterprise has supplemented the beach sediment at Cashel by mechanically removing sediment from the stream bed to the beach. This gives a mean sediment delivery of 11.3 m^3 yr^{-1} which is considerably lower than those obtained by palaeohydrological reconstruction. This is unsurprising as most of the sediment is presumably transported to the delta or alongshore. Given that no other attempts to estimate sediment delivery to the beaches, the results contained herein represent a good first approximation to calculating sediment delivery.

Comparison of Loch Lomond sediment yields with other studies

There are few published rates of sediment yield from British gravel bedded mountain streams and of the internationally published rates. Most rates are estimates subject to varying uncertainty because of the difficulty in quantifying sediment yields.

McManus (1993) describes a pattern of sediment yields derived from Scottish reservoirs where specific yields are higher at lower altitudes than stations further upstream within any particular catchment (Al-Jabbari *et al.* 1990a; McManus 1986). Various examples of sediment yield were compared and smaller streams were recognised as being less efficient transporters of sediment even if sediment supplies were available. Richards and McCaig (1985) estimated an average of

26t km^2 yr^{-1}. of bedload for a catchment of 10 km^2 or 10.4 m^3 km^2 yr^{-1}. These, and data from Owens and Slaymaker (1993) given in Table 6.2 are helpful for comparisons with this study. Catchment characteristics (precipitation, vegetation, land use, sediment availability) are likely to vary between catchments.

Table 6.2 Examples of Fluvial Sediment Yield for upland catchments

River	Location	Data Years	Catchment Area (km^2)	Yield ($m^3 km^{-2} yr^{-1}$)
Cashel (1)	this study	1	9.2	109
Cashel (2)	this study	1	0.42	209
Milarrochy (3)	this study	1	0.9	7.1
Milarrochy (4)	this study	1	0.98	31
Milarrochy (5)	this study	1	12	9.8
Allt a'Mhuillin	Scotland	12	6.2	9.8
Earn	Scotland	2	782	26.9-51.2
Almond	Scotland	3	175	6.9-26.0
Lyon	Scotland	3	391	9.8 -23.9
Tay	Scotland	3	3212	17.24-80.7
Tummel	Scotland	3	1720	10.4-41.8
Isla	Scotland	5	367	15.7-42.8
Forth	Scotland	5	397	65.5-118.8
Teith	Scotland	5	518	3.6-4.9
Ardoch	Scotland	4	48	4.4-7.32
Allan Water.	Scotland	5	161	4.2-7.9
Leven	Scotland	2	424	3.2-85.2
Central Creek	B.C. Canada	?	2.4	2.12
Miller Creek	B.C. Canada	?	21.6	13.6
Seymour	B.C. Canada	?	148	24
Lillouet	B.C. Canada	35	3150	215

Sources: this study; Richards and McCaig (1985); McManus (1993); Owens and Slaymaker (1993).

The results given from 5 streams in this study (Table 5.8) are calculated using 15 minutes per month at maximum stage and maximum sediment delivery. The Owens and Slaymaker (1993) estimates from British Columbia are from small lakes with low sedimentation rates and are derived from suspended sediment transport records and delta advances for coarse clastic material. The estimates of yields from this study are higher than those of McManus (1993) and Owens and Slaymaker (1993). Interestingly Stream 2 at Cashel, which is ephemeral, has the highest yield per area of catchment and it feeds the only accreting area of beach in the study. The estimate in this study derived from the shore protection procedures (Watson 1983 *pers. com.*) gives a lower estimate. Richards and McCaig (1985) note that the sediment delivery ratio falls faster for bedload than suspended load. Thus small catchments should have significantly higher specific yields than larger ones.

These results represent the only detailed cliff retreat measurements and sediment yields calculated within the Loch Lomond catchment. Although covering a relatively short time span, these results contribute to the sediment budget calculations and make a valuable contribution to the understanding of beach variability within the catchment.

6.2.3.3 Sediment storage

Fundamental to the concept of a sediment budget (Fig. 2.15) is the role of the beach as a sediment store. The aim of this section is to draw together and interpret the results on beach sediment storage and the sediment budget, and to consider the implications of these findings in the context of wave activity water level and wave variation.

A positive annual volumetric sediment budget has been calculated from beach surveys for Cashel (+4031 m^3) and a negative budget for Milarrochy (-5351 m^3). However, both beaches are characterised by a landward recession and a destruction of back beach features, responses normally associated with deficient sediment supply, rising water level, a higher energy wave climate or combination of these. The Cashel budget especially suggests that beach recession is not caused by a sediment deficit, but is related to sediment circulation and distribution within the beach. Of particular significance in Loch Lomond is the fact that the coarse sediment remains within the beach/nearshore system. Deltas at all the stream exits act as sediment sinks or stores, as well as being suppliers of sediment for the beach when reworked by wave action. The deltas therefore represent a second source of sediment to the beach budget. The rest of the shore may thus undergo recession whilst sediment is accumulating if this sediment remains stored in the deltas. It seems as if the problem of shore erosion at Loch Lomond is not one of a sediment deficit, but is related to sediment distribution and the inability of the wave climate to redistribute sediment rapidly from areas of storage to areas of deficit. At Milarrochy, similar principles of sediment storage occur, and as at Cashel sediment distribution is a key to beach behaviour, particularly in terms of shore recession. The sediment deficit at Milarrochy is closely related to rollover and recession as well as sediment storage and distribution.

Deltas are highly significant in lake beach sediment budgets. Morgan (1970b) defines four major controls on large scale delta progradation as: 1) river regime; 2) coastal processes; 3) tectonic structure; and 4) climate (influencing vegetation growth and sediment yield). Four controls on delta dynamics have been identified at the smaller scale of the Loch Lomond beaches. They influence whether the delta operates as a sediment store or a sediment supply within the beach budget at a given time interval. These controls are sediment supply, stream discharge, water level and wave action. The first two have been discussed in the preceding paragraphs. Deltas develop where there is prolonged accumulation of river sediment (of all grain sizes). The lake water level is important because it determines the area of deposition of fluvially carried sediment. High water levels mean that the stream enters the lake further up the beach profile and so deposition occurs much higher up the beach. Typically, under high winter water levels with calm conditions, and high fluvial sediment yields, delta development is greater and higher up the beach profile. If the conditions remain constant but wave activity increases (the fourth control), this is likely to result in the delta function changing from a sediment store to a sediment supply. Wave activity moves the sediment in the direction of the prevailing wind and wave direction thus depleting the delta sediment store and redistributing the beach sediment. This helps to explain the complex pattern of beach profile changes (section 5.3) and beach sediment distribution (section 5.4). The Loch Lomond results suggest that delta development and delta dynamics provides a highly significant role in the beach sediment budget.

Beach storage: further areas of uncertainty

In the calculation of the sediment budget, beach change was calculated from surveyed volumes. In addition to survey errors (section 3.4.2.2) beach compaction and beach porosity are important. If the beach sediment is compressed and voids reduced, an erosional profile may be indicated where this is not the case. The cause of beach compaction is car parking on the beach. (relevant at Milarrochy only). This may further account for some of the sediment deficits calculated volumetrically. Summer surveys taken over a two week period in Summer 1993 suggest that compaction reduces beach surface elevations by approximately 0.08 m during the Summer period. Compaction may also cause armouring of the surface layer so that sediment is less able to be reworked by wave activity. This may be a contributary factor to poor sediment mobilisation and distribution the upper beach after the Summer tourist season at Milarrochy.

Further uncertainty in the calculations is attributable to profiles extended to closure depths in the calculations (a standard practice and area of uncertainty). Similarly, estimated sediment delivery figures may be over-estimates. When compared with other Scottish mountain stream sediment delivery values, the results are of a similar order however (Table 6.2). Overall a high degree of confidence can be placed in the sediment budget figures because of the relatively low energy regime and the sedimentologically defined closure depths, although the extent of the inactive gravel beach is unclear.

6.2.3.4 Sediment transfer alongshore and offshore

Quantification of the offshore and alongshore sediment transfer components is often the area of greatest uncertainty in budget calculations (e.g. Schuisky and Scwartz 1983; Kondolf and Matthews 1991; Pierce 1976). The budgets computed herein focus on coarse (> 2mm/< -1ϕ) sediment transfer and as discussed in the previous sections, the headlands and nearshore closure depths (defined by the nearshore limit of the coarse sediments) provide the outer margins for sediment transfer. The volumetric morphological sediment budget (Tables 5.15 and 5.16 highlight the alongshore areas of sediment gain and loss over 1994, so erosional and accretional areas can be clearly seen at this annual scale. These are closely related to proximity to sediment supply, stream exits and exposure and elevation of specific areas of shore (Table 4.1). Thus for the purposes of the 1994 budget no alongshore (beyond the bays) or offshore sediment loss is incorporated.

6.2.3.5 Summary comparison of Cashel and Milarrochy Sediment budgets

So far most of the results from the two beaches have been presented separately. This section briefly compares results from Cashel and Milarrochy. Morphologically (section 5.1.2). Cashel is a larger beach with a highly developed back berm along a significant length of the beach. Milarrochy is smaller, and has a higher proportion of finer grades of sediment. Although Cashel has only two feeder streams rather than three at Milarrochy, higher volumes of sediment are delivered. Both beaches show considerable alongshore variation in response to process conditions. Different sections of beach behave very differently depending on controls such as macro-scale geology and geomorphology, beach elevation, beach exposure wave activity and sediment supply. Cashel has a positive net sediment budget for 1994, + 4031 m^3 and Milarrochy a negative budget of -5351 m^3.

Reconnaissance surveys in 1992/93 suggested very different beach responses to similar conditions, as much of Cashel beach appears relatively stable whereas Milarrochy is recessional.

When examined in detail, the volumetric budget changes (Tables 5.15 and 5.16) reveal responses related to beach exposure, elevation, sediment supply and fluvial influence. Greatest volumetric change is observed in the central more exposed areas of both beaches, whereas headland sheltered beach is less mobile. Over 1994, beach areas adjacent to streams e.g. Milarrochy Profile 2 and Cashel Profile G show volumetric loss (-26.2 m^3 and -197.8 m^3 respectively) as fluvial currents transport sediment away from the upper beach into deltaic storage. These areas are also more exposed to wave activity. Both beaches operate as individual sediment cells bounded by headlands, thus sediment circulation is within each bay. Both beaches have deltas which develop within them and which help to control sediment distribution. Beach variability is closely related to local conditions adjacent to particular profiles (section 5.5). The recessional response of Milarrochy beach during 1994 has been very similar to that of Cashel, particularly between profiles I and E1. Although, Cashel cliff recession is mostly controlled by water level, whereas at Milarrochy sub-aerial processes dominate. The Cashel section of beach from E1 to A has not been recessional primarily due to its elevation and large back berm. Sediment loss at Milarrochy is primarily accounted for by rollover landward recession and within beach storage e.g. deltas and spits. These processes constitute an important dimension in the understanding of beach behaviour.

The sediment budgets for the two beaches provide two different examples which illustrate (at different scales) the lake coastal zone processes in operation. The budgets also show similar process responses and interrelationships on beaches which exhibit initially different geomorphological features. The results illustrate the compartmentalised nature of these lake beaches.

6.2.3.6 Sediment budgets: limitations and comparisons

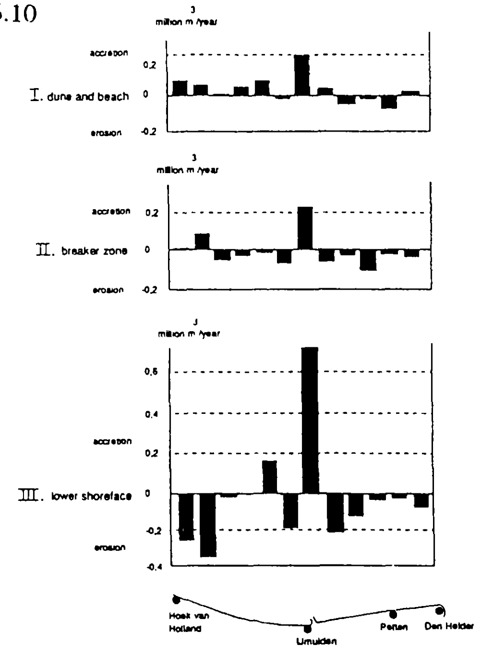
Throughout this work, estimates of uncertainty have been given for all calculations. The clear nearshore limit to coarse sediment and the relatively low energy environment both ensure reduced uncertainty in the results and increase confidence in the sediment budget figures. The following discussion addresses the limitations of sediment budget calculations, so that the Loch Lomond data can be interpreted to the appropriate level of confidence.

As sediment budgets can be calculated in a variety of ways from computer modelling to field based approaches, and with a variety of densities of data collection, comparisons must be made with some caution. Kondolf and Matthews (1991) caution that net errors can range from 1% to over 100% of the total sediment export. Few papers critically examine the general effectiveness of sediment budgets, but tend to consider site specific implications. Ideally a sediment budget should account for all gains and losses. In practice, however, usually one or more parts of the budget are known with less certainty, so the 'unknown' factors tend to be allocated to a particular section (Kondolf and Matthews 1991). In this study, the fluvial sediment delivery and delta storage are known with less certainty than the other components of the budgets.

The following coastal examples illustrate the magnitude and variability of sediment budgets and set the Loch Lomond results in a broader context. Chapter 2 cites a number of examples of published sediment budgets, although most are for sandy beaches. Allen (1981) describes variations in erosion alongshore at Sandy Hook, New Jersey, USA, using aerial photograph analysis to delimit littoral drift cells (section 2.5). For 1971 to 1978 an erosional budget, with a deficit of 270 000m^3 yr^{-1} for 7650 m of shoreline (or 35.3 m^3 km^{-1}) was identified. This was attributed primarily to sediment starvation (reduced sediment supply), an increase in storminess, an offshore loss of sediment as the beach profile readjusted to the response of transgression associated with a rise in mean sea level, and overwash losses due to dune destruction and storms. This example highlights the significance of sediment supply in coastal stability as well as alongshore variation in erosion rates related to exposure as observed at Loch Lomond. It also provides a marine comparison for the budget contained herein.

de Ruig and Louisse (1991) calculated a sediment budget in equilibrium for part of the Dutch sandy coast. When accounting for sea level rises there is a deficit of 7.1^5 m^3 over the whole study area over a 20 year period (1965 and 1985). There are fluctuations from year to year, typically with an erosion or accretion rate of up to 48 m^3 m^{-1} yr^{-1}, rates which fall within the mild category of erosion/accretion rates (Oertal *et al.* 1989). The maximum mean accretion rates (between 1963-1986) is approximately 250 m^3 yr^{-1} and the erosion rate 150 m^3 yr^{-1}. The de Ruig and Louisse (1991) results (Fig. 6.10) shows averaged annual budget changes alongshore for three morphologic zones: dune and beach; breaker; lower shoreface. Alongshore variability is pronounced particularly at the lower shoreface (nearshore zone) with variability between adjacent sections of beach. When compared with the Loch Lomond results, whilst the magnitudes are very much greater in the marine environment, overall trends of variability are not dissimilar. The de Ruig and Louisse (1991) results (Fig. 6.11) also show year to year variability in beach volumes at the various morphologic zones, which highlights variability over a longer temporal scale as sediment is redistributed. Establishing a timescale appropriate to the spatial scale of the study is important with larger beaches needing longer timescales to demonstrate their overall equilibrium.

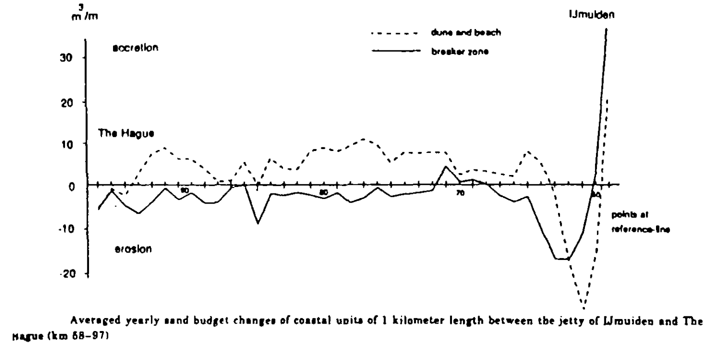
Fig. 6.10



Averaged yearly sand budget changes of the three morphological zones: (1) dune and beach (11) breaker zone; (111) lower shoreface, for stretches of 10 km length.

