A SEDIMENT BUDGET ANALYSIS OF PEGASUS BAY

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Abstract

A sediment budget of Pegasus Bay is presented in order to build up a comprehensive account of sediment movements and potential shoreline behaviour of the region. The bay has been extensively researched on a local scale but very few works examine the bay as a entire unit. This thesis gives an overview of the bay as a whole as well as examining site specific areas which leads to the derivation of a sediment budget for Pegasus Bay.

The principal objective is to establish and quantify the sources, sinks and transfers of sediment within the Pegasus Bay coastal system. This is achieved by establishing annual river yields, estuary and lagoon sedimentation rates; profile volume analysis; longshore transport calculations based on wave observations; and examining sedimentation on the Canterbury Continental Shelf.

It is found that the Avon-Heathcote Estuary and Brooklands Lagoon are sinks of sediment, storing 3,000$m^3.yr^{-1}$ and 1,000$m^3.yr^{-1}$ respectively. The annual river sediment yields are found to be 3,005,000$m^3.yr^{-1}$ with the Waimakariri River contributing 78%. A predominant southerly component of longshore transport is discovered in the south (281,000$m^3.yr^{-1}$) and mid Pegasus Bay (1,572,000$m^3.yr^{-1}$) while north Pegasus Bay exhibits net northerly transport (203,000$m^3.yr^{-1}$). The onshore/offshore exchange examinations reveal that there is net onshore transport for the bay of 1,190,000$m^3.yr^{-1}$.

The gross sediment budget for the region sums to 20,571,000 $m^3.yr^{-1}$. The net sediment budget for Pegasus Bay at 5,843,000$m^3.yr^{-1}$ represents 30% of the gross budget of which rivers are the most significant source contributing 55% to the net budget. The net budget exhibits a surplus of sediment for the each sector of the bay. This is not reflected in five sectors which are in either an erosionary or equilibrium state. Despite this anomaly a positive correlation between the state of the beach and the amount of surplus for each sector is identified. The relationship is represented by a critical line which marks the point at which a beach may change its state.

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Chapter One
Introduction

1.1 Thesis Statement

Pegasus Bay is a dynamic stretch of coastline which has been subject to several previous studies located at different points of the shore and/or in ways directed at limited topics of investigation. Existing studies of the area are almost entirely limited to research by students and staff at the University of Canterbury. Relatively little is known on the scale of the whole bay system and some of the previous studies give conflicting indications about the overall behaviour of the coastal system. This lack of knowledge highlights the importance of further scientific research into the area. This thesis entails the calculation of a sediment budget for Pegasus Bay. A sediment budget identifies the inputs and outputs of sediment to a coastal system and in calculating one for Pegasus Bay, the sources, sinks and transfers of material are examined. This will build up a comprehensive account of sediment movements and potential shoreline behaviour of the bay.

Very little research conducted within Pegasus Bay encompasses the entire region. Most work is site specific, for example Brown's (1976) thesis looks at southern Pegasus Bay south of the Waimakariri, and Siemelink's (1984) thesis looks at the Leithfield Beach region. Neither of these studies is representative for the whole of Pegasus Bay. Furthermore only specific elements are regarded at each location allowing for little cross referencing between the locations. Consequently some important elements, such as the input of river derived sediment to the coast and the overall progradational/erosional state of the beaches are unknown.

The significance of the limitation of site specific investigations can be highlighted through the following scenario. Post 1935 the Waimakariri River mouth shifted to its present position after which the Brooklands Spit was built up by natural processes from sediment derived from the Waimakariri River. At the same time the South Brighton Spit experienced prolonged erosion which has always been attributed to channel changes in the estuary. It is suggested here as a hypothesis, that sediment from the Waimakariri River, previously deposited on the South Brighton Spit was instead being used to build up Brooklands Spit. As a result the South Brighton Spit eroded. This hypothesis has never been tested as the information to do so has not been available. A sediment budget for Pegasus Bay will provide the information for testing such theories. Furthermore it can lead to informed decision making and management of the coast.

The derivation of a sediment budget for Pegasus Bay is necessary in order to:

1. establish the boundaries of the sediment budget within Pegasus Bay;

2. calculate the annual contribution of coarse sediment to the coast from the Avon, Heathcote, Waimakariri, Ashley, Kowai and Waipara Rivers;

3. establish any additions to or losses from the beach sediment budget;

4. establish any contributions to or losses from the system through longshore transport, on and offshore transport, or through human activity;

5. establish the state of balance or imbalance in the sediment budget and relate it to trends in coastal behaviour.

This study will look at the problem of the relationship between river flow patterns and sediment yields, onshore/offshore cycling, littoral drift, human activities and the consequences of these for stability of the Pegasus Bay coastline. Sources and sinks of sediment will be identified, with consideration given to dunes, river outputs, longshore transport and onshore/offshore movements. Coastal managers and planners can then use this information, whether it be the entire budget or a specific component, in their decision making process.

1.2 Thesis Rationale

The establishment of a sediment budget for Pegasus Bay is a desirable exercise in the present state of knowledge. There are specific deficiencies in previous research that could be rectified by a sediment budget analysis. The ensuing is a list of problems that have arisen from previous research together with how they can be solved with regards to a sediment budget.

1. Predictive Models

In order to provide a predictive model for an area, all contingencies must be considered. This is particularly true for modelling of future shore positions and form as a response to sea level rise. Hicks, (1993a), attempted to model long term changes of the Pegasus Bay shoreline. However there are many gaps in the data he used. Hicks states *'that to significantly improve the reliability of the model predictions, much better information is required.'* The areas that Hicks stated as lacking in knowledge and that a sediment budget of Pegasus Bay can serve to enhance are:

* sediment supply from rivers
* shoreline movements
* sand bypassing in and out of Pegasus Bay
* changes in sedimentation of the Avon-Heathcote Estuary and Brooklands Lagoon
* net longshore transport

2. Dune Re-contouring

The beaches of Christchurch City are backed by sand dunes with an average height of around 8m. Kirk, (1979) describes these dunes as a natural buffer which protect the adjacent residential area from inundation during storms or tsunami and from wind blown sand. Recent Christchurch City Council action, contravening Kirk's description of the dunes, has lowered three dune regions to only 3m to 4m above the mean low tide mark. This type of dune removal, now proposed on a large scale, has the potential to create a huge deficit in the sediment budget. The budget for Pegasus Bay can be used to demonstrate how such removals of sand from the system can cause problems elsewhere as the sediment from other regions within the Bay is used to restore the equilibrium of the dunes.

3. Erosion of Northern Pegasus Bay

Within the past fifteen years the gravel shoreline of Amberley Beach has been eroding (D. Todd, Coastal Investigations Officer, Canterbury Regional Council *pers. comm.*, 1995). The extent of the erosion is not well documented. The Amberley Beach residential area was flooded during the August 1992 snow storm by a combination of sea inundation and flooding of Amberley Creek. After the storm a gravel barrier was designed and constructed to share the natural beach characteristics and to protect residents from further inundation. A sediment budget for Pegasus Bay can provide the information to assess whether Amberley Beach is eroding in the long term, possibly resulting in further inundation and hazards, or alternatively if it was a combination of the high tide, high seas, high rainfall and flooding of the Amberley Creek that caused the episode of inundation in 1992. Furthermore the practicality of the gravel barrier can be assessed.

4. Previous Views on Progradation

Prior to 1964 the Pegasus Bay coastline was thought to be in a constant state of 'healthy' progradation. In southern Pegasus Bay progradation of 12km in 4,000 - 5,000 years has occurred representing an average growth rate of the shoreline of over two metres per year (Kirk 1979). Surveys and photo analysis show that this trend has decreased dramatically. It has also been suggested that for the past one hundred years the shoreline of Pegasus Bay has been in long term equilibrium (Kirk 1979). However Todd (1994) shows that progradation is occurring in the centre of the bay, around Pines Beach and Woodend, at an average rate of $0.33 m.yr^{-1}$; and it has already been shown that the coast further north, at Amberley, is presently eroding. It is important to establish how these changes to different sectors of the bay interact. A sediment budget analysis of Pegasus Bay can determine the actual state of the shoreline and indicate possible future trends of erosion or progradation.

5. Changes to Rivers

The rivers of Pegasus Bay are the most important source of sediment to the coastline. A change in river catchment conditions can have major impacts on the shoreline through diminished or increased amounts of sediment supply to the coast. For example the Roxburgh dam on the Clutha River, Central Otago, reduced the sediment yield of the river from 3.44 million tonnes per year to 1.6 million tonnes per year (Carter *et al.* 1985). None of the rivers in Pegasus Bay are dammed, but just as importantly gravel is extracted from river beds which has impacts on the coastline. The extent of this impact can be realised through sediment budget investigation.