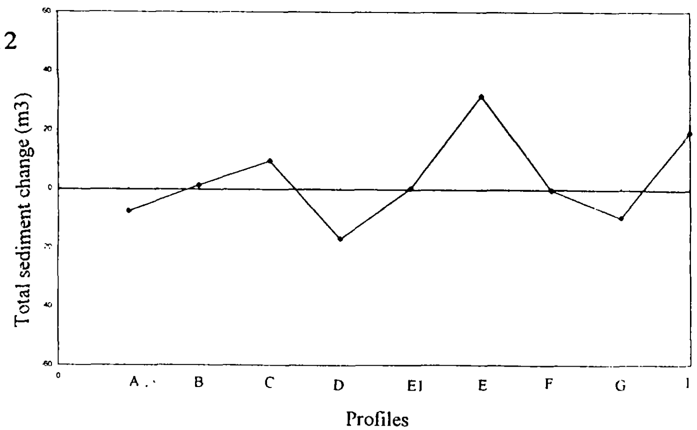
Fig. 6.11

(after de Ruig and Louisse 1991)



Averaged yearly sand budget changes of coastal units of 1 km length between the Ijmuidem jetty and the Hague.

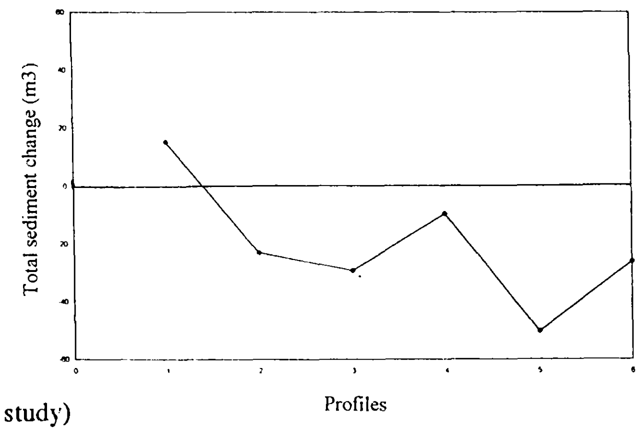
Fig. 6.12



Alongshore volumetric change: Cashel 1994

(This study)

Fig. 6.13



Alongshore volumetric change: Milarrochy 1994

What makes the Loch Lomond results distinctive (Figs. 6.12 and 6.13) are relatively small volumes of sediment involved and the closed nature of the sediment budget. The computed budgets show the roles of different processes in each of the budget compartments, and the significance of beach sediment storage. Unlike marine coasts and high energy large lake systems, the lack of available sediment is not because sediment is lost to the budget through routing offshore or alongshore, but because it is temporarily unavailable whilst contained within delta and beach stores.

The main strengths of the sediment budgets determined herein are the use of detailed (high resolution) field data, and a systemic approach to the dynamics of the generally poorly researched area of lake coasts. As previously stated a high degree of confidence can be placed in the results because of the low energy conditions and closure depths used. A sediment budget allows sediment dynamics to be partially quantified, further areas to research to be identified, and provides a useful method for assessing coastal zone change.

6.3. Controls over beach behaviour at Loch Lomond

Throughout this discussion, beach variability and the processes affecting it have been explored. In recent years the Loch Lomond shore zone has been subject to flooding and erosion attributable to increased precipitation and rising water levels (Pender *et al.* 1993; Ventura 1995). Investigation of beach variability, cliff recession and nearshore processes (waves and water levels) have shown important controls over beach behaviour. This section serves to integrate and summarise the main controls over beach variability.

Water levels constitute a fundamental control on the shoreline via their underlying control on the effects of waves (section 4.2 and 6.1). Higher water levels reduce the extent of the sub-aerial beach allowing degradation of the upper beach and backshore under storm conditions. Direct action on the cliffs by waves at high water levels was recorded with the resultant erosion. Beach elevation in relation to water level is a significant factor in beach variability, as shown by differences in the northern and southern sections of Cashel beach, and the lower-lying beach at Milarrochy.

Periods of rapid rise/fall in water levels (relating to catchment precipitation trends), which occur bi-annually (section 4.2) cause the most significant changes in beach profile type and in overall beach variation (sections 5.3.1.3 and 6.2).

The restricted fetch, high frequency waves cause considerable beach variation. During 1994 the maximum wave heights were recorded during August at relatively low water levels. This resulted in beach profile readjustment (section 5.3), but had limited affect on the upper beach and backshore. When the highest wave heights coincide with onshore winds/waves and the highest water levels as in 1990 (e.g. Pender *et al.* 1993) the beaches respond by major morphological readjustment, landward roll-over of sediment and backshore degradation.

The dominant westerly waves during 1994 affected both beaches with the more exposed sections of beach experiencing greater variability on an annual scale (sections 4.1.1; 5.3; 5.6; 6.2). Considerable longshore variation occurred at both beaches. Sections of beach were represented by individual profile types (section 5.3.1) which persisted from month to month. These types reflected exposure, elevation, sediment supply particle size and proximity to stream exits.

Fluvial discharge exerts an important control over beach development affecting sediment entrainment and delivery, distribution and storage within the beach. Periods of highest sediment delivery occur during the winter months and the deltas and small scale forms have been identified as important sediment storage areas (sections 5.3.2; 5.3.3; 6.2.2.3) often for long time periods (years). At high water levels, deltaic sediments often remain below wave base and are therefore not entrained and transported. This limits the sediment available for beach morphological redistribution and shore defence.

6.4 Wider Implications of this research

Throughout the preceding discussion reference has been made to the importance of considering space and time scales in interpreting the research results. In a critical review of sediment budgets Clayton (1990) warns of the danger of scaling up short term observations. Related to this, the first part of this section offers a cautionary note on the applicability of these results within the context of geomorphic system controls at different space and time scales. Different variables have been measured in this research at different scales, related to the scale of variability of the phenomena and the time available for the study. Discussion of temporal variability will be considered first, followed by spatial variability. Recognition of the significance of the scale of study enables better comprehension and future application of the results. The second part of this section considers the implications in terms of future research.

6.4.1 Scale dependent controls on the beach system

The wave data and sediment budgets were measured during a single calendar year (1994), although beach response to incident processes is ongoing. Any research period represents a sample in the longer timescales of landform development and change discussed in section 3.1. Schumm and Lichty (1965) identified temporal scales at which variables affecting geomorphological systems are designated as cyclic, graded and steady time. Cyclic time refers to long timescales, as discussed in relation to water levels in chapter 6.1. Giving examples is hard as the appropriate 'cycles' depend on the system under consideration, however, a glacial-interglacial time period seems to be appropriate for the factors discussed herein. Graded time represents a short span of cyclic time during which a dynamic equilibrium exists and steady time where a steady state exists. The role of relevant variables depends on the scale considered. At any one scale the relevant variables show inter-dependence. The importance of a variable depends on the context set by those processes operating at larger scales. If one variable changes, the change may affect the other variables within the system.

The idea of landform and process sensitivity (Brunsden and Thornes 1979; Brunsden 1990) is important. Magnitudes of change required to perturb or disturb parts of the system need investigation together with the relationship between phases of stability and instability. These ideas are closely related to concepts of equilibrium, discussed below. Forbes *et al.* (1995) identify several external controls in the long-term evolution of paraglacial coastal systems. These are the geological and physiographic setting, relative sea level change, time varying sediment supply, the climate system and controls such as tides or river discharge. At Loch Lomond the status of these controls as well as the timescale over which they operate is important. Interpretation of the results within the context of time is important. Firstly, to try to understand the system dynamics *per se,* at the appropriate timescales and secondly to recognise the implications of these inter-dependences where human activity affects the system. In the coastal context, Pethick (1988) uses the scale of beach profile variation as an illustration of steady time, and beach plan as one which changes over graded time, although the two are fundamentally linked. Large scale coastal configuration ('capes and bays') would be defined as operating over cyclic time. Because of short-term variability, landform systems monitored for long periods tend to have better defined causal responses. At the scale studied, the Loch Lomond results did not reveal close linkages between monthly mean wave activity and beach morphology. A clear causal association between rapid rises and falls in water level and profile change was apparent. The landforms (back berms, Cashel ridge, nearshore-offshore sedimentology) suggest that over a longer timescale different linkages will become apparent. Lake shape, size and orientation influence the effects of forcing functions shown in Fig. 6.1 (e.g. wind (affecting waves) barometric pressure (affecting seiches) and gravity (affecting tides)).

The wave controls on beach modification have greatest impact when water levels are very high or are very low. When low, sediment stores are entrained and mobilised, when water levels are high, upper beach morphology is redefined. The biannual period of rapid water level change identified herein (sections 5.3 and 6.1) is associated with the main period of beach profile change. It is also important to understand wave activity at the micro-scale, as prolonged action by waves with frequencies of less than a second can redefine beach morphology. It is the cumulative effect of a series of wave conditions which causes the most noticeable changes over the monthly timescale used for beach morphology. Stream inflow has been identified as a control on sediment delivery, and sediment storage. On the macro-timescale, the availability of sediment is the primary control, at the meso-scale of this work, stream flow is more important. Thus when the present results are compared with Sly (1995; Fig. 6.1) for the meso-scale, the most significant controls are wind (controlling waves) and precipitation (affecting water level) followed by stream inflow. The effects of solar radiation, barometric pressure and gravity are outwith the remit of the present study, but have generally minor impact. At the macro-scale, precipitation and its' affect on water level assumes a greater importance as it determines the range within which other variables operate.

Whilst the 1994 data provides some indication of the appropriate scales of variability (some longer datasets are available which set the 1994 data in a longer context), how these compare to variability in other years is not known. There is a need for longer timescales of lake gravel beach study in order to verify the observed behaviour. For example, the maximum water level recorded (in 1990) has been described as a 100 year maximum (Curran and Poodle 1995). This is an uncertain estimate because of the short period of record available but also because of the underlying assumption of stationary conditions may be violated. Such water level limits may be exceeded more frequently than such an estimate suggests. Quantifying beach morphological change under different water level conditions, to complement water level data would enhance understanding of the processes in operation. Longer study would increase the chance of measuring and assessing the impact of extreme events, and longer records would enable the statistical range of behaviour to be determined. For example, longer term beach monitoring might reveal the conditions required to re-distribute sediment currently stored in the deltas. With the 1994 data alone, these parameters cannot be defined, only estimated.

The temporal scale of research affects the results and their interpretation, and the inter-site comparison of results. In this research, the shortest timescale used was in the monitoring of waves. Whilst the wave records represent a *sample* of total wave activity during 1994, they illustrate the nature of the waves at Loch Lomond. As a very detailed temporal wave recording system was used the significance of the high wave frequency was recognised. Within the lake wave climate, such wave frequencies are very important. The longer term mean shore recession rate at Cashel was less than rates recorded from this study. This may imply that mean recession rates have increased, 1994 could represents an anomaly, or an above average year in a statistical series. Already discussed in section 6.2.3 is the variety of timescales seen suitable for cliff erosion figures to be considered reliable. Profile monitoring over many years for example is likely to better highlight seasonal trends, whilst daily monitoring can show closer links with wave and water level conditions. Fluvial sediment delivery calculations can be better constrained with records of longer- term flow or sediment supply. The point is that interpretation of results should be carefully set within the temporal framework of system dynamics (Kennedy 1975), which highlights the need for further research into lake beach processes as that framework is poorly developed.

Spatial constraints on beach variability have been more clearly identified by this research than temporal limits. The use of profiles has enabled cross-beach and longshore beach variation to be determined at both beaches. Spatial controls in methods and results must be recognised in the interpretation and inter-site comparison (e.g. two beaches; profile spacing; the use of one wave recorder site). The spatial definition of the beach and sediment budget area have shown that for Loch Lomond different beaches operate independently from each other with the headlands constituting barriers to sediment drift. Within the beach unit there is considerable spatial variation related to exposure, sediment supply and beach elevation. The results suggest that sediment supply and fluvial hydraulics have a strong control on beach variability and sedimentation patterns. The importance of the spatial component is emphasised by the differences between established process-form relationships derived from the marine coast theory and the findings of this lake research. At its simplest level, the lake basin size controls fetch, wave development and thus the energy regime at the shore. Because of restricted fetches, wave development is limited and therefore the energy available for coastal modification is limited compared to the marine coast scenario.

Both temporal and spatial variability can be understood with reference to the concept of equilibrium (section 2.4.4). An equilibrium shoreline is defined as "the dynamic state in which the geometry of the beach reflects a balance between materials, processes and energy levels. The ideal equilibrium beach has curvature and sand prism characteristics which are adjusted so closely that energy available transports the detritus supplied over a period to be measured in years rather than months, days or seconds" (Goudie *et al.* 1994, p.184). Determining whether or not the Loch Lomond beaches are in equilibrium is not straightforward. Both show trends of dis-equilibrium at the annual scale in that Cashel has a positive sediment budget and Milarrochy a negative one.

Most coastal equilibrium theories are related to predicting shoreline response under conditions of changing water level, wave conditions or engineering protection works (e.g. Bruun 1962; Dean 1991; Hanson and Kraus 1989 (GENESIS model)). These all assume that all beach profiles behave similarly under similar process conditions. The Loch Lomond results show generally similar average process responses at the two beaches (Chapter 5), but specific behaviour is dependent on antecedent conditions and local variability in for example, exposure, elevation and sediment characteristics (sections 5.3; 5.4). The extent of alongshore variation on these lake beaches is important in this context. Equilibrium profiles for one profile may be very different from another. Pilkey *et al.* (1993) are particularly critical of the concept of shoreface profile equilibrium and conclude, like Bruun (1992), that a beach profile is.... "very dynamic and subject to considerable variances. Its' behaviour may be better described in statistical rather than physical terms" (p. 275).

Changes in a natural system which stress the system beyond defined limits or thresholds of stability can cause a major response to occur (Gage 1970; Schumm 1979; Brunsden 1990), after which new equilibrium conditions develop. At Loch Lomond thresholds between different types of behaviour have been identified. Macro beach form assumes winter and summer type profiles with rapidly changing intermediate types in response to water level fluctuations. The rapid rises/falls of water levels twice annually seems to be the threshold for changing profile type (section 5.3). Fluvial discharge and thus sediment input also follows seasonal trends. Wave patterns are highly variable, but seasonal water level changes significantly affect the potential impact of waves on the beaches. It seems from the results herein that the most significant forcing function for the beach system is rapid water level change. The overall scale at which such changes are assessed affects perception of whether such changes constitute 'catastrophic' or purely 'cyclic' changes, but these are cyclic changes in the context of usual research timescales. In the context of the Loch Lomond results further longer term monitoring of beach variability would enhance understanding of the complexities of the lake coastal zone.

6.4.2 Recommendations for further research

A number of issues have been raised in the preceding discussion. Some suggestions for further research have been identified, the most significant of which are given below:

1. Lake wave recording at a range of lake sizes is required to evaluate scales of wave amplitudes and frequencies. This would enable better determination of fetch controls on processes operating within lakes, and therefore potential wave energies at lake sites. The data would also complement the marine wave data models and clarify the differences and overlap between marine and lacustrine wave climates. Such data is valuable for setting energy thresholds for sediment transport and sediment budgets. It also provides fundamental information for engineering applications such as soft and hard shore protection schemes, building within the coastal zone and coastal zone management.

2. One of the biggest deficits in the literature concerns the estimation of gravel sediment transport on beaches. Whilst in the last two decades there have been rapid developments in the understanding, modelling and prediction of river gravel transport (e.g. Ashworth and Ferguson 1989; Parker 1990; Hassan and Church 1992), the collection of field data to improve the calibration of models is important. Parameters for gravel entrainment related to flow, the influence of slope and the transport of mixed size fractions constitute areas for further research. In the context of coastal research these are significant for better sediment delivery prediction. On beaches, gravel sediment transport is poorly researched, most research focusing on sand transport (e.g. Komar 1977). A gravel sediment transport equation is needed which includes relative and absolute size effects. Lake beaches with a clear longshore drift system would provide a good field starting point for calibrating this because of the lower energies than the marine coast. Field testing of gravel entrainment theories which take into account beach sediment sorting, packing, shape, densities and sorting along with wave and current activity is long overdue.

3. Sediment storage times within the beach system need to be better understood. Research into controls on sediment transfer between fluvial, beach, delta and offshore systems would enable better understanding of wave energy or water level thresholds affecting the balance of sediment transfer change. Both field and experimental work especially with tracers would be of benefit thus identifying detailed sediment circulation patterns. This may become easier as tracer technology improves.

4. Long term (e.g 10 years) beach profile measurement is needed to better determine the inherent variability in beach systems. Such measurements can then be linked with process changes, particularly water level variation. Few studies of lake beach variability are available, especially in small lakes, where fluvial activity and water level variation can at times dominate over wave activity. Further research into potential contrasts between high and low sediment supply to beaches would highlight magnitudes of likely beach change, and differing sediment supply related responses. Long term monitoring of backshore position and cliff retreat is required. This would show both short and long term variability and enable landward recession to be better quantified. Linkages with water level and wave conditions can then be made over longer timescales.

5. All the above have signifcant implications for coastal zone management, particularly in small lakes where reduced energy may require different management methods from those commonly applied to the open coast. Of particular value is the sediment-based approach to management strategy which highlights erosional and accretional areas and volumes of sediment supply and circulation. The lack of an overall strategy and enforceable policy for coastal zone management at Loch Lomond is a problem (Pierce 1996). Research into the effects of piecemeal 'shore protection efforts' and beach feeding projects is long overdue. Continual monitoring of shore response to human as well as physical variables is required so that the environment can be conserved for the future.

6.5 Chapter and Research Summary

This research has provided the first quantitative investigation into the variability of the Loch Lomond coastal zone. Within this chapter, the results have been discussed and the nature of interrelationships between variables established within the constraints of the available information. Seasonal water level variation where there is a rapid rise/fall of mean level has emerged as an important control on beach variability. Water level is also significant in that it sets the base-line for wave activity. At high water levels waves cause more beach degradation as the backshore and cliff foot are affected. The wave climate records show the range falls at the extremes of the published spectral models with a high frequency, relatively low energy wave regime, limited by fetch. Incident wave direction is more significant than wave refraction at these beaches. Sediment transport rates are low in the light of published rates and the limit of coarse sediment transport in the nearshore is significant in understanding sediment storage and distribution within the beach system. Water level also exerts a significant control on the spatial extent of sediment movement. Beach morphological variation alongshore is related to both macro-scale geology and exposure to prevailing conditions relating to sediment exchange both alongshore and up and down the profile. The magnitudes of these lake beach volume changes are small within the context of marine coast literature, although similar trends are recognised. The sediments show evidence of both alongshore (mostly on the upper beach) and cross-beach sediment movement, the latter being more pronounced. The upper beach sediments show distinct trends form the mid and lower beach. The findings suggest that sediment movement is restricted to individual bays which behave as sediment cells. Small deltas exert an important control over sediment storage within the overall sediment budget. The results are set within the wider context of spatial and temporal scales, landform and process sensitivity and equilibrium ideas. The wider implications of the research, and suggestions for future research have been presented.

From this analysis of the lake coastal zone processes and responses, much clearer evidence is now available for further, clearly directed, detailed study. The methods are transferable, and the results could provide a marker for comparison with other lake coasts.

Chapter 7 CONCLUSIONS

The results and discussion in the preceding chapters have suggested a number of conclusions and highlighted areas for future research. This chapter briefly summarises the main findings of this research into lake waves and low energy lake gravel beach variation and considers implications for future research.

7.1 Conclusions

1. Waves were successfully recorded throughout 1994 using a wave probe. The Loch Lomond wave climate is distinctive, characterised by small amplitude, high frequency steep waves and periods of calm within this restricted fetch environment. Mean significant wave height was 0.08 m (excluding calms) and mean frequency (T_c) was 0.92 seconds. Spectral analysis showed the Loch Lomond wave spectra fall at the high frequency/low energy extremes of the published spectral models. Within the Loch Lomond basin, wave directions are highly variable. From the eastern shoreline perspective of the research, westerly winds were dominant during 1994, followed by north-easterly. Thus dominant wave activity was focused on the longest fetches affecting both Cashel and Milarrochy beaches. The wave record contained herein constitutes a relatively long record of lake wave climate data for the UK, and contributes to the definition and recognition of a distinctive wave environment.

2. Water levels are a fundamental control on the beach variability, both in rates of fluctuation and in that they provide the underlying control on the effects of waves. The water level range during 1994 was 1.76 m with high winter and low summer levels. Daily fluctuation may be up to approximately 0.2 m and levels are unstable. Periods of rapid rise/fall in water levels which occur bi-annually produced the most significant changes in beach profile type and overall beach variation. Beach elevation in relation to water level ranges is a significant factor in beach variability. At high water levels the extent of the sub-aerial beach is reduced when high levels are combined with wave activity, degradation of upper beach and backshore results. Higher water levels expose some areas of cliff to direct action by waves with resultant erosion.

3. Gravel beach variability was examined with respect to morphological change. The beach profiles were classified into 8 types based on profile form. Considerable and persistent longshore variation was observed on both beaches. Sections of beach represented by individual profile types show profile types may persist from month to month except when affected by seasonal

rapid water level rise or fall. Survey results showed both cross-beach and alongshore variation although overall variability is relatively constrained compared to sediment-rich environments (e.g. Forbes *et al.* 1995).

4. Volumetric sediment budgets were calculated for 1994 for the two beaches; Cashel showed a positive budget and Milarrochy a negative budget (+4031 m^3 and -5351 m^3 respectively). The cliffs at Milarrochy and Cashel are recessional, the Cashel cliffs being more directly affected by waves and the Milarrochy cliffs by sub-aerial weathering. The retreat rate in 1994 at Cashel was surveyed to be 0.54 m yr^{-1} and 0.29 m yr^{-1} at Milarrochy, which is greater than long term retreat rates.

5. Fluvial discharge exerts a significant control on beach development, as it affects sediment entrainment and delivery, distribution and storage within the beach. Periods of highest sediment delivery occurred during the winter months. Water level is also significant in beach sediment redistribution. The deltas are major sediment stores within the beach sediment budgets, often for long time periods (years). At high water levels, delatic sediments are often below wave base and are therefore not entrained and transported. This limits sediment availability for beach morphological re-adjustment and shore defence.

6. The controls exerted by water level, waves and fluvial discharge affect sediment entrainment, transport and deposition. During 1994, on-shore off-shore processes dominated within the nearshore. Within the lake sub-aerial and sub-aqueous beaches sediment transport distances are small. Sediment transport of coarse material (>2mm/< -1ϕ) is restricted to redistribution within the bays and bathymetric and sediment surveys showed a clear closure depth defined by the limit of coarse sediment in the nearshore. Both beaches exhibit mixed sedimentological compositions with little alongshore sorting. An overall trend of cross beach sediment fining occurs from the sub-aerial beach into the offshore zone, with a poorly sorted nearshore zone and abrupt limit to coarse sediment.

Research outcome

The outcomes of this research were: to quantify wave variability during 1994; to obtain and estimate of shore recession; to determine the scale of beach morphological and sedimentological variation; to calculate annual sediment budgets; and to better understand the mechanics of geomorphological change within the coastal zone. The research can be sub-sectioned into discrete units of lake wave hydrodynamics, and lake beach variability although these units are closely inter-related. The main finding from the wave results was the definition of the 1994 wave climate of high frequency waves. The main finding of lake beach variability was the control exerted on beach form by the bi-annual periods of rapid rises/falls in water level and areas of sediment storage within the beaches. Simultaneous field-monitoring of spatial and temporal variability within the nearshore and shore zones has enabled such trends to be identified.

Within coastal geomorphology, lake hydrodynamics and limnology this research contributes to the understanding of small lake margin variability both in the nearshore and shore zones. Set within the broader context of environmental change the field evidence from this research contributes to quantifying perceived variability. This research is important in terms of recognising spatial and temporal coastal responses under conditions of environmental change (e.g. water level rise; variation in wave activity), responses which have implications with reference to sea level rise.

7.2 Implications for further research

This research raises numerous possibilities for future research which can be grouped into the following categories:

Firstly, the need for further lacustrine coastal research has been highlighted. In contrast to the open marine coast, processes operate at different timescales and exert different controls on beach development. Spatial and temporal scales of operation of these processes need to be determined as scales of operation have not yet been fully investigated. Whilst this research has identified controls on lake beach behaviour (e.g. seasonal water level change; sediment circulation and supply, elevation and exposure) beach monitoring for longer time periods may identify other controls. Further field monitoring is required, over say a further 5 years which would give clear evidence of the range of beach varaibility.

Secondly, the need for gravel beach sediment transport and storage mechanisms has been raised, both in the marine and lacustrine environments. The lower energy frameworks within the lacustrine environment predispose it to further investigation as monitoring sediment routing may be simpler than in a higher energy environment. Field testing and the development of suitable gravel beach transport equations is a research priority. The findings of this research are important in terms of beach sediment mobility, distribution and storage, factors which have considerable importance in future beach behaviour.

As identified in chapters 1 and 2 most of the gravel beach literature refers to beaches where sediment is plentiful. Of interest are differences between these and sediment-poor beach responses, a large area for further research. As the results contained herein have identified relatively rapid change in a low energy, sediment-poor environment, it suggests that with greater sediment availability, beach behaviour may be quite different.

The finding of a relatively low energy, high frequency wave environment at Loch Lomond reveals the deficit in wave data for lower energy water bodies such as lakes and small seas. Further definition of wave climates at the lower energy end of the recorded range is of particular interest. When combined with shore response data, further understanding of beach behaviour within restricted fetch environment can be gained. This reveals another area for further research.

Integrated lake coastal zone management strategies are needed at Loch Lomond and elsewhere. Invariably beach management is undertaken in an *ad hoc* manner with the implementation of numerous engineering shore protection schemes with limited geomorphological investigation and understanding. The findings in terms of shore recession, beach rollover, sediment storage within deltas, and volumes of sediment moved are important for developing future management plans. Considerable potential for development of 'soft' shore protection strategies is suggested by the findings of this research alone both at Loch Lomond and at other sites. Further research into the effectiveness or otherwise of 'hard' engineering solutions deployed at Loch Lomond will also yield informative results.

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Appendix A

Bulk beach density

For the sediment budget calculations, beach volumetric change is particularly important (as measured by profiling). Beach volume depends on variables such as sediment quantity, size, shape, water content and packing, which is complex on a coarse clastic beach. As the beach sediment is predominantly fluvially derived, the value of a bulk beach density of 1800 kg m^{-3} was used. This assumes a standard density of 2650 kg m^{-3} with a porosity of 0.32 (voids) and 0.68 gravel (Gale and Hoare 1981).

Phi-unit (ϕ)	Millimetres (mm)	Micrometres (μm)	Particle-size category	Particle-size subcategory
−10.00	1024.000			
−9.75	861.078			
−9.50	724.077			
−9.25	608.874			
−9.00	512.000			boulder
−8.75	430.539			
−8.50	362.039			
−8.25	304.437			
−8.00	256.000			—
−7.75	215.269			
−7.50	181.019			
−7.25	152.219			
−7.00	128.000			
−6.75	107.635			cobble
−6.50	90.510			
−6.25	76.109			
−6.00	64.000			—
−5.75	53.817		gravel	
−5.50	45.255			
−5.25	38.055			
−5.00	32.000			
−4.75	26.909			
−4.50	22.627			
−4.25	19.027			
−4.00	16.000			
−3.75	13.454			pebble
−3.50	11.314			
−3.25	9.514			
−3.00	8.000			
−2.75	6.727			
−2.50	5.657			
−2.25	4.757			
−2.00	4.000			—
−1.75	3.364			
−1.50	2.828			
−1.25	2.378			granule
−1.00	2.000			—
−0.75	1.682			
−0.50	1.414			very coarse
−0.25	1.189			sand
0.00	1.000			—
0.25	0.841			
0.50	0.707			coarse
0.75	0.595			sand
1.00	0.500		sand	—
1.25	0.420			
1.50	0.354			medium
1.75	0.297			sand
2.00	0.250			—
2.25	0.210			
2.50	0.177			fine
2.75	0.149			sand
3.00	0.125			—
3.25	0.105			
3.50		88.388		very fine
3.75		74.325		sand
4.00		62.500		—
4.25		52.556		
4.50		44.194		coarse
4.75		37.163		silt
5.00		31.250		—
5.25		26.278		
5.50		22.097		medium
5.75		18.581		silt
6.00		15.625	silt	—
6.25		13.139		
6.50		11.049		fine
6.75		9.291		silt
7.00		7.813		—
7.25		6.570		
7.50		5.524		very fine
7.75		4.645		silt
8.00		3.906		—
8.25		3.285		
8.50		2.762		coarse
8.75		2.323		clay
9.00		1.953		—
9.25		1.642		
9.50		1.381		medium
9.75		1.161	clay	clay
10.00		0.977		—
10.25		0.821		
10.50		0.691		fine
10.75		0.581		clay
11.00		0.488		—

Appendix C Loch Lomond wave statistics

The following tables are the wave statistics from the 1994 wave records. Gaps are due to logger failure. Tz = zero-up crossing period (s) ; Tc = crest period (s); H1 highest recorded wave (m); Hs = Significant wave height; E = spectral width parameter (after Hardisty 1989).

RESULTS: Loch Lomond Wave Records, January 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	Hl (m)	Hs (m)	E
No Data							
LL2001	13/01/94	1800hrs	0.9	0.42	0.07	0.05	0.9
LL2007	13/01/94	2306hrs	1.15	0.53	0.09	0.05	0.89
LL2008	14/01/94	1151hrs	calm				
LL2014	14/01/94	0530hrs	calm				
LL2022	14/01/94	1151hrs	calm				
No data							
LL2029	14/01/90	1748hrs	0.82	0.41	0.07	0.05	0.86
LL2036	14/01/90	2345hrs	calm				
LL2043	15/01/90	0542hrs	0.88	0.44	0.07	0.04	0.86
LL2050	15/01/90	1139hrs	calm				
LL2057	15/01/90	1736hrs	1.6	0.5	0.1	0.07	0.95
LL2064	15/01/90	2337hrs	1.18	0.47	0.08	0.05	0.92
LL2069	16/01/90	0348hrs	1.46	0.61	0.07	0.05	0.9
LL2071	16/05/90	0530hrs	1.05	0.46	0.08	0.05	0.9
LL2078	16/01/90	1127hrs	calm				
LL2085	16/01/90	1724hrs	1.18	0.62	0.06	0.03	0.85
No data							
LL4001	17/01/90	1200hrs	1.75	1.6	0.16	0.1	0.38
LL4002	17/01/90	1800hrs	1.41	1.32	0.11	0.07	0.36
LL4003	18/01/90	0000hrs	electronic fault				
LL4004	18/01/90	0600hrs	electronic fault				
LL4005	18/01/90	1200hrs	1.49	1.4	0.12	0.08	0.33
No data							
F3002	26/01/90	1300hrs	calm				
F3007	26/01/90	1806hrs	2.43	1.2	0.05	0.03	0.86
No data							
LL4001	17/01/90	1200hrs	1.75	1.62	0.16	0.1	0.38
LL4002	17/01/90	1800hrs	1.41	1.32	0.11	0.07	0.36
LL4003	18/01/90	0000hrs	electronic fault				
Ll4004	18/01/90	0600hrs	electronic fault				
LL4005	18/01/90	1200hrs	1.49	1.4	0.12	0.08	0.33
No data							
No data							
field obs	08/02/90	0900hrs			0.6	0.4	
No data							

RESULTS: Loch Lomond Wave Records, February 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs (m)	E
No data							
field obs	09/02/94	0900hrs			0.6	0.4	
No data							
M2001	22/02/94	1200hrs	0.74	0.58	0.03	0.02	0.63
M2002	22/02/94	1800hrs	0.83	0.67	0.04	0.03	
M2003	23/02/94	0000hrs	0.95	0.83	0.06	0.04	0.51
M2004	23/02/94	0600hrs	0.93	0.8	0.05	0.03	0.52
M2005	23/02/94	1200hrs	0.98	0.87	0.06	0.04	0.47
M2006	23/02/94	1800hrs	0.85	0.72	0.04	0.03	0.53
M2007	24/02/94	0000hrs	0.81	0.61	0.02	0.02	0.66
M2008	24/02/94	0600hrs	1.07	0.64	0.01	0.01	0.8
M2009	24/02/94	1200hrs	calm				
M2010	24/02/94	1800hrs	calm				
M2011	25/02/94	0000hrs	0.68	0.41	0.02	0.01	0.8
M2012	25/02/94	0600hrs	calm				
M2013	25/02/94	1200hrs	0.79	0.6	0.04	0.02	0.65
M2014	25/02/94	1800hrs	0.92	0.8	0.06	0.04	0.51
M2015	26/02/94	0000hrs	0.84	0.73	0.05	0.03	0.51
M2016	26/02/94	0600hrs	0.8	0.59	0.03	0.02	0.67
M2017	26/02/94	1200hrs	1.11	0.65	0.06	0.06	0.81
M2018	26/02/94	1800hrs	0.8	0.63	0.03	0.02	0.62
M2019	27/02/94	0000hrs	0.88	0.77	0.07	0.04	0.48
M2020	27/02/94	0600hrs	calm				
M2021	27/02/94	1200hrs	0.87	0.7	0.06	0.04	0.59
M2022	27/02/94	1800hrs	0.92	0.61	0.04	0.03	0.74
M2023	28/02/94	0000hrs	calm				
M2024	28/02/94	0600hrs	calm				
M2025	28/02/94	1200hrs	calm				
M2026	28/02/94	1800hrs	0.9	0.58	0.02	0.01	0.77