1.3 Pegasus Bay Coastline

Figure 1.1 locates the coastline of this study and the place names referred to in the text. Pegasus Bay is situated on the east coast of the South Island of New Zealand. It extends for approximately 50 km from Shag Rock in the south, to Double Corner in the north (Figure 1.1). The southern boundary is bordered by Banks Peninsula which is late Tertiary and Pleistocene volcanic cones joined to the Southern Alps by the outwash gravels of the Canterbury Plains. The northern limit of the Bay ends abruptly at the Cass Range, an uplifted and folded Tertiary Complex. The surface geomorphology of the coastal plains is such that raised beaches and marine terraces are clearly visible landward of the active coastal area. These are indicative of coastline emergence (Jobberns, 1927). Evidence for Holocene progradation, (12km over 4,000 years), in Pegasus Bay is also apparent (Shulmeister and Kirk, 1993). A low cliff north of Leithfield which extends to 1km north of Saltwater Creek, (Figure 1.1), is believed to be of marine origin and marks the maximum Holocene transgression, (Shulmeister and Kirk, 1993).

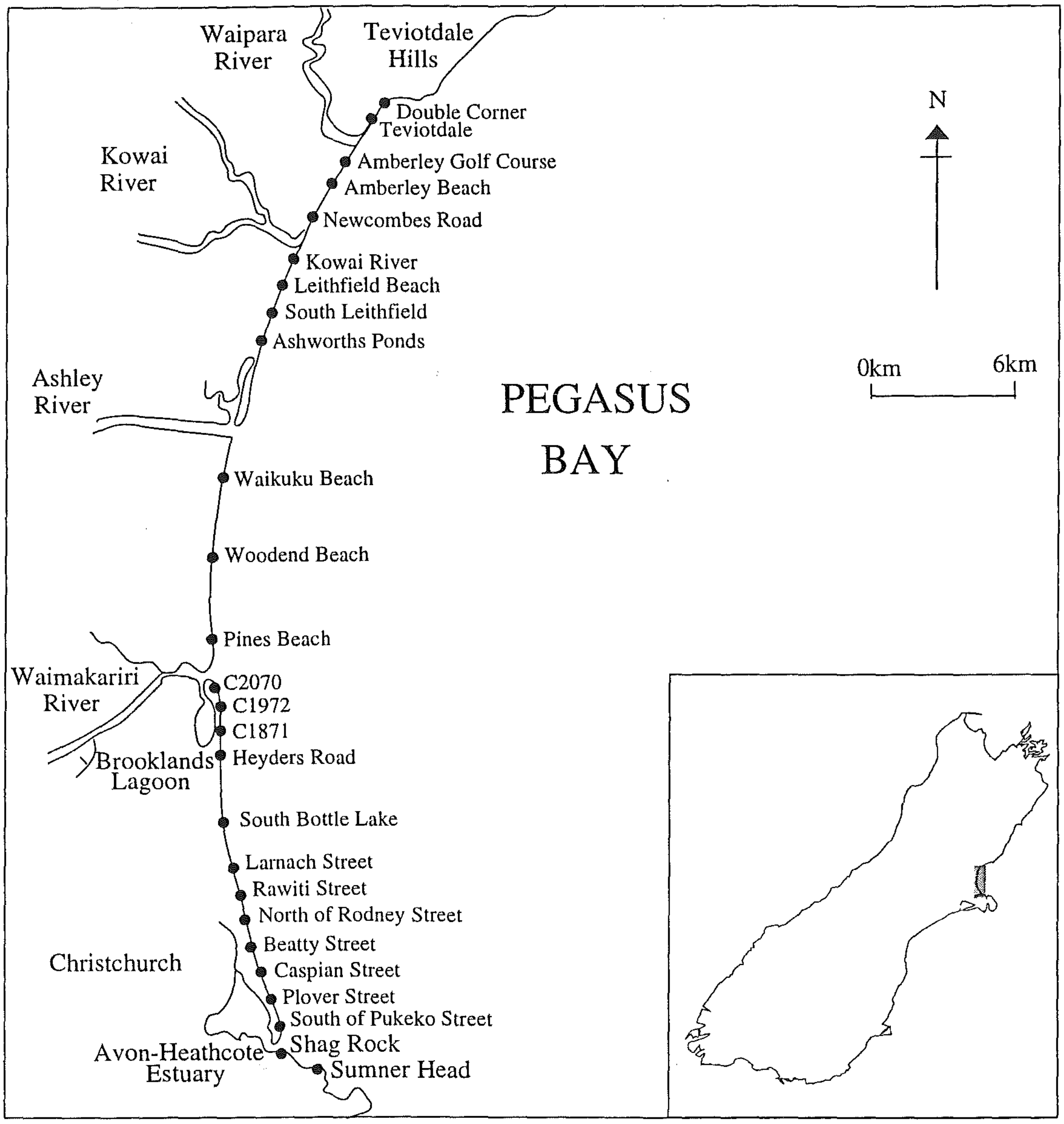

Figure 1.1 *Location map of Pegasus Bay showing profile sites*

The Canterbury Plains landward of Pegasus Bay are comprised of outwash gravels brought down from the Southern Alps by the rivers which now cut across them. The intersection of uplifted marine sediments with the outwash gravels from the rivers identifies the western boundary of the region that has been influenced by the sea. This boundary can be seen in Figure 1.2 which shows the North Canterbury post glacial marine transgression.

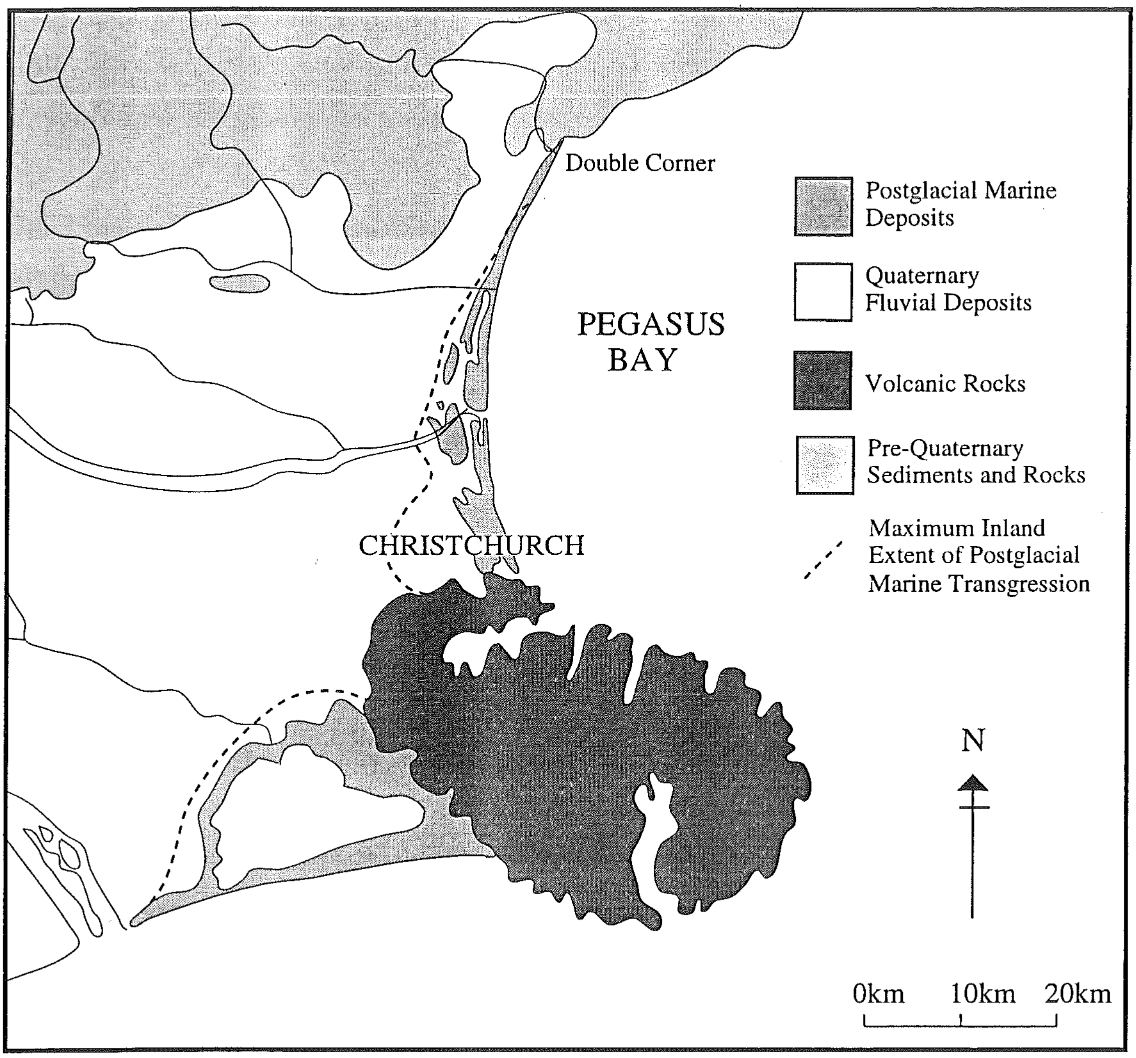

Figure 1.2 *North Canterbury postglacial marine transgression*
After Brown and Weeber (1992)

Present within Pegasus Bay are relic sand dunes in the south and remnant gravel ridges in the north. Parts of Christchurch are built upon relic dunes. For example Brown & Weeber (1992) illustrate the significant relic dune upon which the Linwood Cemetery is located. Surficially these sand dunes are not obvious due to urban development of Christchurch. In parts of the region the series of dune ridges are interspersed with hollows which are low lying marsh areas prone to flooding or ponding during excessive wet periods (Blake, 1964). The series of dune and gravel ridges show the past coast lines and are indicative of geologically recent progradational episodes.