RESULTS: Loch Lomond Wave Records, March 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs (m)	E
M2028	01/03/94	0000hrs	calm			0	
M2029	01/03/94	0600hrs	calm			0	
M2030	01/03/94	1200hrs	1.1	0.6	0.01	0.01	0.84
M2031	01/03/94	1800hrs	1.34	1.03	0.03	0.02	0.64
M2032	02/03/94	0000hrs	calm			0	
M2033	02/03/94	0600hrs	calm			0	
M2033	02/03/94	1200hrs	1	0.8	0.04	0.03	0.57
Mar12001	02/03/94	1800hrs	calm			0	
Mar12002	03/03/94	0000hrs	calm			0	
Mar12003	03/03/94	0600hrs	calm			0	
Mar12004	03/03/94	1200hrs	calm			0	
Mar12005	03/03/94	1800hrs	calm			0	
Mar12006	04/03/94	0000hrs	calm			0	
Mar12007	04/03/94	0600hrs	calm			0	
Mar12008	04/03/94	1200hrs	calm			0	
Mar12009	04/03/94	1800hrs	calm			0	
Mar12010	05/03/94	0000hrs	calm			0	
Mar12011	05/03/94	0600hrs	calm			0	
Mar12012	05/03/94	1200hrs	calm			0	
Mar12013	05/03/94	1800hrs	calm			0	
Mar12014	06/03/94	0000hrs	calm			0	
Mar12015	06/03/94	0600hrs	calm			0	
Mar12016	06/03/94	1200hrs	calm			0	
Mar12017	06/03/94	1800hrs	calm			0	
Mar12018	07/03/94	0000hrs	calm			0	
Mar12019	07/03/94	0600hrs	calm			0	
Mar12020	07/03/94	1200hrs	calm			0	
Mar12021	07/03/94	1800hrs	calm			0	
Mar12022	08/03/94	0000hrs	calm			0	
Mar12023	08/03/94	0600hrs	calm			0	
Mar12024	08/03/94	1200hrs	calm			0	
Mar12025	08/03/94	1800hrs	calm			0	
Mar12026	09/03/94	0000hrs	calm			0	
Mar12027	09/03/94	0600hrs	calm			0	
Mar12028	09/03/94	1200hrs	calm			0	
Mar12029	09/03/94	1800hrs	calm			0	
Mar12030	10/03/94	0000hrs	power failure				
Mar12031	10/03/94	0600hrs	calm			0	
Mar12032	10/03/94	1200hrs	calm			0	
Mar12033	10/03/94	1800hrs	calm			0	
Mar12034	10/03/94	0000hrs	calm			0	
Mar12035	11/03/94	0600hrs	calm			0	
Mar12036	11/03/94	1200hrs	logger fault				
Mar12037	11/03/94	1800hrs	calm			0	
Mar12038	12/03/94	0000hrs	logger fault				
Mar12039	12/03/94	0600hrs	calm			0	
No data							

RESULTS: Loch Lomond Wave Records, April 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	Hl (m)	Hs (sec)	E
Apr20001	13/04/94	1200hrs	0.91	0.77	0.05	0.03	0.54
Apr20002	13/04/94	1800hrs	1.38	0.88	0.02	0.02	0.7
Apr20003	14/04/94	0000hrs	calm			0	
Apr20004	14/04/94	0600hrs	calm			0	
No data							
Apr26001	19/04/94	1800hrs	1.85	0.6	0.02	0.01	0.93
Apr26002	20/04/94	0000hrs	1.82	0.62	0.02	0.01	0.94
Apr26003	20/04/94	0600hrs	1.55	0.55	0.02	0.01	0.95
Apr26004	20/04/94	1200hrs	2.4	0.82	0.02	0.01	0.94
Apr26005	20/04/94	1800hrs	2.05	0.67	0.02	0.01	0.93
Apr26006	21/04/94	0000hrs	1.6	0.54	0.02	0.01	0.93
Apr26007	21/04/94	0600hrs	1.52	0.53	0.02	0.01	0.94
Apr26008	21/04/94	1200hrs	1.49	0.54	0.05	0.01	0.96
Apr26009	21/04/94	1800hrs	1.64	0.54	0.02	0.01	0.94
Apr26010	22/04/94	0000hrs	2.27	0.62	0.01	0.01	0.94
Apr26011	22/04/94	0600hrs	1.59	0.55	0.01	0.01	0.94
Apr26012	22/04/94	1200hrs	calm			0.01	0.9
Apr26013	22/04/94	1800hrs	calm			0.01	0.94
Apr26014	23/04/94	0000hrs	1.9	0.58	0.01	0.01	0.93
Apr26015	23/04/94	0600hrs	1.85	0.62	0.02	0.01	0.93
Apr26016	23/04/94	1200hrs	1.59	0.58	0.02	0.01	0.95
Apr26017	23/04/94	1800hrs	1.66	0.59	0.02	0.01	0.4
Apr26018	24/04/94	0000hrs	2.17	0.65	0.02	0.01	0.95
Apr26019	24/04/94	0600hrs	1.69	0.58	0.02	0.01	0.95
Apr26020	24/04/94	1200hrs	calm			0	0
Apr26021	24/04/94	1800hrs	2.2	0.66	0.02	0.01	0.94
Apr26022	25/04/94	0000hrs	calm			0.24	0.24
Apr26023	25/04/94	0600hrs	calm			0.25	0.31
May5001	25/04/94	1200hrs	1.8	1.75	0.36	0.21	0.28
May5002	25/04/94	1800hrs	1.75	1.67	0.37	0.03	0.69
May5003	26/04/94	0000hrs	1.62	1.55	0.32	0.21	0.67
May5004	26/04/94	0600hrs	1.14	0.83	0.04	0.07	0.77
May5005	26/04/94	1200hrs	2.1	1.49	0.2	0.08	0.4
May5006	26/04/94	1800hrs	2.13	1.36	0.1	0.12	0.33
May5007	27/04/93	0000hrs	1.37	1.25	0.12	0.25	0.3
May5008	27/04/94	0600hrs	1.27	1.2	0.19	0.12	0.36
May5009	27/04/94	1200hrs	1.35	1.28	0.24	0.05	0.45
May5010	27/04/94	1800hrs	1.28	1.2	0.18	0.15	0.28
May5011	28/04/94	0000hrs	1.11	1	0.08	0.13	0.35
May5012	28/04/94	0600hrs	1.28	1.23	0.22	0.13	0.35
May5013	28/04/94	1200hrs	1.43	1.34	0.2	0.08	0.29
May5014	28/04/94	1800hrs	1.44	1.34	0.2	0.07	0.42
May5015	29/04/94	0000hrs	1.16	1.1	0.13	0.08	0.32
May5016	29/04/94	0600hrs	1.06	0.96	0.1	0.07	0.37
May5017	29/04/94	1200hrs	1.1	1	0.13	0.08	0.32
May5018	29/04/94	1800hrs	1.03	0.96	0.1	0.06	0.38
May5019	30/04/94	0000hrs	0.9	0.59	0.01	0.01	0.75
May5020	30/04/94	0600hrs	1.3	0.75	0.01	0.01	0.83
May5021	30/04/94	1200hrs	1.41	1.17	0.1	0.06	0.57
May5022	30/04/94	1800hrs	1.14	0.83	0.06	0.04	0.69

RESULTS: Loch Lomond Wave Records, May 1994

File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs(m)	E
May5019	01/05/94	0000hrs	0.9	0.59	0.01	0.01	0.75
May5020	01/05/94	0600hrs	1.3	0.75	0.01	0.01	0.83
May5021	01/05/94	1200hrs	1.41	1.17	0.1	0.06	0.57
May5022	01/05/94	1800hrs	1.14	0.83	0.06	0.04	0.69
May5023	02/05/94	0000hrs	calm				
May5024	02/05/94	0600hrs	calm				
May5025	02/05/94	1200hrs	1.44	1.15	0.04	0.02	0.61
May5026	02/05/94	1800hrs	1.18	1	0.09	0.05	0.39
May5027	03/05/94	0000hrs	0.75	0.62	0.05	0.03	0.58
May5028	03/05/94	0600hrs	0.8	0.69	0.05	0.03	0.51
May5029	03/05/94	1200hrs	0.96	0.86	0.1	0.06	0.43
May5030	03/05/94	1800hrs	1.67	1.54	0.09	0.06	0.4
May5031	04/05/94	0000hrs	0.71	0.5	0.03	0.02	0.71
May5032	04/05/94	0600hrs	1.12	1.04	0.03	0.1	0.06
May5033	04/05/94	1200hrs	1.75	1.69	0.32	0.21	0.26
May5034	04/05/94	1800hrs	1.34	1.33	0.2	0.12	0.16
May5035	05/05/94	0000hrs	1.31	1.27	0.27	0.18	0.26
May5036	05/05/94	0600hrs	1.24	1.8	0.18	0.11	0.32
May10001	05/05/94	1200hrs	0.76	0.61	0.03	0.02	0.58
May10002	05/05/94	1800hrs	1.48	1.41	0.31	0.21	0.3
May10003	06/05/94	0000hrs	1.11	1.02	0.17	0.11	0.38
May10004	06/05/94	0600hrs	1.61	1.5	0.39	0.26	0.36
May10005	06/05/94	1200hrs	1.68	1.62	0.35	0.23	0.27
May10006	06/05/94	1800hrs	1.53	1.43	0.1	0.07	0.35
May10007	07/05/94	0000hrs	calm				
May10008	07/05/94	0600hrs	calm				
May10009	07/05/94	1200hrs	1.65	1.58	0.3	0.2	0.29
May10010	07/05/94	1800hrs	calm			0	
May10011	08/05/94	0000hrs	calm			0	
May10012	08/05/94	0600hrs	calm			0	
May10013	08/05/94	1200hrs	calm			0	
May10014	08/05/94	1800hrs	calm			0	
May10015	09/05/94	0000hrs	calm			0	
May10016	09/05/94	0600hrs	calm			0	
May10017	09/05/94	1200hrs	calm			0	
May10018	09/05/94	1800hrs	calm			0	
May10019	10/05/94	0000hrs	calm			0	
May10020	10/05/94	0600hrs	calm			0	
May10021	10/05/94	1200hrs	calm			0	
May12001	10/05/94	1800hrs	1.06	0.97	0.03	0.02	0.39
May12002	11/05/94	0000hrs	1.04	0.92	0.03	0.02	0.48
May12003	11/05/94	0600hrs	0.92	0.79	0.01	0	0.5
May12004	11/05/94	1200hrs	0.82	0.69	0.02	0	0.56
May12005	11/05/94	1800hrs	0.88	0.78	0.01	0.01	0.48
May12006	12/05/94	0000hrs	0.95	0.82	0.01	0	0.5
May12007	12/05/94	0600hrs	0.91	0.79	0.01	0	0.49
No data							
May18001	17/05/94	1200hrs	calm			0	
May18002	17/05/94	1800hrs	calm			0	
May18003	18/05/94	0000hrs	calm			0	
May18004	18/05/94	0600hrs	calm			0	

No data							
May26001	20/05/94	1200hrs	0.93	0.53	0.07	0.05	0.82
May26002	20/05/94	1800hrs	1.05	0.69	0.12	0.07	0.75
May26003	21/05/94	0000hrs	calm			0	
May26004	21/05/94	0600hrs	0.9	0.56	0.09	0.06	0.78
May26005	21/05/94	1200hrs	0.98	0.62	0.07	0.05	0.77
May26006	21/05/94	1800hrs	0.98	0.67	0.1	0.07	0.73
May26007	22/05/94	0000hrs				0.01	
May26008	22/05/94	0600hrs	calm			0	
May26009	22/05/94	1200hrs	1.09	0.75	0.09	0.06	0.73
May26010	22/05/94	1800hrs	1.26	0.75	0.09	0.06	0.8
May26011	23/05/94	0000hrs	calm			0	
May26012	23/05/94	0600hrs	calm			0	
May26013	23/05/94	1200hrs	calm			0	
May26014	23/05/94	1800hrs	0.94	0.59	0.07	0.04	0.78
May26015	24/05/94	0000hrs	0.79	0.4	0.04	0.03	0.86
May26016	24/05/94	0600hrs	calm			0	
May26017	24/05/94	1200hrs	0.76	0.4	0.04	0.02	0.85
May26018	24/05/94	1800hrs	1.02	0.67	0.09	0.06	0.75
May26019	25/05/94	0000hrs	calm			0	
May26020	25/05/94	0600hrs	calm			0	
May26021	25/05/94	1200hrs	0.96	0.64	0.07	0.05	0.75
May26022	25/05/94	1800hrs	0.87	0.54	0.07	0.04	0.78
May26023	26/05/94	0000hrs	calm			0	
May26024	26/05/94	0600hrs	calm			0	
Jun1001	26/05/94	1200hrs	2.63	1.32	0.01	0.01	0.86
Jun1002	26/05/94	1800hrs	calm		0.01	0.01	
Jun1003	27/05/94	0000hrs	calm			0	
Jun1004	27/05/94	0600hrs	1.7	0.86	0.03	0.02	0.86
Jun1005	27/05/94	1200hrs	1.4	0.8	0.12	0.07	0.82
Jun1006	27/05/94	1800hrs	1.09	0.83	0.13	0.08	0.64
Jun1007	28/05/94	0000hrs	electronic fault				
Jun1008	28/05/94	0600hrs	calm			0	
Jun1009	28/05/94	1200hrs	0.86	0.65	c0.08	0.08	0.65
Jun1010	28/05/94	1800hrs	1.13	0.89	c0.24	0.24	0.62
Jun1011	29/05/94	0000hrs	calm			0	
Jun1012	29/05/94	0600hrs	1.87	0.94	0.03	0.02	0.86
Jun1013	29/05/94	1200hrs	1.21	0.75	0.07	0.05	0.78
Jun1014	29/05/94	1800hrs	0.95	0.7	0.11	0.07	0.67
Jun1015	30/05/94	0000hrs	calm		0.01	0.01	
Jun1016	30/05/94	0600hrs	1.65	0.83	0.01	0.01	0.86
Jun1017	30/05/94	1200hrs	1.2	1.02	0.23	0.15	0.53
Jun1018	30/05/94	1800hrs	1.23	1.05	0.26	0.16	0.52
Jun1019	31/05/94	0000hrs	1.16	0.95	0.17	0.11	0.58
Jun1020	31/05/94	0600hrs	1.53	1.38	0.37	0.24	0.44
Jun1021	31/05/94	1200hrs	1.47	1.29	0.32	0.22	0.47
Jun1022	31/05/94	1800hrs	1.31	1.14	0.27	0.18	0.5

RESULTS: Loch Lomond Wave Records, June 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs (m)	E
Jun1023	01/06/94	0000hrs	1.03	0.8	0.14	0.09	0.63
Jun1024	01/06/94	0600hrs	1.05	0.84	0.17	0.12	0.61
Jun1025	01/06/94	1200hrs	1.22	1.01	0.2	0.13	0.56
Jun8001	01/06/94	1600hrs	0.97	0.78	0.17	0.11	0.59
Jun8002	01/06/94	2200hrs	1.1	0.72	0.09	0.06	0.73
Jun8003	02/06/94	0400hrs	calm		0	0	
Jun8004	02/06/94	1000hrs	1.23	0.62	0.05	0.04	0.86
Jun8005	02/06/94	1600hrs	1.28	0.65	0.04	0.03	0.86
Jun8006	02/06/94	2200hrs	1.2	0.94	0.13	0.29	0.68
Jun8007	03/06/94	0400hrs	1.3	0.85	0.09	0.05	0.79
Jun8008	03/06/94	1000hrs	0.79	0.46	0.07	0.04	0.8
Jun8009	03/06/94	1600hrs	calm		0	0	
Jun8010	03/06/94	2200hrs	1.12	1.1	0.01	0.01	0.47
Jun8011	04/06/94	400hrs	1.06	0.9	0.27	0.18	0.52
Jun8012	04/06/94	1000hrs	1.49	1.24	0.29	0.19	0.55
Jun8013	04/06/94	1600hrs	electronic fault			0.02	
Jun8014	04/06/94	2200hrs	1.16	0.96	0.24	0.15	0.56
Jun8015	05/06/94	0400hrs	1	0.78	0.19	0.12	0.64
Jun8016	05/06/94	1000hrs	1.32	1.03	0.19	0.12	0.62
Jun8017	05/06/94	1600hrs	1.2	1.07	0.34	0.22	0.46
Jun8018	05/06/94	2200hrs	electronic fault				
Jun8019	06/06/94	0400hrs	1.16	1.02	0.32	0.21	0.47
Jun8020	06/06/94	1000hrs	1.19	0.91	0.16	0.1	0.65
Jun8021	06/06/94	1600hrs	1.19	0.91	0.16	0.1	0.65
Jun8022	06/06/94	2200hrs	1.16	1.48	0.59	0.39	0.38
Jun8023	07/06/94	0400hrs	1.07	0.9	0.26	0.17	0.54
Jun8024	07/06/94	1000hrs	1.31	1.15	0.38	0.25	0.47
Jun8025	07/06/94	1600hrs	1.24	1.13	0.31	0.2	0.42
Jun8026	07/06/94	2200hrs	1.34	1.24	0.46	0.3	0.38
Jun8027	08/06/94	0400hrs	1.16	0.86	0.09	0.06	0.68
Jun8028	08/06/94	1000hrs	1.02	0.87	0.24	0.16	0.52
Jun16001	08/06/94	1800hrs	1.31	1.19	0.42	0.27	0.41
Jun16002	09/06/94	0000hrs	1.07	0.89	0.23	0.15	0.56
Jun16003	09/06/94	0600hrs	1.34	1.21	0.36	0.24	0.41
Jun16004	09/06/94	1200hrs	1.36	1.3	0.36	0.24	0.3
Jun16005	09/06/94	1800hrs	1.36	1.21	0.44	0.29	0.44
Jun16006	10/06/94	0000hrs	1.48	1.05	0.1	0.07	0.71
Jun16007	10/06/94	0600hrs	calm			0	
Jun16008	10/06/94	1200hrs	0.87	0.65	0.18	0.11	0.66
Jun16009	10/06/94	1800hrs	1.18	1.05	0.28	0.18	0.56
Jun16010	11/06/94	0000hrs	1.07	0.72	0.09	0.05	0.74
Jun16011	11/06/94	0600hrs	1.15	0.86	0.14	0.09	0.07
Jun16012	11/06/94	1200hrs	0.96	0.8	0.26	0.16	0.55
Jun16013	11/06/94	1800hrs	1.09	0.88	0.21	0.14	0.6
Jun16014	12/06/94	0000hrs	1.05	0.72	0.1	0.06	0.73
Jun16015	12/06/94	0600hrs			0.01	0.01	
Jun16016	12/06/94	1200hrs	1.01	0.85	0.17	0.11	0.54
Jun16017	12/06/94	1800hrs	0.96	0.81	0.19	0.12	0.54
Jun16018	13/06/94	0000hrs	0.9	0.64	0.1	0.06	0.71
Jun16019	13/06/94	0600hrs	1.79	0.88	0.03	0.02	0.86
Jun16020	13/06/94	1200hrs	1.3	0.74	0.07	0.05	0.82
Jun16021	13/06/94	1800hrs	1.13	0.96	0.24	0.16	0.51
Jun16022	14/06/94	0000hrs	1.23	1.07	0.38	0.25	0.5
Jun16023	14/06/94	0600hrs	1.04	0.88	0.21	0.14	0.54
Jun16024	14/06/94	1200hrs	1.18	1.06	0.37	0.24	0.45
Jun16025	14/06/94	1800hrs	1.21	1.08	0.31	0.2	0.45
Jun16026	15/06/94	0000hrs	1.13	1	0.29	0.19	0.46
Jun16027	15/06/94	0600hrs	1.11	0.93	0.31	0.2	0.54
Jun16028	15/06/94	1200hrs	1.19	1.04	0.27	0.18	0.49
Jun16029	15/06/94	1800hrs	1.14	0.99	0.29	0.18	0.5
Jun16030	16/06/94	0000hrs	1.17	1.06	0.32	0.2	0.43
Jun16031	16/06/94	0600hrs	1.07	0.9	0.22	0.14	0.53

Jun16032	16/06/94	1200hrs	1.16	0.97	0.04	0.03	0.81
Jun16033	16/06/94	1800hrs	calm			0	
Jun16034	17/06/94	0000hrs	calm			0	
Jun16035	17/06/94	0600hrs	1.22	1.05	0.32	0.21	0.51
Jun22001	17/06/94	1200hrs	1.15	1.01	0.3	0.2	0.47
Jun22002	17/06/94	1800hrs	1.18	1.07	0.34	0.22	0.44
Jun22003	18/06/94	0000hrs	1.11	0.95	0.27	0.18	0.52
Jun22004	18/06/94	0600hrs	0.8	0.56	0.12	0.07	0.7
Jun22005	18/06/94	1200hrs	1.84	1.7	0.6	0.4	0.3
Jun22006	18/06/94	1800hrs	1.7	1.6	0.7	0.45	0.35
Jun22007	19/06/94	0000hrs			0.1	0.1	
Jun22008	19/06/94	0600hrs	1.18	1	0.26	0.17	0.52
Jun22009	19/06/94	1200hrs	1.38	1.31	0.34	0.23	0.32
Jun22010	19/06/94	1800hrs	1.03	0.83	0.15	0.1	0.59
Jun22011	20/06/94	0000hrs	calm			0	
Jun22012	20/06/94	0600hrs	calm			0	
Jun22013	20/06/94	1200hrs	1.31	1.16	0.3	0.19	0.46
Jun22014	20/06/94	1800hrs	1.23	1.01	0.29	0.19	0.57
Jun22015	21/06/94	0000hrs	1.04	0.83	0.33	0.22	0.6
Jun22016	21/06/94	0600hrs	1.11	0.96	0.24	0.16	0.51
Jun22017	21/06/94	1200hrs	1.33	1.15	0.31	0.2	0.5
Jun22018	21/06/94	1800hrs	1.99	1.07	0.3	0.19	0.44
Jun22019	22/06/94	0000hrs	1.16	0.85	0.09	0.06	0.67
Jun22020	22/06/94	0600hrs	1.49	1.42	0.49	0.33	0.32
Jul4001	22/07/94	1200hrs	1.93	1.8	0.64	0.42	0.35
Jul4002	22/06/94	1800hrs	1.56	1.39	0.37	0.25	0.56
Jul4003	23/06/94	0000hrs	1.2	0.93	0.18	0.11	0.64
Jul4004	23/06/94	0600hrs	1.21	0.7	0.07	0.04	0.82
Jul4005	23/06/94	1200hrs	0.78	0.47	0.07	0.04	0.8
Jul4006	23/06/94	1800hrs	1.78	0.9	0.05	0.03	0.86
Jul4007	24/06/94	0000hrs	calm			0	
Jul4008	24/06/94	0600hrs	calm			0	
Jul4009	24/06/94	1200hrs		0.5	0.04	0.5	0.85
Jul4010	24/06/94	1800hrs	1.4	0.88	0.09	0.05	0.7
Jul4011	25/06/94	0000hrs	calm			0	
Jul4012	25/06/94	0600hrs	calm			0	
Jul4013	25/06/94	1200hrs	0.97	0.65	0.09	0.06	0.74
Jul4014	25/06/94	1800hrs	1	0.78	0.15	0.09	0.63
Jul4015	26/06/94	0000hrs	1.17	0.81	0.13	0.09	0.72
Jul4016	26/06/94	0600hrs	0.81	0.53	0.07	0.04	0.76
Jul4017	26/06/94	1200hrs	1.39	1.23	0.36	0.24	0.47
Jul4018	26/06/94	1800hrs	1.05	0.89	0.62	0.4	0.54
Jul4019	27/06/94	000hrs	calm			0	
Jul4020	27/06/94	0600hrs	1.64	1.36	0.11	0.07	0.56
Jul4021	27/06/94	1200hrs	1.57	1.33	0.15	0.1	0.54
Jul4022	27/06/94	1800hrs	1.09	0.92	0.17	0.11	0.54
Jul4023	28/06/94	0000hrs	calm			0	
Jul4024	28/06/94	0600hrs	1.09	0.81	0.22	0.14	0.61
Jul4025	28/06/94	1200hrs	1.22	1.09	0.32	0.21	0.45
Jul4026	28/06/94	1800hrs	1.32	1.15	0.23	0.15	0.49
Jul4027	29/06/94	0000hrs	1.06	0.87	0.16	0.15	0.57
Jul4028	29/06/94	0600hrs	1.21	1.07	0.29	0.19	0.47
Jul4029	29/06/94	1200hrs	1.59	1.54	0.57	0.38	0.25
Jul4030	29/06/94	1800hrs	1.15	1.03	0.3	0.2	0.45
Jul4031	30/06/94	0000hrs	1.16	0.98	0.19	0.13	0.52
Jul4032	30/06/94	0600hrs	1.04	0.83	0.16	0.11	0.61
Jul4033	30/06/94	1200hrs	0.87	0.69	0.16	0.1	0.61
Jul4034	30/06/94	1800hrs	1	0.73	0.1	0.06	0.69

RESULTS: Loch Lomond Wave Results, July 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs (m)	E
Jul4035	01/07/94	0000hrs	1.82	0.91	0.01	0.01	0.86
Jul4036	01/07/94	0600hrs	calm			0	
Jul4037	01/07/94	1200hrs	0.68	0.38	0.06	0.04	0.82
Jul4038	01/07/94	1800hrs	0.94	0.67	0.08	0.05	0.69
Jul4039	02/07/94	0000hrs	1.35	0.76	0.64	0.41	0.83
Jul4040	02/07/94	0600hrs	1	0.52	0.05	0.03	0.85
Jul4041	02/07/94	1200hrs	0.92	0.6	0.11	0.07	0.76
Jul4042	02/07/94	1800hrs	0.95	0.61	0.07	0.04	0.77
Jul4043	03/07/94	0000hrs	0.96	0.5	0.04	0.03	0.85
Jul4044	03/07/94	0600hrs	1.48	0.75	0.14	0.09	0.86
Jul4045	03/07/94	1200hrs	1.61	1.09	0.11	0.07	0.74
Jul4046	03/07/94	1800hrs	1.04	0.62	0.2	0.13	0.8
Jul4047	04/07/94	0000hrs	calm		0.01	0.01	
Jul4048	04/07/94	0600hrs	calm		0	0	
No data							

RESULTS: Loch Lomond Wave Results, August 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	Hl (m)	Hs (m)	E
No data							
Aug22001	18/08/94	1200hrs	1.17	1.05	0.32	0.21	0.45
Aug22002	18/08/94	1800hrs	1.09	0.82	0.13	0.08	0.66
Aug22003	19/08/94	0000hrs	1.15	1.02	0.37	0.24	0.46
Aug22004	19/08/94	0600hrs	1.04	0.86	0.25	0.17	0.55
Aug22005	19/08/94	1200hrs	1.34	1.2	0.5	0.33	0.39
Aug22006	19/08/94	1800hrs	1.55	1.24	0.02	0.02	0.6
Aug22007	20/08/94	0000hrs	1.22	1.1	0.34	0.22	0.43
Aug22008	20/08/94	0600hrs	1.24	1.09	0.36	0.24	0.49
Aug22009	20/08/94	1200hrs	1.67	1.44	0.51	0.34	0.51
Aug22010	20/08/94	1800hrs	1.43	1.36	0.51	0.34	0.32
Aug22011	21/08/94	0000hrs	0.99	0.83	0.21	0.13	0.55
Aug22012	21/08/94	0600hrs	calm				
Aug22013	21/08/94	1200hrs	1.02	0.88	0.29	0.19	0.51
Aug22014	21/08/94	1800hrs	1.15	0.92	0.16	0.1	0.6
Aug22015	22/08/94	0000hrs	1.19	0.6	0.02	0.01	0.86
Aug22016	22/08/94	0600hrs	2.09	1.04	0.02	0.02	0.86
Aug22017	22/08/94	1200hrs	0.73	0.52	0.06	0.04	0.7
Aug30001	22/08/94	1800hrs	0.78	0.44	0.05	0.03	0.83
Aug30002	23/08/94	0000hrs	electronic fault				
Aug30003	23/08/94	0600hrs	electronic fault				
Aug30004	23/08/94	1200hrs	1.15	0.83	0.11	0.07	0.69
Aug30005	23/08/94	1800hrs	1.02	0.84	0.19	0.12	0.57
Aug30006	24/08/94	0000hrs	0.92	0.5	0.06	0.04	0.84
Aug30007	24/08/94	0600hrs	0.82	0.56	0.13	0.08	0.73
Aug30008	24/08/94	1200hrs	1.08	0.87	0.21	0.13	0.6
Aug30009	24/08/94	1800hrs	1.03	0.57	0.06	0.04	0.83
Aug30010	25/08/94	0000hrs	calm		0.02	0.01	
Aug30011	25/08/94	0600hrs	1.13	0.57	0.02	0.01	0.86
Aug30012	25/08/94	1200hrs	1.31	1.18	0.45	0.29	0.44
Aug30013	25/08/94	1800hrs	1.21	1.09	0.29	0.19	0.43
Aug30014	26/08/94	0000hrs	1.21	1.04	0.32	0.2	0.51
Aug30015	26/08/94	0600hrs	1.12	0.98	0.29	0.19	0.48
Aug30016	26/08/94	1200hrs	1.26	1.13	0.4	0.26	0.45
Aug30017	26/08/94	1800hrs	1.4	1.3	0.51	0.34	0.4
Aug30018	27/08/94	0000hrs	1.57	0.94	0.58	0.37	0.8
Aug30019	27/08/94	0600hrs	0.95	0.73	0.16	0.1	0.64
Aug30020	27/08/94	1200hrs	1.56	1.35	0.54	0.36	0.5
Aug30021	27/08/94	1800hrs	1.41	1.2	0.56	0.38	0.47
Aug30022	28/08/94	0000hrs	1.18	1	0.24	0.15	0.53
Aug30023	28/08/94	0600hrs	1.84	1.66	0.94	0.63	0.43
Aug30024	28/08/94	1200hrs	1.46	1.3	0.46	0.3	0.45
Aug30025	28/08/94	1800hrs	1.33	1.2	0.54	0.36	0.43
Aug30026	29/08/94	0000hrs	1.37	1.14	0.43	0.28	0.42
Aug30027	29/08/94	0600hrs	1.14	0.96	0.22	0.15	0.52
Aug30028	29/08/94	1200hrs	0.98	0.75	0.14	0.09	65
Aug30029	29/08/94	1800hrs	1	0.75	0.18	0.11	0.67
Aug30030	30/08/94	0000hrs			0.01	0.01	
Aug30031	30/08/94	0600hrs	1.29	1.05	0.18	0.11	0.57
Sep6001	30/08/94	1200hrs	1.11	0.57	0.08	0.05	0.86
Sep6002	30/08/94	1800hrs	1.36	0.74	0.05	0.04	0.84
Sep6003	31/08/94	0000hrs	calm		0.02	0.01	
Sep6004	31/08/94	0600hrs	0.86	0.44	0.03	0.02	0.86
Sep6005	31/08/94	1200hrs	0.79	0.5	0.09	0.06	0.77
Sep6006	31/08/94	1800hrs	1.24	0.64	0.05	0.03	0.86