Pegasus Bay receives the outflow and sediment yields of six rivers. The Kowai and Waipara rivers are rarely open to the sea, opening episodically during high flow events. The lower reaches of the Kowai are often dry while the low flow of the Waipara ponds in a lagoon at its mouth. The mouths of these two rivers are usually closed by gravel beach ridges which can be up to 4m high and are contiguous with the adjacent beach ridges. Due to its small catchment, ($552km^2$), the Kowai River mouth rarely opens while the Waipara River opens episodically once or twice every year.

The Ashley and Waimakariri Rivers contribute significant amounts of sediment to the system, the timing and amount depending on the precipitation and/or snow melt within each of their catchments. In the south of Pegasus Bay feeding into the Avon/Heathcote Estuary, are the Avon and Heathcote Rivers. These two rivers flow through urban regions and so operate under different hydrological mechanisms to those rivers north of Christchurch.

The beaches from South Brighton to Leithfield, (Figure 1.1) are comprised of sand. The heights of the foredunes vary greatly and range from five metres to thirteen metres. Between Ashworths and Leithfield the beach composition changes to mixed sand and gravel, although sand dunes are still present. The dunes decrease in sand content from Leithfield north until just south of the Kowai River, where the dunes become beach ridges and are predominantly comprised of gravel.

Corresponding to the reduction in sand content is a reduction in the height of the beach ridge. The beach widths also decrease, while the foreshores are steeper than the sand counterparts. Sandy beaches in the south can extend horizontally for up to 300m from the dune toe to the mean low tide level whereas the mixed sand and gravel beaches of the north are unlikely to be more than 100m from the base of the gravel ridge to the mean low tide level.

1.4 Sediment Budgets

Kirk and Hewson, (1978) put forward the following definition of a beach:

> *"Any beach can be thought of as a three dimensional body of unconsolidated sediment resting on some basement through which a constant stream of materials is passing."*

This description illustrates the dynamic nature of coastal beaches and the importance of sediment to a beach. The morphology or shape of the beach and the position of the coastline are highly dependent on the inputs, outputs and transfers of sediment. An input is an addition of sediment and an output is the removal of sediment to any morphodynamically defined cell. A transfer of sediment is the movement of material within the cell.

Figure 1.3 illustrates a schematic sediment budget model. Contributions of sediment can come from cliffs, dunes, offshore sites, biogenous material, rivers, inlets, estuaries, lagoons and harbours or from longshore transport. Subsequently these features are known as sources. A loss or output of sediment can occur so that the material travels from the cell to the dunes, offshore, into inlets, lagoons, estuaries, harbours, submarine canyons or out of the cell through longshore transport. It follows that these features are sinks of sediment.

The transfers of sediment can be onshore, offshore or alongshore, and are due to wave or wind processes. It can be seen that some landform features can be sources or sinks leading to the complex nature of establishing a sediment budget for a particular coastal region. The impact humans have on a budget is also pivotal to any calculation. Sediment mining, whether it be directly from the beach, in the nearshore zone or from a river feeding the compartment can have a major effect as can structures which trap sediment moving along shore.

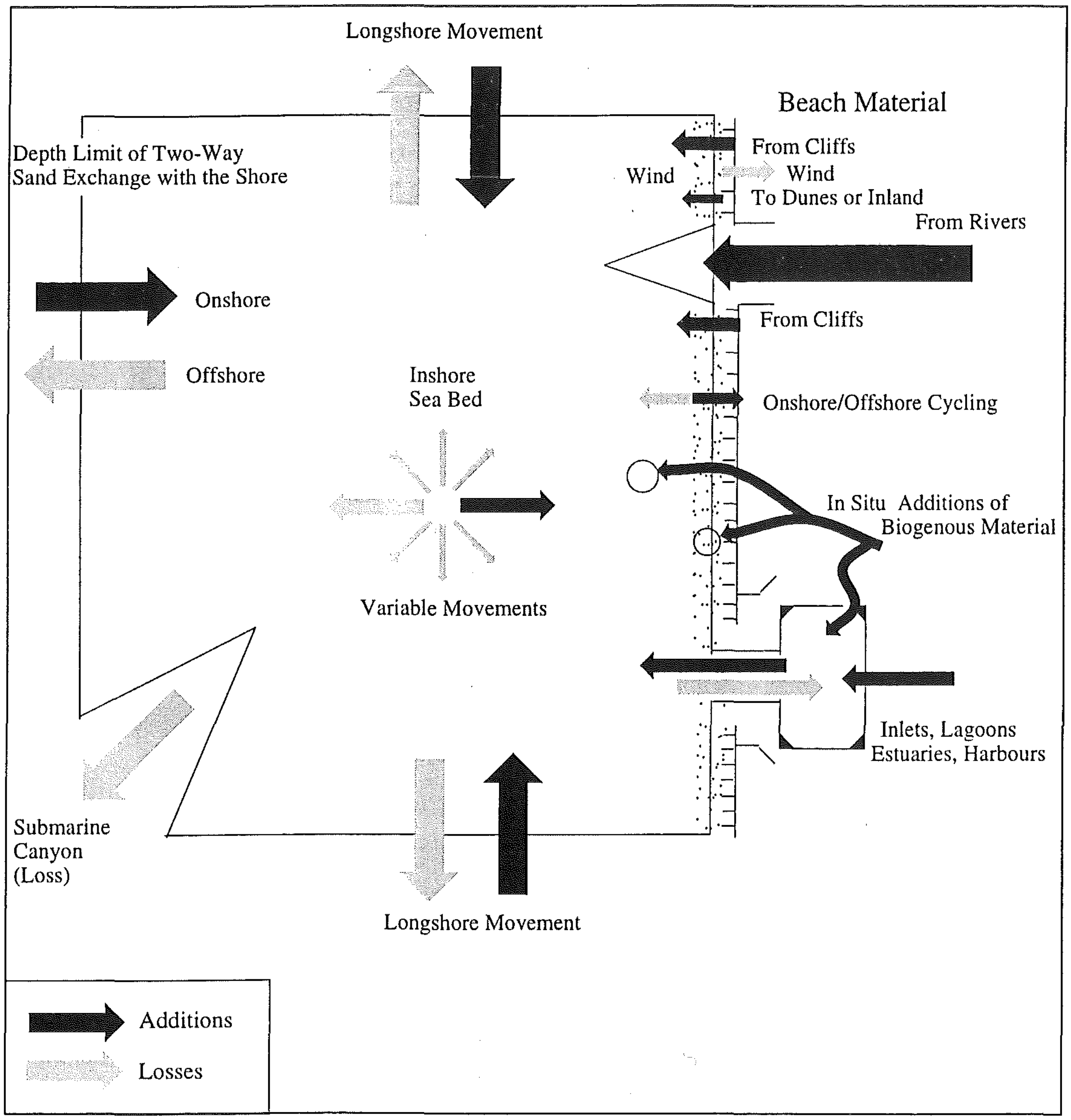

Figure 1.3 *Schematic sediment budget model*

Source: Miller and Zeigler (1958) p423

In order to calculate a sediment budget, the equation as defined in the Shore Protection Manual (Coastal Engineering Research Centre C.E.R.C. 1984) can be used. This equation adds the sum of the sinks to the sum of the sources. Within a balanced budget the difference between the material added by sources and the material taken away by sinks should equal zero so that:

$$\text{Sum of sources - sum of sinks} = 0 \qquad \text{eq. 1.1}$$

A sediment budget is a balance of the sources and sinks and so any unknown can be quantified as the remainder by re-arranging equation 1.1 to the following:

Sum of known sources - sum of known sinks = unknown source/sink eq. 1.2

If there is an unknown source or sink it can be quantified by establishing the other sources and sinks. The sediment budget equation can be more formally written as:

$$\left[\ \Sigma Q_i^{+} + \Sigma Q_i^{*+}\ \right] - \left[\ \Sigma Q_i^{-} + \Sigma Q_i^{*-}\ \right] = 0 \qquad \text{eq. 1.3}$$

Where Q_i denotes a point source and Q_i* denotes a line source, both of which will be examined later in this chapter. The positive and negative superscripts are representative of sources and sinks respectively.