RESULTS: Loch Lomond wave Records, September 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1 (m)	Hs (m)	E
Sep6011	01/09/94	0000hrs	calm			0	
Sep6012	01/09/94	0600hrs	2.97	1.5	0.06	0.06	0.86
Sep6013	01/09/94	1200hrs			0.03	0.03	
Sep6014	01/09/94	1800hrs	1.73	0.98	0.08	0.05	0.83
Sep6015	02/09/94	0000hrs	3.33	1.68	0.03	0.02	
Sep6016	02/09/94	0600hrs	1.62	0.58	0.05	0.03	0.86
Sep6017	02/09/94	1200hrs	electronic fault				
Sep6018	02/09/94	1800hrs	electronic fault				
Sep6019	03/09/94	0000hrs			0.03	0.02	0.86
Sep6020	03/09/94	0600hrs	0.92	0.69	0.12	0.08	0.66
Sep6021	03/09/94	1200hrs	1.18	0.95	0.59	0.38	0.59
Sep6022	03/09/94	1800hrs	1.23	1.05	0.3	0.2	0.53
Sep6023	04/09/94	0000hrs	1.25	1.01	0.22	0.15	0.58
Sep6024	04/09/94	0600hrs	1.43	0.79	0.11	0.07	0.83
Sep6025	04/09/94	1200hrs	1.05	0.68	0.1	0.06	0.76
Sep6026	04/09/94	1800hrs	1.31	1.14	0.42	0.27	0.49
Sep6027	05/09/94	0000hrs	0.66	0.33	0.04	0.03	0.86
Sep6028	05/09/94	0600hrs	1	0.72	0.08	0.05	0.68
No Data							
Sep19001	11/09/94	1800hrs	1.36	0.68	0.05	0.03	0.86
Sep19002	12/09/94	0000hrs	2.9	1.5	0.02	0.01	0.86
Sep19003	12/09/94	0600hrs	calm			0	
Sep19004	12/09/94	1200hrs	calm			0	
Sep19005	12/09/94	1800hrs	0.82	0.42	0.05	0.03	0.86
Sep19006	13/09/94	0000hrs	1.09	0.87	0.22	0.14	0.61
Sep19007	13/09/94	0600hrs	calm			0	
Sep19008	13/09/94	1200hrs	0.91	0.6	0.08	0.05	0.75
Sep19009	13/09/94	1800hrs	0.9	0.51	0.06	0.04	0.82
Sep19010	14/09/94	0000hrs	calm			0	
Sep19011	14/09/94	0600hrs	1.3	0.68	0.03	0.02	0.84
Sep19012	14/09/94	1200hrs	1.25	0.66	0.06	0.04	0.85
Sep19013	14/09/94	1800hrs	1.85	0.97	0.03	0.02	0.85
Sep19014	15/09/94	0000hrs	calm			0	
Sep19015	15/09/94	0600hrs	1.08	0.67	0.1	0.1	0.78
Sep19016	15/09/94	1200hrs	1.19	0.89	0.19	0.13	0.66
Sep19017	15/09/94	1800hrs	1.12	0.86	0.24	0.15	0.64
Sep19018	16/09/94	0000hrs	electronic fault				
Sep19019	16/09/94	0600hrs	1.2	0.63	0.03	0.02	0.86
Sep19020	16/09/94	1200hrs	1.02	0.83	0.24	0.15	0.58
Sep19021	16/09/94	1800hrs	1.4	0.99	0.12	0.08	0.71
Sep19022	17/09/94	0000hrs	2.6	1.33	0.03	0.02	0.86
Sep19023	17/09/94	0600hrs	calm			0	
Sep19024	17/09/94	1200hrs	1.29	0.91	0.14	0.09	0.71
Sep19025	17/09/94	1800hrs	1.21	1	0.19	0.12	0.57
Sep19026	18/09/94	0000hrs	0.63	0.37	0.06	0.03	0.83
Sep19027	18/09/94	0600hrs	1.95	0.97	0.03	0.02	0.87
Sep22001	18/09/94	1200hrs	1.56	0.79	0.02	0.01	0.86
Sep22002	18/09/94	1800hrs	1.21	1.14	0.43	0.28	0.33
Sep22003	19/09/94	0000hrs	1.25	0.66	0.05	0.03	0.85
Sep22004	19/09/94	0600hrs	1.12	0.66	0.08	0.05	0.81
Sep22005	19/09/94	1200hrs	1.65	0.95	0.06	0.04	0.82
Sep22006	19/09/94	1800hrs	1.76	0.89	0.03	0.02	0.86
Sep22007	20/09/94	0000hrs	1.07	0.54	0.02	0.01	0.86
Sep22008	20/09/94	0600hrs	calm			0	
Sep22009	20/09/94	1200hrs	0.75	0.42	0.06	0.04	0.83
Sep22010	20/09/94	1800hrs	calm		0	0	
Sep22011	21/09/94	0000hrs	calm			0	
Sep22012	21/09/94	0600hrs	0.85	0.42	0.02	0.01	0.85
Sep30001	21/09/94	1200hrs	calm			0	
Sep30002	21/09/94	1800hrs	calm			0	

Sep30003	22/09/94	0000hrs	calm			0	
Sep30004	22/09/94	0600hrs	calm			0	
Sep30005	22/09/94	1200hrs	calm			0	
Sep30006	22/09/94	1800hrs	calm			0	
Sep30007	23/09/94	0000hrs	calm			0	
Sep30008	23/09/94	0600hrs	calm			0	
Sep30009	23/09/94	1200hrs	calm			0	
Sep30010	23/09/94	1800hrs	calm			0	
Sep30011	24/09/94	0000hrs	calm			0	
Sep30012	24/09/94	0600hrs	calm			0	
Sep30013	24/09/94	1200hrs	calm			0	
Sep30014	24/09/94	1800hrs	calm			0	
Sep30015	25/09/94	0000hrs	calm			0	
Sep30016	25/09/94	0600hrs	calm			0	
Sep30017	25/09/94	1200hrs	calm			0	
Sep30018	25/09/94	1800hrs	calm			0	
Sep30019	26/09/94	0000hrs	calm			0	
Sep30020	26/09/94	0600hrs	calm			0	
Sep30021	26/09/94	1200hrs	calm			0	
Sep30022	26/09/94	1800hrs	calm			0	
Sep30023	27/09/94	0000hrs	calm			0	
Sep30024	27/09/94	0600hrs	calm			0	
Sep30025	27/09/94	1200hrs	calm			0	
Sep30026	27/09/94	1800hrs	calm			0	
Sep30027	28/09/94	0000hrs	calm			0	
Sep30028	28/09/94	0600hrs	calm			0	
Oct6001	28/09/94	1200hrs	1.41	1.3	0.62	0.41	0.4
Oct6002	28/09/94	1800hrs	1.36	1.19	0.46	0.3	0.48
Oct6003	29/09/94	0000hrs	1.22	0.99	0.37	0.24	0.58
Oct6004	29/09/94	0600hrs	1.08	0.9	0.3	0.19	0.56
Oct6005	29/09/94	1200hrs	1.42	1.27	0.5	0.33	0.44
Oct6006	29/09/94	1800hrs	1.19	0.91	0.23	0.15	0.64
Oct6007	30/09/94	0000hrs	0.86	0.54	0.12	0.07	0.77
Oct6008	30/09/94	0600hrs	3.84	2.02	0.04	0.03	0.085
Oct6009	30/09/94	1200hrs	0.1	0.52	0.06	0.03	0.85
Oct6010	30/09/94	1800hrs	electronic error				

RESULTS: Loch Lomond Wave Records, October 1994							
Oct6011	01/10/94	0000hrs	calm			0	
Oct6012	01/10/94	0600hrs	1.22	1.03	0.32	0.21	0.54
Oct6013	01/10/94	1200hrs	1.22	1.03	0.3	0.2	0.53
Oct6014	01/10/94	1800hrs	1.36	0.8	0.12	0.07	0.81
Oct6015	02/10/94	0000hrs			0.04	0.03	
Oct6016	02/10/94	0600hrs	0.92	0.49	0.06	0.03	0.84
Oct6017	02/10/94	1200hrs	1.39	0.7	0.08	0.05	0.86
Oct6018	02/10/94	1800hrs	1	0.74	0.19	0.12	0.67
Oct6019	03/10/94	0000hrs	1.41	0.71	0.02	0.01	0.86
Oct6020	03/10/94	0600hrs	2.29	1.15	0.04	0.03	0.86
Oct6021	03/10/94	1200hrs	1.1	0.82	0.32	0.21	0.66
Oct6022	03/10/94	1800hrs	1.17	0.93	0.28	0.18	0.6
Oct6023	04/10/94	0000hrs	1.74	0.89	0.06	0	0.86
Oct6024	04/10/94	0600hrs	1.89	1.08	0.06	0.04	0.81
Oct6025	04/10/94	1200hrs	1.08	0.7	0.11	0.06	0.77
Oct6026	04/10/94	1800hrs	1.18	0.95	0.34	0.22	0.6
Oct6027	05/10/94	0000hrs	1.09	0.36	0.23	0.23	0.56
Oct6028	05/10/94	0600hrs	1.12	0.89	0.3	0.19	0.6
Oct6029	05/10/94	1200hrs	1.36	1.22	0.48	0.32	0.44
Oct17001	05/10/94	1800hrs	1.48	1.3	0.41	0.26	0.48
Oct17002	06/10/94	0000hrs	1.37	1.15	0.43	0.28	0.54
Oct17003	06/10/94	0600hrs	1.29	1.08	0.34	0.22	0.55
Oct17004	06/10/94	1200hrs	1.3	1.11	0.38	0.25	0.52
Oct17005	06/10/94	1800hrs	1.05	0.8	0.2	0.11	0.65
Oct17006	07/10/94	0000hrs	1.18	0.9	0.24	0.16	0.64
Oct17007	07/10/94	0600hrs	1.27	0.78	0.11	0.06	0.79
Oct17008	07/10/94	1200hrs	calm			0	
Oct17009	07/10/94	1800hrs	1.23	0.98	0.37	0.24	0.61
Oct17010	08/10/94	0000hrs	1.11	0.56	0.02	0.01	0.86
Oct17011	08/10/94	0600hrs	1.06	0.53	0.02	0.01	0.86
Oct17012	08/10/94	1200hrs	electronic fault				
Oct17013	08/10/94	1800hrs	calm			0	
Oct17014	09/10/94	0000hrs	2.14	1.07	0.02	0.01	0.86
Oct17015	09/10/94	0600hrs			0.04	0.02	
Oct17016	09/10/94	1200hrs	4	2.04	0.02	0.01	0.86
Oct17017	09/10/94	1800hrs	calm			0	
Oct17018	10/10/94	0000hrs	1.09	0.55	0.02	0.01	0.86
Oct17019	10/10/94	0600hrs	calm		0.02	0.01	
Oct17020	10/10/94	1200hrs	calm			0	
Oct17021	10/10/94	1800hrs	calm			0	
Oct17022	11/10/94	0000hrs	calm		0.02	0.01	
Oct17023	11/10/94	0600hrs	calm			0	
Oct17024	11/10/94	1200hrs	1.15	0.58	0.04	0.01	0.86
Oct17025	11/10/94	1800hrs	calm				
Oct17026	12/10/94	0000hrs	calm				
Oct17027	12/10/94	0600hrs	calm			0	
Oct17028	12/10/94	1200hrs	calm			0	
Oct17029	12/10/94	1800hrs	calm			0	
Oct17030	13/10/94	0000hrs	0.92	0.47	0.06	0.03	
Oct17031	13/10/94	0600hrs	1.51	0.76	0.04	0.03	0.86
Oct17032	13/10/94	1200hrs			0.02	0.01	
Oct17033	13/10/94	1800hrs	calm			0	
Oct17034	14/10/94	0000hrs	1.14	0.57	0.02	0.01	0.86
Oct17035	14/10/94	0600hrs	5.17	2.63	0.02	0.01	0.87
Oct17036	14/10/94	1200hrs	1.74	0.88	0.04	0.02	0.86
Oct17037	14/10/94	1800hrs			0.02	0.02	
Oct17038	15/10/94	0000hrs	0.99	0.5	0.08	0.05	0.86
Oct17039	15/10/94	0600hrs	0.85	0.43	0.04	0.02	0.86
Oct17040	15/10/94	1200hrs	1.31	0.9	0.34	0.22	0.87
Oct17041	15/10/94	1800hrs	1.29	0.65	0.06	0.03	0.73
Oct17042	16/10/94	0000hrs	calm		0		
Oct17043	16/10/94	0600hrs	0.92	0.47	0.04	0.02	0.86
Oct24001	16/10/94	1200hrs	calm		0	0	
Oct24002	16/10/94	1800hrs	calm		0	0	
Oct24003	17/10/94	0000hrs	0.88	0.56	0.11	0.07	0.77
Oct24004	17/10/94	0600hrs	0.88	0.51	0.11	0.07	0.77

Oct24005	17/10/94	1200hrs	0.99	0.52	0.09	0.09	0.82
Oct24006	17/10/94	1800hrs	0.87	0.46	0.06	0.04	0.84
Oct24007	18/10/94	000hrs	0.88	0.47	0.06	0.04	0.85
Oct24008	18/10/94	0600hrs	1.52	0.81	0.12	0.08	0.85
Oct24009	18/10/94	1200hrs	1.07	0.56	0.06	0.04	0.84
Oct24010	18/10/94	1800hrs	1.03	0.7	0.13	0.08	0.86
Oct24011	19/10/94	0000hrs	0.97	0.54	0.09	0.05	0.73
Oct24012	19/10/94	0600hrs	0.96	0.52	0.86	0.05	0.83
Oct24013	19/10/94	1200hrs	0.9	0.49	0.06	0.04	0.84
Oct24014	19/10/94	1800hrs	0.89	0.57	0.06	0.04	0.84
Oct24015	20/10/94	0000hrs	1.18	0.78	0.06	0.04	0.82
Oct24016	20/10/94	0600hrs	1.07	0.54	0.04	0.03	0.81
Oct42017	20/10/94	1200hrs	1.12	0.57	0.04	0.03	0.86
Oct24018	20/10/94	1800hrs	0.86	0.44	0.2	0.03	0.86
Oct24019	21/10/94	0000hrs	1.17	0.6	0.08	0.05	0.86
Oct24020	21/10/94	0600hrs	0.9	0.46	0.04	0.03	0.85
Oct24021	21/10/94	1200hrs	0.92	0.46	0.04	0.03	0.87
Oct24022	21/10/94	1800hrs	1.89	1.11	0.04	0.03	0.87
Oct24023	22/10/94	0000hrs	0.91	0.47	0.06	0.04	0.81
Oct24024	22/10/94	0600hrs	1.15	0.64	0.06	0.04	0.85
Oct24025	22/10/94	1200hrs	1.41	0.92	0.42	0.05	0.83
Oct24026	22/10/94	1800hrs	1.41	1.23	0.37	0.24	0.76
Oct24027	23/10/94	0000hrs	1.27	1.1	0.37	0.25	0.49
Oct24028	23/10/94	0600hrs	1.14	0.93	0.26	0.17	0.58
Oct31001	23/10/94	1200hrs	1.58	1.43	0.56	0.37	0.42
Oct31002	23/10/94	1800hrs	1.46	1.31	0.5	0.33	0.44
Oct31003	24/10/94	0000hrs	1.4	1.13	0.32	0.21	0.59
Oct31004	24/10/91	0600hrs	1.1	0.85	0.28	0.18	0.63
Oct31005	24/10/94	1200hrs	1.2	1.02	0.3	0.19	0.53
Oct 31006	24/10/94	1800hrs	calm			0	
Oct31007	25/10/94	0000hrs	calm			0	
Oct31008	25/10/94	0600hrs	calm			0	
Oct31009	25/10/94	1200hrs	1.02	0.76	0.18	0.11	0.65
Oct31010	25/10/94	1800hrs	calm			0	
Oct31011	26/10/94	0000hrs	1.07	0.77	0.14	0.09	0.65
Oct31012	26/10/94	0600hrs	1.36	0.72	0.07	0.04	0.7
0ct31013	26/10/94	1200hrs	1.14	0.7	0.12	0.07	0.85
Oct31014	26/10/94	1800hrs	1.22	0.85	0.15	0.1	0.77
Oct31015	27/10/94	0000hrs	1.32	0.66	0.03	0.02	0.72
Oct31016	27/10/94	0600hrs	1.38	0.8	0.05	0.04	0.86
Oct31018	27/10/94	1200hrs	1.23	0.78	0.16	0.1	0.77
Oct31019	27/10/94	1800hrs	1.23	0.78	0.16	0.1	0.6
Oct31020	28/10/94	0000hrs	0.92	0.49	0.03	0.03	0.77
Oct31021	28/10/94	0600hrs	0.95	0.51	0.06	0.04	0.77
Oct31022	28/10/94	1200hrs	calm			0	
Oct31023	28/10/94	1800hrs	calm			0	
Oct31024	28/10/94	0000hrs	calm			0	
Oct31025	29/10/94	0600hrs	calm			0	
Oct31026	29/10/94	1200hrs	1.32	1.1	0.23	0.15	0.56
Oct31027	30/10/94	0000hrs	1.18	0.73	0.12	0.08	0.78
Oct31028	30/10/94	0600hrs	1.34	0.82	0.1	0.06	0.79
Nov8003	31/10/94	0000hrs	1.57	1.32	0.46	0.3	0.53
Nov8004	31/10/94	0600hrs	1.62	1.45	0.39	0.26	0.45
Nov8005	31/10/94	1200hrs	1.13	0.87	0.18	0.12	0.65
Nov8006	31/10/94	1800hrs	1.42	0.72	0.06	0.04	0.86

RESULTS: Loch Lomond Wave Records, November 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	H1	Hs	E
Nov8003	01/11/94	0000hrs	1.57	1.32	0.46	0.3	0.53
Nov8004	01/11/94	0600hrs	1.62	1.45	0.39	0.26	0.45
Nov8005	01/11/94	1200hrs	1.13	0.87	0.18	0.12	0.65
Nov8006	01/11/94	1800hrs	1.42	0.72	0.06	0.04	0.86
Nov8007	02/11/94	0000hrs	calm			0	
Nov8008	02/11/94	0600hrs	0.96	0.48	0.04	0.03	0.87
Nov8009	02/11/94	1200hrs	0.85	0.5	0.08	0.05	0.81
Nov8010	02/11/94	1800hrs	1.12	0.74	0.08	0.06	0.76
Nov8011	03/11/94	0000hrs	0.87	0.46	0.06	0.04	0.85
Nov8012	03/11/94	0600hrs	calm			0	
Nov8013	03/11/94	1200hrs	1.33	0.8	0.04	0.03	0.8
Nov8014	03/11/94	1800hrs	1.03	0.67	0.12	0.08	0.76
Nov8015	04/11/94	0000hrs	1.11	0.57	0.06	0.04	0.86
Nov8016	04/11/94	0600hrs	1.05	0.53	0.04	0.03	0.87
Nov8017	04/11/94	1200hrs	1.11	0.6	0.04	0.02	0.84
Nov8019	04/11/94	1800hrs	1.43	0.73	0.08	0.05	0.86
Nov8020	05/11/94	0000hrs	calm			0	
Nov8021	05/11/94	0600hrs	1.53	0.77	0.04	0.03	0.86
Nov8022	05/11/94	1200hrs	calm			0	
Nov8023	05/11/94	1800hrs	calm			0	
Nov8024	06/11/94	0000hrs	2.88	1.45	0.02	0.01	0.86
Nov8025	06/11/94	0600hrs	2.8	1.45	0.02	0.01	0.86
Nov8026	06/11/94	1200hrs	1.43	0.72	0.08	0.05	0.86
Nov8027	06/11/94	1800hrs	calm		c0.04	0.02	
Nov8028	07/11/94	0000hrs	calm		c0.04	0.02	
Nov8029	07/11/94	0600hrs	calm		c0.04	0.02	
Nov8030	07/11/94	1200hrs	calm		0.02	0.01	
Nov8031	07/11/94	1800hrs	1.06	0.54	0.06	0.04	0.86
Nov8032	08/11/94	0000hrs	1.15	0.58	0.04	0.03	0.86
Nov14002	08/11/94	1800hrs			c0.03	0.01	
Nov14003	09/11/94	0000hrs	0.9	0.51	0.06	0.04	0.84
Nov14004	09/11/94	0600hrs	1.25	0.63	0.04	0.03	0.86
Nov14005	09/11/94	1200hrs	calm		c0.01	0.01	
Nov14006	09/11/94	1800hrs	0.8	0.41	0.06	0.04	0.86
Nov14007	10/11/94	0000hrs	0.84	0.43	0.06	0.04	0.86
Nov14008	10/11/94	0600hrs	1.34	0.67	0.04	0.03	0.86
Nov14009	10/11/94	1200hrs	2.14	1.07	0.04	0.03	0.86
Nov14010	10/11/94	1800hrs	calm		0.02	0.01	
Nov14011	11/11/94	0000hrs	calm		0.02	0.01	
Nov14012	11/11/94	0600hrs	calm		0.02	0.01	
Nov14013	11/11/94	1200hrs	calm		0.02	0.01	
Nov14014	11/11/94	1800hrs	1.87	0.94	0.02	0.01	0.8
Nov14015	12/11/94	0000hrs	4.05	2.27	0.04	0.03	0.82
Nov14016	12/11/94	0600hrs	1.02	0.52	0.04	0.02	0.86
Nov14017	12/11/94	1200hrs	1.4	0.71	0.04	0.03	0.86
Nov14018	12/11/94	1800hrs	calm			0	
Nov14019	13/11/94	0000hrs	3.74	1.89	0.02	0.01	0.86
Nov14020	13/11/94	0600hrs	1.3	0.66	0.04	0.02	0.86
Nov14021	13/11/94	1200hrs	2.38	1.99	0.67	0.44	0.55
Nov14022	13/11/94	1800hrs	1.17	0.88	0.2	0.13	0.66
Nov14023	14/11/94	0000hrs	1.45	0.74	0.06	0.04	0.86
Nov14024	14/11/94	0600hrs	1.6	1.41	0.36	0.24	0.47
Hov21001	14/11/94	1200hrs	1.92	1.8	0.53	0.36	0.34
Hov21002	14/11/94	1800hrs	1.68	1.47	0.31	0.2	0.49
Hov21003	15/11/94	0000hrs	1.28	1.02	0.16	0.11	0.61
Hov21004	15/11/94	0600hrs	1.57	1.22	0.31	0.2	0.63
Hov21005	15/11/94	1200hrs	1.41	1.13	0.15	0.1	0.6
Hov21006	15/11/94	1800hrs	1.48	1.2	0.18	0.12	0.59
Hov21007	16/11/94	0000hrs	1.43	1	0.16	0.1	0.7
Hov21008	16/11/94	0600hrs	1.23	0.84	0.14	0.09	0.73
Hov21009	16/11/94	1200hrs	1.58	1.24	0.29	0.16	0.62
Hov21010	16/11/94	1800hrs	1.57	1.22	0.19	0.13	0.63
Hov21011	17/11/94	0000hrs	1.29	0.89	0.14	0.09	0.73
Hov21012	17/11/94	0600hrs	1.33	0.92	0.16	0.1	0.72
Hov21013	17/11/94	1200hrs	1.25	0.85	0.14	0.09	0.73
Hov21014	17/11/94	1800hrs	calm		0.01	0.01	
Hov21015	17/11/94	0000hrs	calm		0.02	0.01	
Hov21016	17/11/94	0600hrs	calm		0.02	0.01	
Hov21017	18/11/94	1200hrs	2.4	1.2	0.02	0.01	0.86
Hov21018	18/11/94	1800hrs	1.11	0.56	0.02	0.01	0.86
Hov21019	19/11/94	0000hrs	calm		0.03	0.02	

Hov21020	19/11/94	0600hrs	1.36	0.9	0.12	0.08	0.74
Hov21021	19/11/94	1200hrs	1.27	0.8	0.13	0.08	0.78
Hov21022	19/11/94	1800hrs	1.69	0.88	0.06	0.04	0.86
Hov21023	20/11/94	0000hrs	1.12	0.68	0.1	0.06	0.8
Hov21024	20/11/94	0600hrs	1.56	1.13	0.11	0.07	0.69
Hov21025	20/11/94	1200hrs	1.67	1.21	0.15	0.1	0.69
Hov21026	20/11/94	1800hrs	1.21	0.83	0.11	0.07	0.73
Hov21027	21/11/94	0000hrs	1.13	0.89	0.11	0.72	
Hov21028	21/11/94	0600hrs	1.23	0.88	0.11	0.07	0.7
Nov29001	21/11/94	1200hrs	calm			0	
Nov29002	21/11/94	1800hrs	calm			0	
Nov29003	22/11/94	0000hrs	1.522	1.04	0.0704	0.04	0.72
Nov29004	22/11/94	0600hrs	1.51	1.04	0.17	0.11	0.66
Nov29005	22/11/94	1200hrs	1.39	0.74	0.05	0.03	0.84
Nov29006	22/11/94	1800hrs	calm			0	
Nov29007	23/11/94	0000hrs	1.33	0.74	0.08	0.05	0.83
Nov29008	23/11/94	0600hrs	1.07	0.63	0.09	0.05	0.81
Nov29009	23/11/94	1200hrs	1.71	1.38	0.22	0.15	0.59
Nov29010	23/11/94	1800hrs	1.24	0.83	0.08	0.05	0.74
Nov29011	24/11/94	0000hrs	1.25	0.79	0.07	0.04	0.78
Nov29012	24/11/94	0600hrs	1.23	0.83	0.12	0.08	0.74
Nov29013	24/11/94	1200hrs	1.53	1.06	0.07	0.04	0.73
Nov29014	24/11/94	1800hrs	1.15	0.79	0.08	0.05	0.72
Nov29015	25/11/94	0000hrs	calm			0	
Nov29016	25/11/94	0600hrs	calm			0	
Nov29017	25/11/94	1200hrs	calm				
Nov29018	25/11/94	1800hrs	calm				
Nov29019	26/11/94	0000hrs	1.23	0.74	0.12	0.08	0.8
Nov29020	26/11/94	0600hrs	1.34	0.95	0.16	0.11	0.7
Nov29021	26/11/94	1200hrs	1.07	0.55	0.05	0.03	0.8
Nov29022	26/11/94	1800hrs	0.97	0.62	0.07	0.04	0.77
Nov29023	27/11/94	0000hrs	1.52	0.84	0.03	0.02	0.83
Nov29024	27/11/94	0600hrs	1.54	0.93	0.12	0.08	0.79
Nov29025	27/11/94	1200hrs	1.09	0.69	0.1	0.07	0.78
Nov29026	27/11/94	1800hrs	1.35	1.78	0.09	0.06	0.82
Nov29027	28/11/94	0000hrs	1.17	0.78	0.11	0.07	0.75
Nov29028	28/11/94	0600hrs	1.28	0.92	0.18	0.11	0.69
Nov29029	28/11/94	1200hrs	1.49	1.07	0.16	0.1	0.69
Nov29030	28/11/94	1800hrs	1.13	0.76	0.11	0.07	0.74
Nov29031	29/11/94	0000hrs	2.25	1.56	0.03	0.02	0.74
Nov29032	29/11/94	0600hrs	calm				
Nov29033	29/11/94	1200hrs	calm				
Dec5001	29/11/94	1800hrs	electrical fault				
Dec5002	30/11/94	0000hrs	calm				
Dec5003	30/11/94	0600hrs	calm				
Dec5004	30/11/94	1200hrs	calm				
Dec5005	30/11/94	1800hrs	calm				
Dec5006	01/12/94	0000hrs	calm			0	
Dec5007	01/12/94	0600hrs	calm			0	
Dec5008	01/12/94	1200hrs	calm			0	
Dec5009	01/12/94	1800hrs	calm			0	

RESULTS: Loch Lomond Wave Records, December 1994							
File Name	Date	Time	Tz (sec)	Tc (sec)	Hl (m)	Hs (m)	E
Dec5006	01/12/94	0000hrs	calm			0	
Dec5007	01/12/94	0600hrs	calm			0	
Dec5008	01/12/94	1200hrs	calm			0	
Dec5009	01/12/94	1800hrs	calm			0	
Dec5010	02/12/94	0000hrs	0.85	0.42	0.02	0.01	0.87
Dec5011	02/12/94	0600hrs	calm			0	
Dec5012	02/12/94	1200hrs	calm			0	
Dec5013	02/12/94	1800hrs	calm			0	
Dec5014	02/12/94	0000hrs	calm			0	
Dec5015	03/12/94	0600hrs	1.29	0.87	0.09	0.06	0.73
Dec5016	03/12/94	1200hrs	0.92	0.67	0.12	0.07	0.7
Dec5017	03/12/94	1800hrs	1.19	0.89	0.17	0.11	0.67
Dec5018	03/12/94	0000hrs	1.54	1.31	0.32	0.21	0.52
Dec5019	04/12/94	0600hrs	1.05	0.73	0.1	0.06	0.7
Dec5020	04/12/94	1200hrs	3.5	1.78	0.04	0.03	0.86
Dec5021	04/12/94	1800hrs	calm			0	
Dec5022	04/12/94	0000hrs	calm			0	
Dec5023	05/12/94	0600hrs	calm			0	
						0	
Dec9001	05/12/94	1200hrs	1.04	0.53	0.08	0.05	0.85
Dec9002	05/12/94	1800hrs	1.75	1.52	0.51	0.34	0.49
Dec9003	06/12/94	0000hrs	1.64	1.43	0.34	0.23	0.49
Dec9004	06/12/94	0600hrs	1.57	1.37	0.36	0.24	0.49
Dec9005	06/12/94	1200hrs	1.24	1	0.24	0.16	0.59
Dec9006	06/12/94	1800hrs	1.04	0.65	0.09	0.06	0.78
Dec9007	07/12/94	0000hrs	1.04	0.65	0.09	0.05	0.78
Dec9008	07/12/94	0600hrs	1.64	0.53	0.35	0.23	0.37
Dec9009	07/12/94	1200hrs	1.46	1.26	0.33	0.21	0.[illegible]
Dec9010	07/12/94	1800hrs	1.66	1.42	0.4	0.26	0.51
Dec9011	08/12/94	0000hrs	1.6	1.39	0.35	0.23	0.49
Dec9012	08/12/94	0600hrs	1.15	0.86	0.14	0.09	0.67
Dec9013	08/12/94	1200hrs	1.62	1.42	0.39	0.26	0.47
Dec9014	08/12/94	1800hrs	1.84	1.61	0.34	0.22	0.48
Dec9015	09/12/94	0000hrs	1.55	1.38	0.24	0.16	0.46
Dec9016	09/12/94	0600hrs	1.92	1.69	0.41	0.27	0.47
Dec20001	09/12/94	1200hrs	1.69	1.45	0.32	0.21	0.52
Dec20002	09/12/94	1800hrs	1.59	1.28	0.2	0.13	0.59
Dec20003	10/12/94	0000hrs	1.67	1.48	0.35	0.23	0.46
Dec20004	10/12/94	0600hrs	1.5	1.21	0.16	0.11	0.59
Dec20005	10/12/94	1200hrs	1.74	1.48	0.3	0.2	0.53
Dec20006	10/12/94	1800hrs	1.63	1.33	0.25	0.16	0.58
Dec20007	11/12/94	0000hrs	1.67	1.38	0.25	0.17	0.56
Dec20008	11/12/94	0600hrs			0.01	0.01	
Dec20009	11/12/94	1200hrs	1.7	1.02	0.01	0.01	0.71
Dec20010	11/12/94	1800hrs	1.74	1.66	0.12	0.07	0.74
Dec20011	12/12/94	0000hrs	1.61	1.05	0.09	0.06	0.76
Dec20012	12/12/94	0600hrs	1.71	1.31	0.14	0.09	0.64
Dec20013	12/12/94	1200hrs	1.77	1.4	0.11	0.07	0.61
Dec20014	12/12/94	1800hrs	1.62	1.2	0.11	0.07	0.67
Dec20015	13/12/94	0000hrs	1.46	1.04	0.08	0.05	0.71
Dec20016	13/12/94	0600hrs	calm			0	
Dec20017	13/12/94	1200hrs	calm			0	
Dec20018	13/12/94	1800hrs	calm			0	
Dec20019	14/12/94	0000hrs	calm			0	
Dec20020	14/12/94	0600hrs	calm			0	
Dec20021	14/12/94	1200hrs	calm			0	
Dec20022	14/12/94	1800hrs	calm			0	
Dec20023	15/12/94	0000hrs	calm			0	
Dec20024	15/12/94	0600hrs	calm			0	
Dec20025	15/12/94	1200hrs	calm			0	
Dec20026	15/12/94	1800hrs	1.39	0.93	0.09	0.05	0.74
Dec20027	16/12/94	0000hrs	electronic fault				
Dec20028	16/12/94	0600hrs	1.34	0.77	0.07	0.04	0.82

Dec20029	16/12/94	1200hrs	1.3	0.88	0.06	0.04	0.74
Dec20030	16/12/94	1800hrs	calm			0	
Dec20031	17/12/94	0000hrs	calm			0	
Dec20032	17/12/94	0600hrs	1.73	1.53	0.18	0.12	0.46
Dec20033	17/12/94	1200hrs	2.13	1.68	0.21	0.14	0.61
Dec20034	17/12/94	1800hrs	electronic fault			0	
Dec20035	18/12/94	0000hrs	1.56	1.15	0.13	0.08	0.67
Dec20036	18/12/94	0600hrs	1.2	1.75	0.16	0.11	0.48
Dec20037	18/12/94	1200hrs	electronic fault			0	
Dec20038	18/12/94	1800hrs	1.81	1.56	0.21	0.14	0.51
Dec20039	19/12/94	0000hrs	1.5	1.2	0.13	0.08	0.68
Dec20040	19/12/94	0600hrs	calm			0	
Dec20041	19/12/94	1200hrs	1.34	0.84	0.06	0.04	0.78
Dec20042	19/12/94	1800hrs	calm			0	
Dec20043	20/12/94	0000hrs	calm			0	
Dec20044	20/12/94	0600hrs	calm			0	

Appendix D Monthly weather summary (1994). (Source: Weather Log: January-December 1994).