If a beach has a positive budget it may prograde such that the shoreline position will advance seaward. The beach shape may also be altered such that the foreshore slope steepens and widens while dunes grow in height and width (Kirk & Hewson 1978). A deficit budget will show the reverse effects. The beach position may migrate landward as sediments are eroded. This may be evident in the lowering and narrowing of the foreshore and decrease in bulk of the dunes behind. In the case of a balanced budget the beach will maintain an equilibrium position and form about which it fluctuates. The equilibrium may occur over a period of hours to years. A storm may severely erode a beach in a few hours which then takes swell waves years to repair. This beach can be considered as an equilibrium beach so long as the spatial scale encompasses both of these processes.

temporal

To determine the loss or addition of sediment from a coastal cell, the boundary must be well defined. Figure 1.4 shows the coastal environment in profile and the terms used to describe its features. The mean low water level, mean high water level and the dune toe mark internal boundaries of the cell. The zone between mean low water level and mean high water level is the active region of the beach known as the foreshore. The backshore which is between mean high water level and the dune toe is less active as it is not always directly acted on by the sea. Longshore transport and onshore/offshore cycling all occur in the nearshore zone which is beyond the cell boundary. However these processes serve to bring sediment in and out of the morphodynamically defined cell and so are pertinent to the sediment budget. Losses in and out of the system move between the beach and the dunes or nearshore zone. The dunes and the nearshore zone will both be included in the budget calculations as sources, sinks or transfers of sediment.

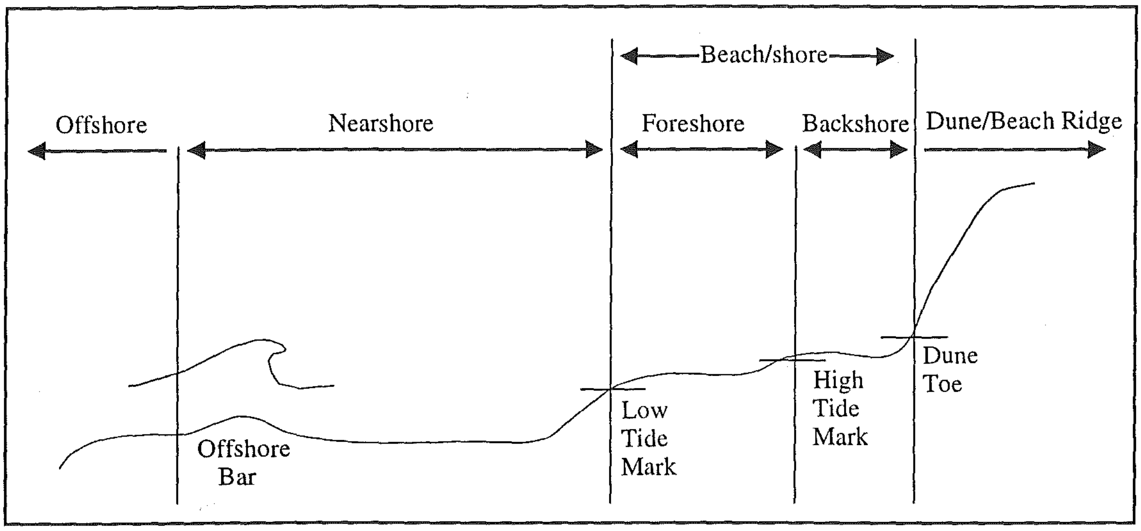

Figure 1.4 *Coastal environment nomenclature*

1.4.1 Sources, Sinks and Transfers of Sediment

Sources of sediment are regions or points from which sediment is added to a morphodynamically defined cell. This can be material from the offshore or nearshore zones or from the dune (Figure 1.4). Alternatively, examining Figure 1.3 demonstrates that a source could be from a lagoon, harbour, estuary or river. These can be broken down further into point sources or line sources. A point source as defined by C.E.R.C. (1984) is one which adds material across a limited section of the defined cell boundary, for example a river. Conversely a line source is one which adds material over an extended reach of the cell such as a dune system. Chapter Three looks at the different types of sources active within Pegasus Bay.

A sink results from any process whereby sediment is lost from the budget compartment. As with sources, sinks can be either points or lines depending on the nature of the sink and/or the compartment. Many of the sources shown in Figure 1.3 and Figure 1.4 can also be sinks of sediment. Examples of this are dune systems, lagoons, estuaries and harbours. Within Pegasus Bay several active sinks are operational such as the dune system, the Canterbury Continental Shelf, the Avon-Heathcote Estuary and Brooklands Lagoon. These are illustrated in Chapter Four.

The sediments within a coastal area are not static, they are moving from sources to sinks and back again, and through the system. These movements are often not calculated in sediment budgets and can account for significant amounts of sand in the coastal system at any one time. In order to transport material within the coastal cell it is often necessary for the material to be removed from the system before it can be deposited elsewhere. The transfers of sediment within and into or out of an area are examined in Chapter Five.

1.4.2 Tasks Involved in Calculating a Sediment Budget

The first stage of calculating a sediment budget is to establish the area of interest, in this case, Pegasus Bay. Often a problem exists which needs solving and the sediment budget may be employed to do so. Some of the problems existing in Pegasus Bay are detailed in Section 1.2. In preparing for a sediment budget study the individual cell boundaries must be clearly defined. Following this is the identification of sources, sinks and transfers which exist in the cell. Once each of the sources, sinks and transfers have been identified the quantification of these components of the sediment budget must be carried out. Ultimately this will lead to the establishment of the sediment budget model for Pegasus Bay.

One means of establishing sources and sinks is by recourse to historical information. By examining past maps and aerial photographs, areas of erosion (sources) and areas of accretion (sinks) can be identified. Sedimentological investigation can also lead to the identification of possible source regions. Anecdotal evidence is a rich source of information that can lead to establishing sources and sinks. Physical studies and measurements of the features within the coastal environment can also lead to the identification of sources, sinks and transfers of sediment.

Quantification of sediment inputs from rivers to the coast can be made through direct measurement of the bedload and suspended load transportation over a predetermined period. The techniques available are far from precise and results may be inaccurate. Calculations can also be made from river flow velocity data. Unfortunately these calculations give the potential sediment transports rather than the actual sediment transport. In the case of Pegasus Bay it was not an option to make direct measurements of sediment load or calculations from flow velocities. Instead values obtained from previous works have been applied to this study.

Four methods for acquiring longshore sediment drift values are outlined by C.E.R.C. (1984). The first is to use known values of longshore sediment drift from adjacent sites. Another means is to use historical data such as charts, surveys and dredging records. In this case charts can be used to show changes in topography in the littoral zone and surveys may also be consulted. Although these two methods give an idea of the littoral drift it is difficult to ascertain average annual drift volumes.

The third method outlined by C.E.R.C. (1984) is that of using either measured or calculated wave conditions to compute a longshore component of wave energy flux which is related through an empirical curve to the longshore transport from mean annual breaker height. The last method is to estimate gross longshore transport from mean annual breaker height. Of the two calculated methods the last is the most unsatisfactory as it gives gross transport rates instead of the preferred net transport rates. Wave measurements within Pegasus Bay mean that method three, which will be explained fully in in Chapter Five, has been adopted for this study. Analysis of sediments along the coastline can also give an indication of the longshore transport direction.

In order to determine rates of loss of sediment to estuaries and lagoons, rates of infill or loss of these features can be measured directly through comparing incoming sediment with outgoing sediment or alternatively by surveying the feature relative to a fixed position so that any increase in the base of the feature can be taken as infill and subsequently worked out as an infill rate. As these means were not available previous research has been consulted for this study.

Beach systems are dynamic. In order to quantify changes over short time periods direct measurements of beach profiles and sediment volumes can be made and compared to previous measurements. This has been done for Pegasus Bay to compare form and position of the beach and to calculate the volumes of sediment removed or added to the beach system over different time periods. Onshore/ offshore cycling is perhaps the hardest to quantify without the use of sophisticated equipment. Research of this type has not been attempted for the Pegasus Bay region and there is a void in the available knowledge. It will therefore be assumed that one part of the missing volume of sediment from the calculated budget may be the onshore/offshore component.