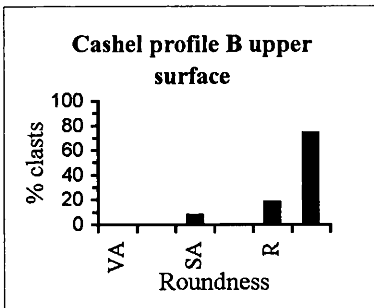
Month (1994)	Weather Summary
January	'Heavy rain and gales at times, with peak gusts of 104 km hr^{-1} on 23^{rd};' wettest January on record.
February	'3^{rd} cyclonic month in succession'. In contrast to Dec and Jan there was a marked south-easterly bias with pressure well above average. The 1^{st} 10 days were the wettest with frequent westerly and southerly winds and snow'.
March	'Westerlies dominated to an almost unprecedented extent in March. From the 1^{st} to the 15^{th}, a vigorous west to south-westerly flow covered the British Isles, several depressions tracked between Scotland and Iceland, with active fronts crossing the country. Persistent rain in the N and W, often accompanied by gale force winds. Strong south-westerlies returned later on the 21^{st}, bringing widespread rain and a rise in temperature. On the 22^{nd}, Sloy (NW Loch Lomond) recorded 55 mm of rain'.
April	'Frequently north-westerly and northerly winds during the first half of the month gave way to southerly and anticyclonic types during the last 10 days. Heavy snowfalls on the 8^{th} and 9^{th}.' Rainfall was above normal.
May	'Easterly and south-westerly weather systems were more frequent than usual. Generally dry and sunny. During the last 3 days of the month, westerlies returned to Scotland with strong winds and rain.'
June	'Westerly types dominated overall. During the first week, westerly winds, blustery and showery. North-westerly winds lasted from the 8^{th}-11^{th}. On the 17^{th} and 18^{th} windy weather spread across Scotland. The Glasgow area had 50% above average rainfall.'
July	Anticyclonic conditions prevailed for most of July. Heavy precipitation was recorded at the end of the month (31^{st}).
August	'Variable conditions, with a succession of short lived pressure types, including stormy and thundery conditions. Heavy rain in Scotland 21^{st}-22^{nd}. Variable winds: cyclonic southerly type during the first four days with storms, anticyclonic westerlies on the 5^{th} and 6^{th}, north-westerlies brought drier weather from the 12^{th}. On the 16^{th} and 17^{th} southerly winds prevailed, followed by westerlies.'
September	'Westerly cyclonic conditions until mid-month, and variable after that. Scotland was drier and sunnier than average. During the last few days Scotland became windy and unsettled.'
October	'Mainly anticyclonic the first half and cyclonic with heavy rain the second'
November	'Southerly and south-westerly winds blow almost without a break, but

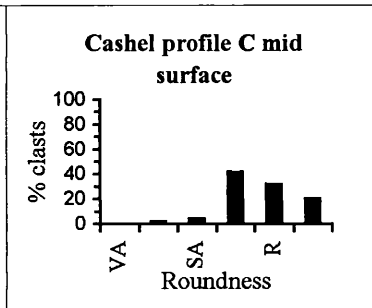
	considerable contrast between a mainly cyclonic first week and much more anticyclonic conditions from the 20th. A strong south-westerly flow persisted from the 13th to 20th.'
December	'Mild south-westerlies prevailed for most of the month, with a brief anticyclonic interlude just before Christmas. 10th-11th-prolonged heavy rain, flooding particularly serious in Glasgow, Kirkintilloch. At Loch Sloy (NW of Loch Lomond) 170 mm fell on the 10th, and 330 mm over a week. Milder weather from 22nd. Glasgow had one of wettest Decembers this century.'

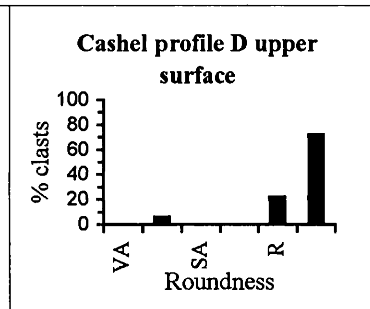
APPENDIX E Beach Powers' Roundness Results

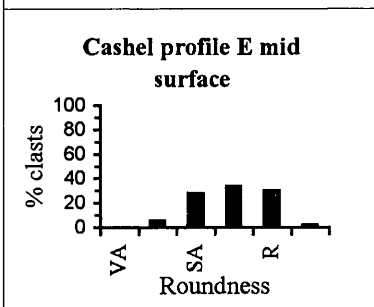
Powers' Roundness results: VA = very angular; A = angular; SA = sub-angular; Sr = sub-rounded; R = rounded; WR = well rounded

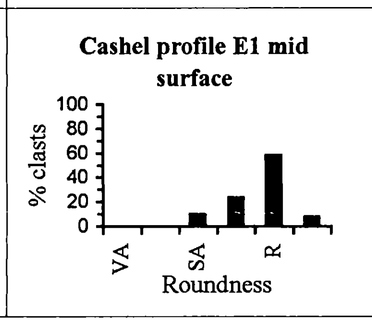
Cashel

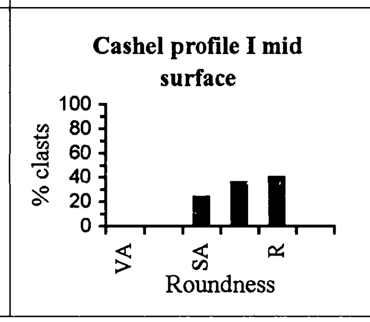




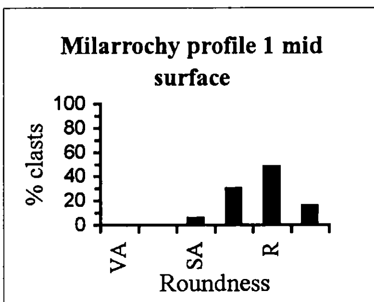


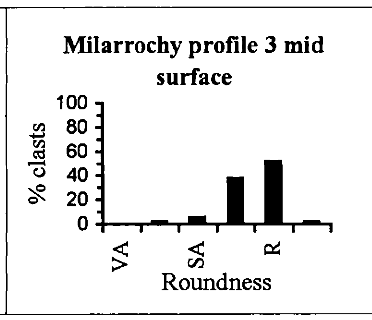


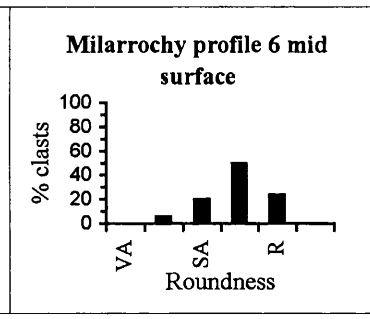




Milarrochy







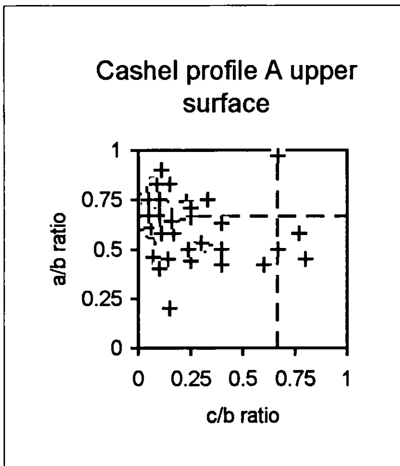
Appendix F
Sub-surface sediment particle sizes for Cashel and Milarrochy

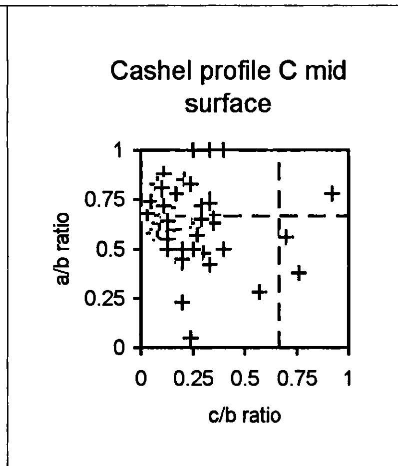
Summary Particle Size Analysis: Cashel, Sub-surface Samples.										
Upper Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-2.02	-0.58	-2.45		-2.87	-3.09	-4.04	-4.42	-4.23	-4.14
Sorting	1.12	0.88	1.51		0.82	1.01	0.71	0.36	0.71	0.75
Skewness	0.18	-0.16	-0.15		0.07	-0.08	0.03	0.02	0	-0.2
Median	-1.85	-0.67	-2.62	3.6	-2.83	-3.07	-4.21	-4.4	-4.21	-4.23
phi 16	-0.87	0.35	-0.8		-2.06	-2.06	-3.27	-4.08	-3.5	-3.34
phi 84	-3.33	-1.41	-3.91		-3.73	-4.13	-4.78	-4.8	-4.96	-4.84
Mid Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-1.34	-4.27	-5.53	1.47	-1.89	-3.77	-2.66	-3.66	-5.75	-3.51
Sorting	1.41	1.62	1.73	2.78	1.96	1.09	0.76	0.63	1.64	0.93
Skewness	-0.07	-0.86	-0.31	0.8	-0.16	-0.26	0.06	0.12	0	-0.05
Median	-1.33	-5.12	-1.91	3.11	-2.14	-3.89	-2.65	-3.65	-5.75	-3.49
phi 16	-0.13	-2.33	0.5	3.75	0.39	-2.7	-2.02	-3.07	-3.76	-2.58
phi 84	-2.51	-5.38	-3.18	-2.46	-3.91	-4.73	-3.3	-4.27	-4.48	4.44
Lower Beach										
Profiles	I	H	G	F	E	E1	D	C	B	A
Mean	-5.9	-4.73	-5.11	-4.38	-5.31	-3.5	-3.5	-2.37	-3.67	-2.08
Sorting	0.4	0.67	0.38	0.6	1	0.98	0.39	1.08	1.69	1.13
Skewness	-0.08	-0.41	-0.06	-0.56	0.06	0.06	-0.3	-0.53	0.58	-0.2
Median	-5.9	-4.87	-5.14	-4.57	-5.66	-3.47	-3.56	-2.68	-4.26	-2.27
phi 16	0.49	-0.08	-1.01	-2.84	-3.13	0.32	-1.65	-1.23	-1.72	-0.25
phi 84	-4	-3.96	-3.31	-4.68	-5.78	-0.85	-2.48	-3.2	-5.02	-5.35

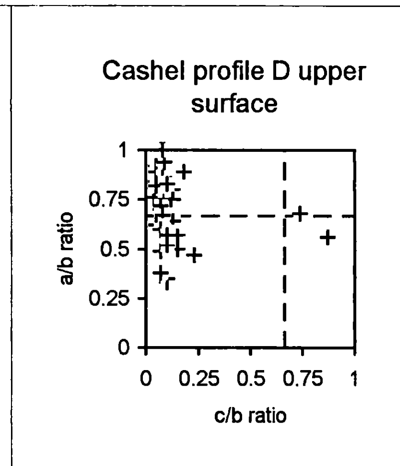
Summary Particle Size Analysis: Milarrochy, Sub-surface Samples						
Upper Beach						
Profiles	1	2	3	4	5	6
mean	0.89	-1.42	-1.23		-1.61	-2.47
sorting	0.94	1.56	1.99		2.04	1.92
Skewness	0.19	-0.67	-0.3		-0.45	0.5
Median	0.98	-2.22	-1.65	1.41	-2.14	-1.46
phi 16	1.68	0.68	1.13		0.65	-1.09
phi 84	0	-2.73	-3.17	0.59	-3.35	-4.85
Mid Beach						
profiles	1	2	3	4	5	6
mean	-0.02	-0.81	-0.36	-3.24	-2.2	-3.45
sorting	1.21	1.9		0.63	2.53	1.86
skewness	-0.17	0.06	-1.82	-0.25	0.25	-0.45
median	2.6	-0.74		-3.29	-1.36	-3.75
phi 16	1.44	1.29	-1.82	-2.62	0.06	-1.09
phi 84	-1.32	-2.98	-2.47	-3.81	-5.3	-4.79
Lower Beach						
Profiles	1	2	3	4	5	6
mean	-1.4	-0.08	-0.5	-2.39	-2.86	-2.85
sorting	1.46	1.11	1.92	2.57	2.69	2.73
skewness	0.02	-0.16	0.55	-0.35	-0.61	-0.69
median	-1.36	-0.17	1.05	-3	-4.03	-4.29
phi 16	0.02	1.21	1.93	0.77	0.76	1.03
phi 84	-2.85	-1.29	-1.49	-4.94	-5.31	-5.28

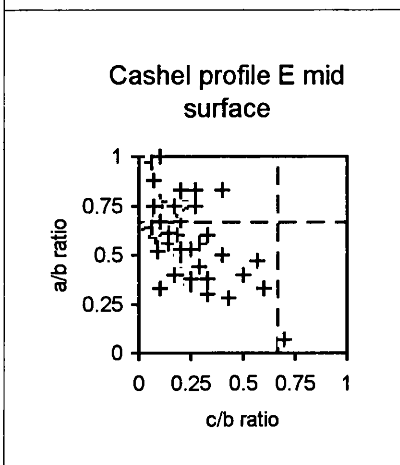
Appendix G Zingg shape diagrams from beach surface samples.

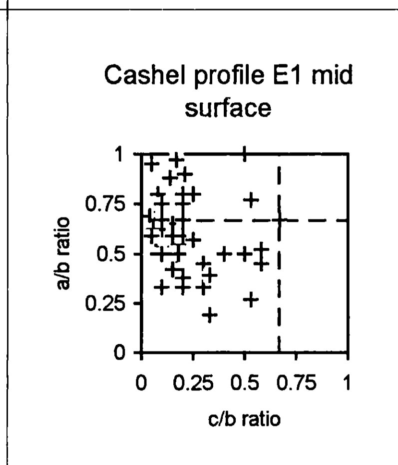
Cashel

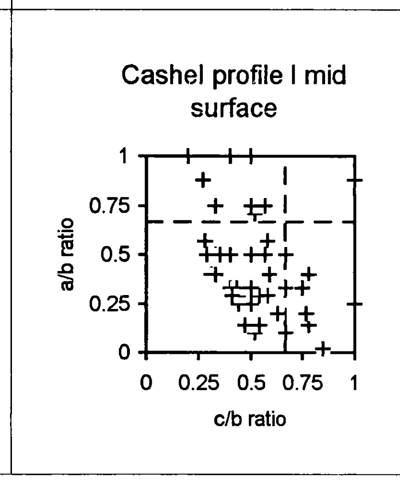


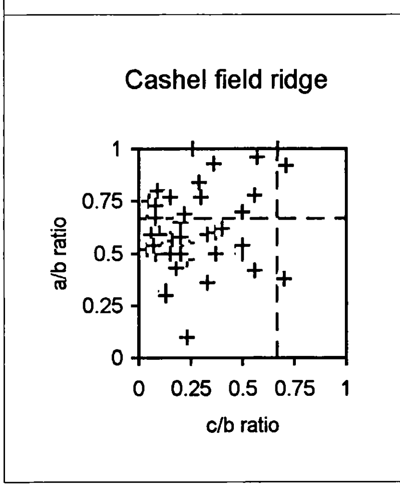




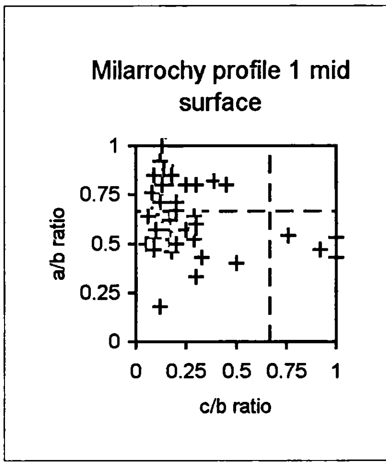


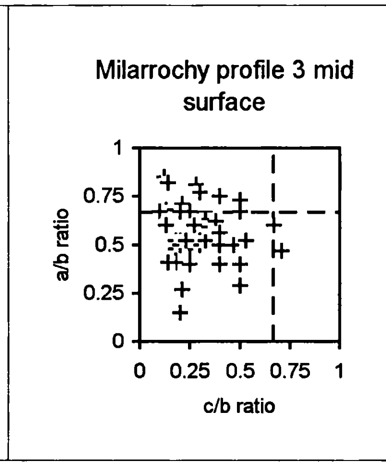






Milarrochy


Milarrochy profile 1 mid surface
a/b ratio
c/b ratio
0
0.25
0.5
0.75
1


Milarrochy profile 3 mid surface
a/b ratio
c/b ratio
0
0.25
0.5
0.75
1

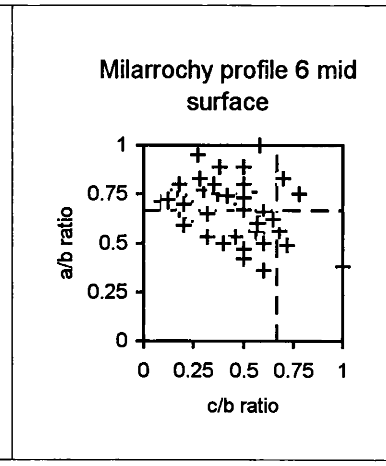

Milarrochy profile 6 mid surface
a/b ratio
c/b ratio
0
0.25
0.5
0.75
1

Fig. 5.1 Geomorphology Cashel
Note stream numbers (see text, section 5.4) and location of pit for stratigraphic log (marked x).

Fig. 5.2 Geomorphology: Milarrochy
Note stream numbers (see text, section 5.4) and location of pit for stratigraphic log (marked x).
Since 1994, there has been extensive re-modelling of the upper beach, including removal of backshore vegetation, flattening of the upper berm, introduction of shore defences including rip-rap, and the construction of car-parking areas.