Once all of the above have been identified and quantified the values can be put into the sediment budget model. While the eq. 1.3 itself is relatively straight forward the processes involved in solving it and presenting a sediment budget model are complex.

> *'Although simple in principle, the application of this concept to the real situation is not straight-forward. No study has ever demonstrated a sediment budget which is based entirely on verified empirical data. Most budgets rely on a host of assumptions to compute sediment fluxes.'*
>
> (Dolan *et al.*, 1987)

While some phenomena may be measured directly, such as the bulk of a sand dune, others must be calculated from assumed relationships. Foremost is the longshore drift component of the sediment budget which is calculated from the wave data which in itself is not entirely reliable. Even dune volume measurements are not exact as they are taken in one or several points in space and extrapolated for the rest of a particular coastal cell.

1.5 Thesis Outline

Chapter One has introduced the nature of the research assignment. Included are the aims and reasons for the study. The research area is introduced and briefly described. The sediment budget theory and the budget itself are introduced and explained. The ways in which a budget can be calculated detailed. The importance of a sediment budget as an information base for sustainable management is also outlined.

The following chapter looks at the process environment of Pegasus Bay. Processes within the coastal environment are the driving forces behind the distribution of sediment within the area. The wind, wave, nearshore and rivermouth processes are specifically examined. Information presented here includes details from past research as well as observations and recordings taken in the field during the research period.

Sources of sediment for Pegasus Bay are identified in Chapter Three. Quantification of the river contributions to the coast are presented. A possible scenario for the limit of onshore/offshore exchange is also investigated.

Pegasus Bay sinks of sediment are highlighted in Chapter Four. Deposition estimates for the Avon-Heathcote Estuary and Brooklands Lagoon from previous research are detailed. The volumes of sediment contained in the dune and gravel ridge systems as well as the beach system are calculated. A description of the beaches within Pegasus Bay is presented.

Chapter Five details the sediment characteristics and the mechanisms which transport them. Longshore sediment transport directions are inferred. The potential longshore transport and the onshore/offshore exchange for Pegasus Bay are quantified.

The culmination of the thesis is Chapter Six which outlines the sediment budget for Pegasus Bay. This chapter brings together the information which has previously been presented to compile a quantitative sediment budget for Pegasus Bay.

Ultimately Chapter Seven produces the conclusions of the study. Included here are the problems encountered as well as the problems solved. Also mentioned are recommendations for future work that is required within Pegasus Bay in order to fully represent this coastal environment.

Chapter Two
The Process Environment

2.1 Introduction

This chapter presents and analyses the process environment of Pegasus Bay. These processes act to shape and mould the morphologies present along a stretch of coastline. Winds, tides, currents and waves all play important roles in transporting sediment and distributing material on the shore. It is for this reason that the examination of processes is important to the formulation of a sediment budget.

Processes can act against or in conjunction with one another. An example of this can be illustrated using winds and waves. An opposing wind can decrease the energy of waves by causing them to steepen and break before they reach the shore, dissipating their energy. Conversely a wind direction similar to the wave approach can increase the energy of the waves. The wave height, steepness and period all increase resulting in a higher energy environment. The amount of energy in an environment is a significant determining factor in the amount of sediment moved and where it is moved to.

Consequently this chapter examines the process environment of Pegasus Bay. Past research and fieldwork carried out in this investigation are used to describe each of the processes pertinent to the establishment of the sediment budget of Pegasus Bay. The interaction of these processes with each other and with sediment transport at different temporal and magnitudinal scales will also be detailed.

2.2 Wave Environment

Waves are the principal source of energy input into the coastal environment. The highest proportion of waves are wind generated. Waves that are generated at considerable distances from the shore arrive as swell. These are regular, long flat waves. In contrast to this are waves generated locally by wind producing sea state waves, which are irregular and steep.

Unfortunately wave records for Pegasus Bay are rather scant. There are no ports or rigs in Pegasus Bay from which measurements may be made. Some records have been taken by Masters students in both the Geography and Geology Departments of the University of Canterbury. None of these records have been measured instrumentally but instead visual observations have been made at the shore in various locations. While the observations taken by one observer may be consistent there may be differences between individual observers. This in turn may produce anomalies between the records.

During the study period wave records were made from New Brighton Beach, Woodend Beach, Waikuku Beach, Leithfield Beach and Amberley Beach by residents from each area. Unfortunately, as the work was voluntary some discrepancies in the data have been found. Only the Amberley Beach and the Waikuku Beach data was consistently reliable. These measurements were made according to the Littoral Environment Observation (L.E.O.) data collection program (Schneider 1981). This program requires the observation of the following littoral wave variables; breaker height, wave period and wave direction. The data was collected from the various sites on a daily basis at a regular time each day so as to observe the waves during different tidal phases. The instruction sheet for wave and wind observations is Appendix One.

The observed wave data for the Pegasus Bay region has been augmented by data obtained from the following sources: Burgess (1968) for the period December 1967 to May 1968, Brown (1976) for the period November 1975 to August 1976, as well as sporadic records from Spencer Park during 1994.

2.2.1 Wave Height

Wave height has the potential to increase or decrease the capacity of a wave to transport sediment. An increase in wave height means that the wave will break further offshore. In turn the surf zone is widened and more material may be set in motion (C.E.R.C. 1984). Wave height for the study was observed to the nearest 0.25m as the wave broke. Unfortunately wave height is the most subjective of all measurements taken and will therefore vary slightly depending on the observer. These variations are difficult to verify when the observations are taken from different locations by different people. No standardisation of the wave height records was made for this study. However it was considered that the variation or error range was less than 0.5m.

Burgess (1968) suggested that there is no seasonality to wave heights in Pegasus Bay due to the sheltering from stormy southerly swells reaching the beaches north of Banks Peninsula as her study was located in the south of Pegasus Bay. At the time of Burgess' study there was a lack of comprehensive wave records for northern Pegasus Bay where the sheltering effect of Banks Peninsula may be diminished. Alternatively Brown (1976) stated that there is a marginal seasonality to the wave heights in Pegasus Bay with a slight increase in winter wave heights. The records taken at Amberley during this study cover both summer and winter months and do show an increase in height from summer to winter, as can be seen in Figure 2.1.

The wave records taken by Burgess (1968) were measured in feet rather than metres. This data has therefore been converted to metres for direct comparison to the 1995 data. These are displayed in (Table 2.1) along with data from Spencer Park, Waikuku and Amberley Beach and the average value for the Pegasus Bay region. This table shows that wave heights are greater in the south of Pegasus Bay.

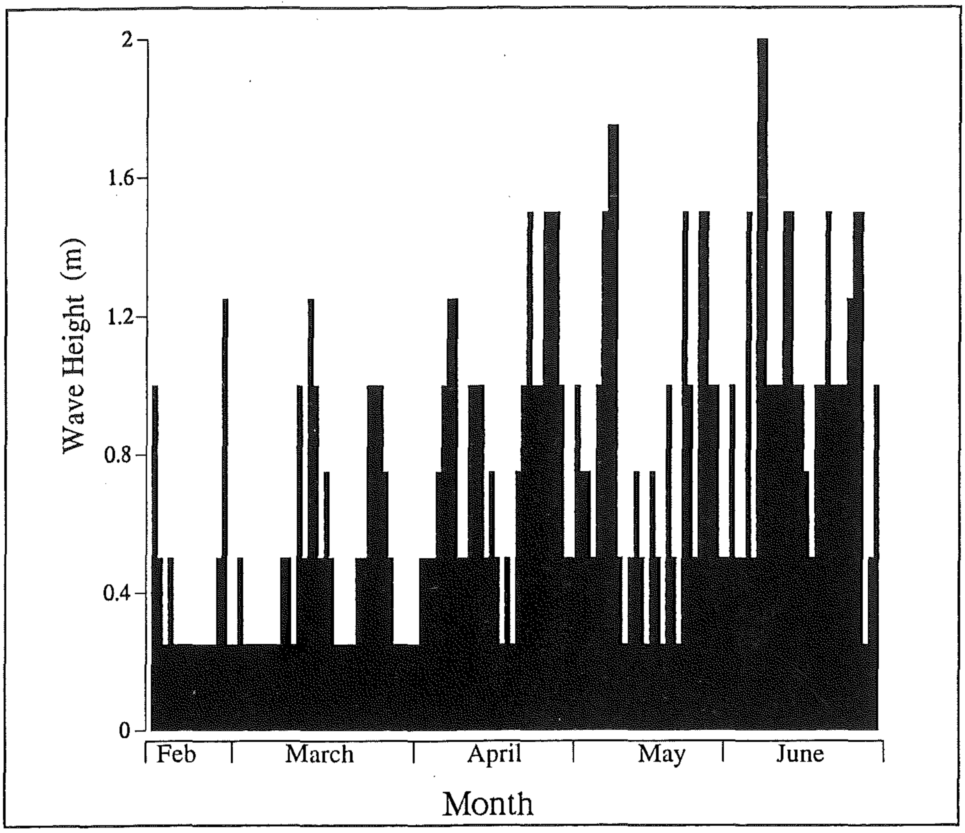

Figure 2.1 *Wave heights for Amberley Beach* from February to June 1995

Table 2.1 *Wave height percentages at various locations in Pegasus Bay*

<table>
<tr><th>Wave Height (m)</th><th>Spencer Park (%)</th><th>Waikuku (%)</th><th>Amberley (%)</th><th>Burgess (%)</th><th>Average (%)</th></tr>
<tr><td>.25</td><td>30</td><td>7</td><td>23</td><td rowspan="2">14</td><td rowspan="2">54</td></tr>
<tr><td>.5</td><td>42</td><td>34</td><td>27</td></tr>
<tr><td>.75</td><td>24</td><td>11</td><td>9</td><td rowspan="2">44</td><td rowspan="2">23</td></tr>
<tr><td>1</td><td>4</td><td>27</td><td>23</td></tr>
<tr><td>1.25</td><td>0</td><td>0</td><td>4</td><td rowspan="2">28</td><td rowspan="2">10</td></tr>
<tr><td>1.5</td><td>0</td><td>15</td><td>12</td></tr>
<tr><td>1.75</td><td>0</td><td>1</td><td>1</td><td>9</td><td>1</td></tr>
<tr><td>2</td><td>0</td><td>2</td><td>1</td><td rowspan="3">5</td><td rowspan="3">2</td></tr>
<tr><td>2.25</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>2.5</td><td>0</td><td>3</td><td>0</td></tr>
</table>

Only 1% of waves at Amberley Beach during the study time were over 2m contrasting to 5% at Waikuku and none at Spencer Park. A maximum wave height of 2.5m was recorded at Waikuku and these waves occur 3% of the time.

At the other end of the scale 72% of waves arriving at Spencer Park were under 0.5m with 41% and 50% under 0.5m at Waikuku and Amberley respectively. The results obtained by Burgess at South Brighton show that 72% of waves observed at this location were between 0.75m and 1.5m.

The average value for wave height (Table 2.1) which is quite dissimilar to site values illustrates the difference between the locations. This reiterates the concept that one site is not representative of the entire bay and highlights the need for comprehensive wave observation collections at various sites within Pegasus Bay.

2.2.2 Wave Period

Wave period is the average time period between consecutive wave crests passing a point. Changes in wave period can cause differing amounts of sediment to move onshore or offshore. For the purpose of this study wave period was measured by the following means. The number of waves breaking during a time interval of at least one minute and the total time period were recorded. The timing was stopped and started on the arrival of a wave with the initial wave being zero. The number of waves is then divided into the time recorded to give the wave period.

During the study period there was great variability in the wave periods recorded (Figure 2.2). The shortest wave period for Amberley was 5.9 seconds and 6 seconds for Waikuku. Unexpectedly extremely long wave periods of 21.7 seconds for Amberley and 31.5 seconds for Waikuku were recorded. These values seem unrealistically high for the Pegasus Bay coastline and so are more likely to be observation errors. Brown, (1976), states that longer period waves coincide with the south-easterly swells of winter while short period waves are characteristic of north-east seas. Brown's assumption holds true for this study.

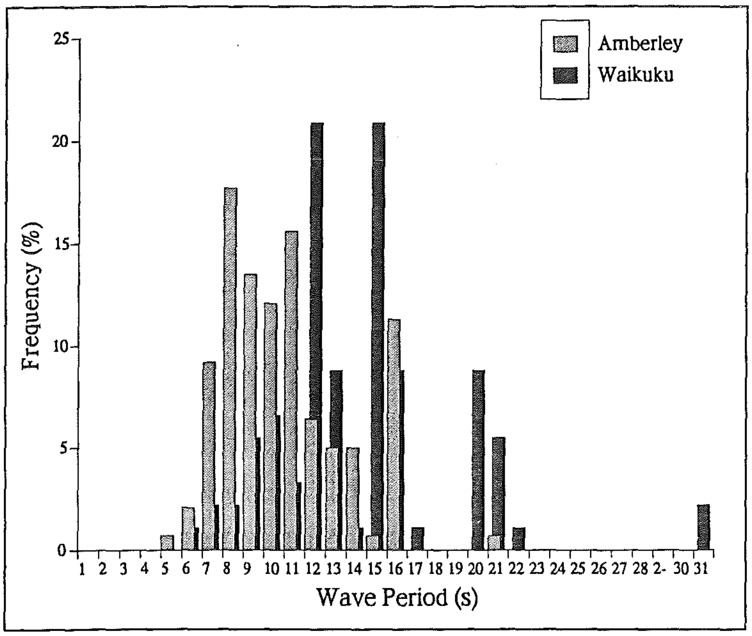

Figure 2.2 *Wave period for Waikuku Beach and Amberley Beach*

2.2.3 Wave Steepness

Wave steepness relates to the shape of the wave. In turn the steepness may determine the extent of the energy that is applied to the beach slope. Flat waves have little turbidity and are likely to transport sediment onshore. Conversely steep waves are characteristic of a high energy environment and tend to transport sediment from the beach. Wave steepness is the ratio of the wave height to wave length.

Wave length can be evaluated using the following equation:

$$L_0 = 1.56.T^2 \qquad \text{eq. 2.1}$$

where: L_0 = deep water wave length
T = wave period

However this equation gives the wave length of a deep water wave which is different to that of a shallow water wave. Despite this an approximation to wave steepness can be made by using the following equation:

$$S = h_b/1.56.T^2 \qquad \text{eq. 2.2}$$

where: h_b = breaker height

C.E.R.C., (1990) established critical wave steepness values for transporting material on and off shore. These values are as follows:

<0.00014 – accretion highly probable
≤ 0.00027 - accretion probable
≥ 0.00027 - erosion probable
>0.00054 - erosion highly probable

Source: C.E.R.C. (1990)

These values fail to allow for an equilibrium beach where neither erosion or accretion occurs and assumes that the beach is continuously in a state of flux as there is no critical steepness at which sediment is not transported onshore or offshore. Furthermore the model does not allow for wave angle so the beach is considered as two dimensional and does not consider movement alongshore.

Bearing the above limitations in mind, the critical steepness values can be applied to Pegasus Bay to give a general idea of the possible sediment movements. According to the critical values from C.E.R.C., erosion was highly probable on all but seven days of the 138 days surveyed at Amberley. Steepness values for the remaining seven days indicate that accretion was highly probable. Waikuku showed slightly different results with erosion highly probable for 76 days of the 89 days surveyed and probable for one day, and accretion highly probable for 9 days and probable for 3 days.

The predicted results from the model appear to correspond to the observed state of the beach. Waikuku Beach was accreting throughout the survey period (Appendix Three) which is reflected in the high proportion of days when the critical steepness value indicates that accretion is either highly probable or probable.

The same correlation exists for the Amberley profile. Examination of the steepness values in conjunction with the profiles show that there is a strong positive correlation between the observed state and the predicted state. This highlights the applicability of this model.

2.2.4 Wave Angle

Wave direction is an important variable in determining rate and direction of longshore transport. The wave approach was determined according to Figure 2.3. An observer stands on the shore as indicated and determines from which sector the waves are approaching. This technique is derived from the L.E.O. method. The use of sectors instead of compass directions allows for the calculation of longshore sediment transport. In the case of Pegasus Bay the differing shore orientations at each site are accounted for so that direct comparisons between the sites can be made.

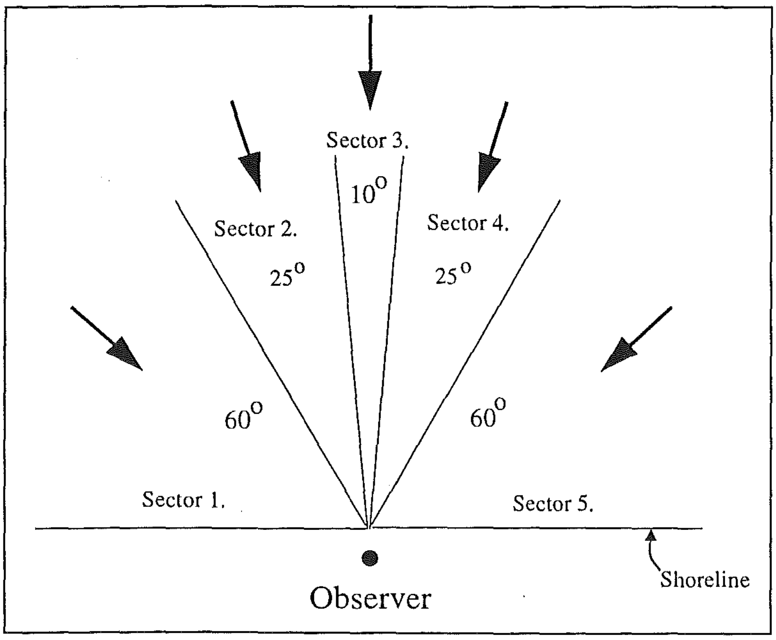

Figure 2.3 *Sextant wave angle diagram as determined by the L.E.O. method*

Table 2.2 shows the frequency values of the wave angle approach from each sector for Waikuku and Amberley beaches. The highest proportion of waves recorded approached from sector 3 indicating a shore normal approach. Wave data collected by Burgess, (1968), has not been collected in the same way and has been described using qualitative terms such as north-east. These figures have been standardised to the L.E.O. method by correlating the orientation of the beach and the compass readings to the sectors determined by the L.E.O. method. Burgess' results are also displayed in Table 2.2. As can be seen on average one half of the waves arriving at the Pegasus Bay coastline are shore normal. Waikuku and Amberley exhibit similar frequencies for waves from Sector 3, 46% and 43% respectively, (Table 2.2). The main differences between the two regions are for wave angles in Sectors 1, 2 and 4.

Table 2.2 *Wave angle frequencies for various locations in Pegasus Bay*

Wave Angle Sector	Spencer Park (%)	Waikuku (%)	Amberley (%)	Burgess (%)	Average (%)
1	0	7	0	0	2
2	16	42	28	33	29
3	62	46	43	44	50
4	22	5	29	23	19
5	0	0	0	0	0

No waves for sector 1 were recorded at Amberley, while 7% of waves approached from this sector at Waikuku. This may be attributed to the short fetch north of Amberley Beach, as the cliffs at Double Corner shelter the beach from waves from this sector. Waikuku is less influenced by the Double Corner cliffs as it is further south allowing for the formation of significant waves approaching in sector 1. The same reasoning can be extrapolated to incorporate waves in sector 2 which exhibit an increase in frequency with distance from Double Corner until Spencer Park. Burgess' results show a similar pattern but with a high percentage (33%) of waves approaching from the north-east.

The Waikuku and Amberley data show that frequencies of waves from Sector 4, decrease closer to Banks Peninsula. This is likely to be due to the sheltering effect of Banks Peninsula limiting waves from the southerly quarter. Banks Peninsula is also an obstruction about which waves are refracted so that they approach with a more easterly component. These preliminary findings would indicate longshore components both to the north and the south with a net southerly component at Waikuku and Burgess' site and a net northerly component at Spencer Park and no apparent net longshore component at Amberley.

2.3 Wind Environment

Wind action is an important process in moving beach sediments in Pegasus Bay. Synoptic winds also have a role in the amount of rain and subsequent runoff from river catchments. This in turn controls the discharge rates at the mouth of these rivers. Apart from tsunamis all waves which reach the shore are created by wind. Currents are also generated by winds in the nearshore environment and these act to transport material within this region. Return currents can also be set up and are equally important in the transportation of sediment. Deep water waves created by wind systems several kilometres from the coast are then modified by winds at the shore.

The wind environment for Pegasus Bay was established from the following sources: daily observations carried out by the residents conducting wave observations between February and June 1995 at Amberley Beach and Waikuku Beach; similar but irregular records for Spencer Park between March and October 1994; records covering the period from November 1975 to August 1976 obtained from Browns (1976) thesis, and records from June 1962 to May 1963 from Blake's (1964) thesis. Additionally data collected from Bromley, 1967 - 1972 in McKendry's (1985) thesis has been used to establish a long term wind regime. Unfortunately the records for the study period are irregular and consequently may not be representative of the whole year due to the predominance of records taken over the summer months in particular.

2.3.1 General Wind Climate of Canterbury

New Zealand is a mid-latitude country and is subjected to the mid latitude westerlies of the Southern Hemisphere. Canterbury however is sheltered from these airflows by the north-east / south-west orientated Southern Alps. Records of wind direction at Christchurch International Airport show a predominant north-easterly or south-westerly component (Kirk 1979, McKendry 1985). Canterbury winds also exhibit seasonal trends. North easterlies reach maximum frequencies in summer, while south westerlies are most frequent in winter months. North west winds are predominant in the spring (Brown 1976, McGann 1983). Diurnal variations have also be noted by Mckendry and McGann.

2.3.2 Wind Directions

The wind observations for the periods 1962 - 1963, 1967 - 1972, 1994 and 1995 have been grouped into four categories. These categories have been determined based on frequency of occurrence and their influence on the wave characteristics at the beach. Table 2.3 shows frequency values for these four wind direction categories for the various study periods. Very few westerly winds are felt at the sites within Pegasus Bay. 10% of winds at Bromley were from the west. This slightly higher percentage for this direction than at the other sites may be due to the inland location of this station. The wind records in Table 2.3 support the general trends as indicated in "Climate of Christchurch" (McGann 1983). Nor-easterlies and easterlies predominate being approximately one half of the winds occurring followed closely by a high frequency of winds from the southern quarter. There appears to be no definite spatial differences between the sites with regard to wind direction. This variable is consistent throughout Pegasus Bay.

Table 2.3 *Wind direction frequencies at various locations in Pegasus Bay*

	Bromley 1967 -1972 McKendry	South Shore 1962 Blake	New Brighton 1976 Brown	SpencerPark 1994 This study	Pines 1963 Blake	Waikuku 1995 This study	Amberley 1962 Blake	Amberley 1995 This study
Nor - west Northerly	11	7	8	9	12	22	22	20
Nor - east Easterly	55	64	39	59	56	45	51	45
Sou - east Southerly Sou - west	24	24	39	32	29	33	23	33
Westerly	10	0	3	0	0	0	0	2

Onshore Winds

Onshore winds are significant in terms of the coastal sediment budget. They are related to the return flow of water from the beach and therefore the transport of sediment from the shore. When an onshore wind is present the bottom return current has a greater velocity and therefore a higher propensity to transport sediment (Bascom 1980). From the data for the study period 58% of winds were onshore at Waikuku and 53% at Amberley Beach. It was found that onshore winds can also contribute to the swash reaching further up the beach slope and so more material is available to be transported. Wind blown sand is an important component of the coastal sediment budget. Onshore winds serve to transport sediment from the foreshore to the dunes and/ or from the dunes inland.

Offshore Winds

Equally significant to transporting sediment is the influence of offshore winds. Velocities of bottom return currents are dramatically reduced as too is the ability of that current to transport sediment (Bascom 1980). Additionally the swash cannot extend as far up the beach slope exposing less sediment to the erosive powers of the sea. During the study period only 6% of winds are offshore at Waikuku, and 19% of winds at Amberley Beach originated inland. Offshore winds also transport sand from the dunes to the beach system and to the nearshore.

Longshore Winds

Longshore drift can be accentuated by winds travelling parallel to the shoreline. Conversely wave generated longshore currents could be cancelled or modified if an opposing local wind of sufficient velocity was present. Amberley Beach experienced 24% of its winds in a shore parallel direction and Waikuku 36%. Longshore winds at Amberley were accompanied by oblique wave angles from the same sector 72% of the time and 64% of the time at Waikuku.

2.3.3 Wind Speed

The wind speed affects the ability of either the air or the sea to transport sediment. The wind speed frequencies for Spencer Park, Waikuku and Amberley are presented in Table 2.4. The diagram illustrates that the wind speeds at Amberley are much greater than those at Waikuku and Spencer Park. By comparing these with wind direction, (Figure 2.4a and b), it can be seen that a significant percentage, (35%) of these high wind speeds approach from the northerly quarter. These high speed winds are not felt on the beach at Spencer Park or Waikuku due to the sheltering influence of the sand dunes and pine plantations in these locations.

Table 2.4 *Wind speeds at various locations in Pegasus Bay*

Wind Speed ($km.hr^{-1}$)	Amberley Beach (%)	Waikuku Beach (%)	Spencer Park (%)
<1	4	27	45
1 to 5	5	45	14
6 to 11	25	15	23
12 to 19	22	9	0
20 to 28	25	4	18
29 to 38	18	0	0
39 to 40	1	0	0

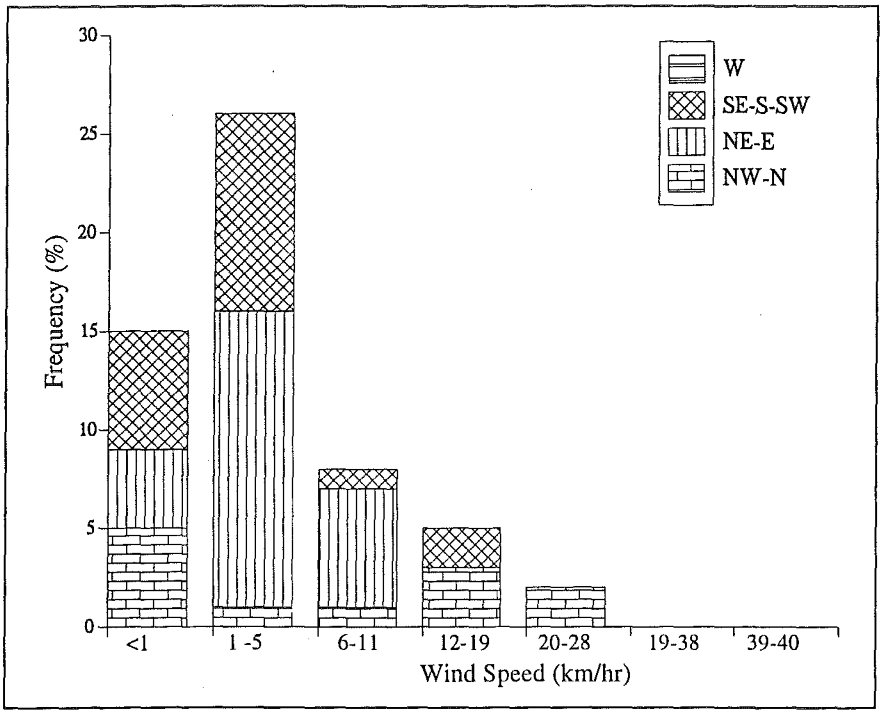

Figure 2.4(a) *Wind speed and direction for Waikuku Beach*

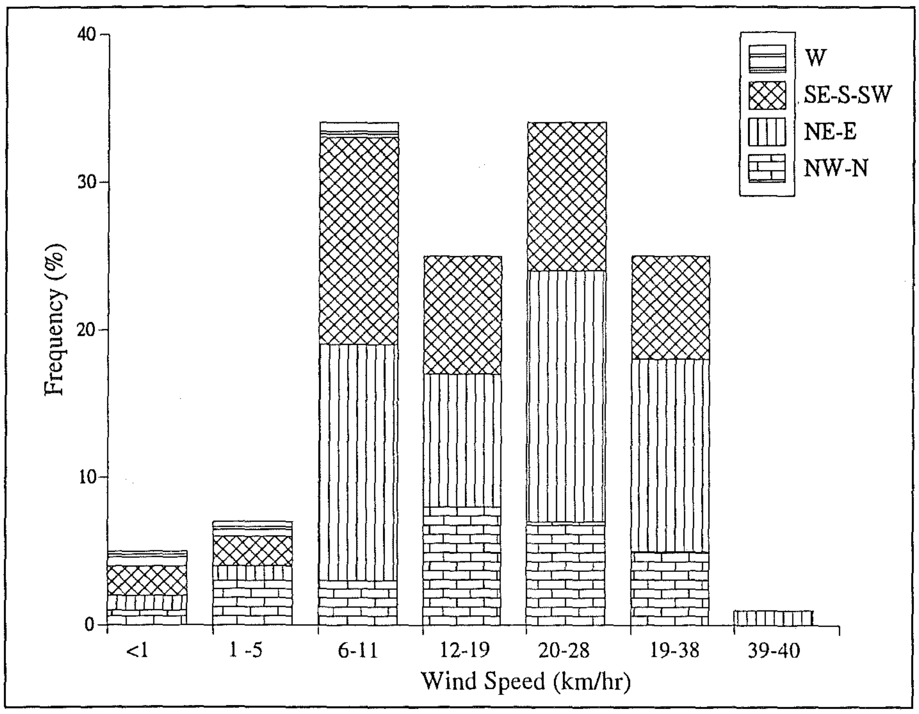

Figure 2.4(b) *Wind speed and direction for Amberley Beach*

The influence of wind direction whether it be onshore, offshore or alongshore on transporting sediment is exaggerated when the velocity of said wind increases (Pethick 1984). Frictional drag causes a zero wind velocity layer which has a depth equivalent to $^{1}/_{30th}$ of the average surface grain diameter. Only sand grains with a diameter greater than the zero wind velocity depth are transported. Saltation of sand grains is the most common transportation mechanism of wind blown sand and occurs for average dune sands when the wind velocity is approximately $4m.sec^{-1}$ (Pethick 1984). This value equates to a wind velocity of $14.3km.hr^{-1}$ which was exceeded for 7% of the study period at Waikuku and for 58% of the study period at Amberley. It is important to note that although higher wind speeds are experienced more frequently at Amberley, there is less sand available for transportation due to the beach composition. This means that more sand is likely to be transported at the sandy beaches of southern and mid Pegasus Bay. Also evident is the stronger winds from the south at Amberley Beach, (22%). Waikuku and Spencer Park do not exhibit this trend. This can be attributed to the sheltering effects of Banks Peninsula slowing down the winds in southern Pegasus Bay. As has been illustrated Amberley has a much higher energy wind environment than southern regions of Pegasus Bay.

2.4 Currents

In the coastal zone, currents exhibit energetic characteristics which are pertinent to sediment budgets through the redistribution or transfer of sediment within and between cells. The velocity of the current determines the potential quantity of material that could be transported and the distance travelled. The following sections look at the different generating mechanisms behind currents active in the Pegasus Bay region.

2.4.1 Shore Normal Currents

Shore normal currents are wave induced and appear in conjunction with the wave disturbance. They are produced by the orbital motion of the water particles within the waves (Hansom,1988, Pethick, 1984). In shallow water these orbits are ellipses which progressively flatten as the water depth decreases so that much of the water moves onshore and offshore along a line. The velocities of these two currents are not equal. Onshore currents have a greater intensity and a lesser duration than the offshore component. The result is water moving onshore and offshore. These currents have not been measured in the Pegasus Bay environment during this study period and so can not be quantified. The orbital velocity required to move fine sand is 10cm.sec^{-1} (Carter and Herzer 1979). From their drift card experiments the minimum velocity of the fastest card was 10cm.sec^{-1} which suggests that excepting extreme events little sediment is transported by shore normal currents.

2.4.2 Return Currents

Return flow is often difficult to quantify. The water from waves that wash on the shore must return to the sea body. Much of the swash is returned through percolation but the rest returns through backwash. Two types of return currents can be identified; longshore currents and rip currents.

Longshore currents are caused by waves which approach at oblique angles to the shore (Figure 2.5). The waves run up the beach at an angle corresponding to the wave approach angle. The water then returns under gravity normal to the shore resulting in a net displacement of water, sediment and energy in an alongshore direction.

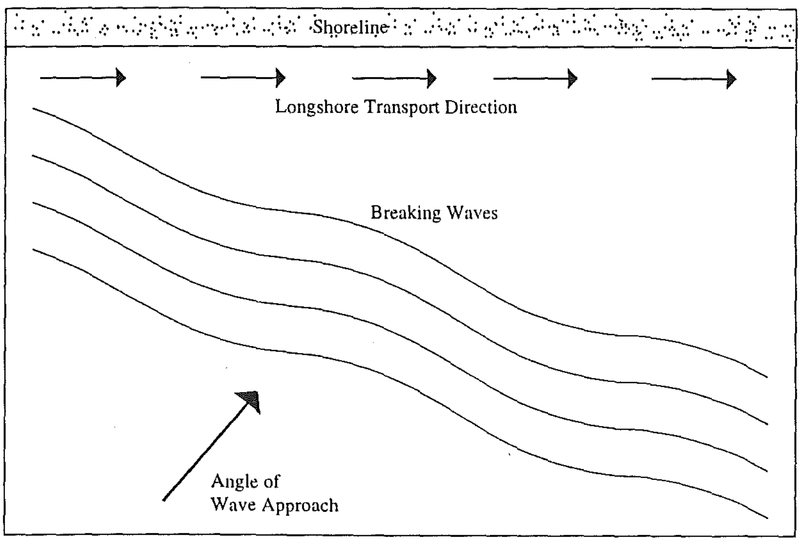

Figure 2.5 *Longshore currents caused by oblique wave approach*

Rip currents are a form of cell circulation. Such a system consists of onshore currents and longshore currents which then feed strong rips which extend past the breaker zone, as shown in Figure 2.6. The causes of these rip currents are areas of higher waves and subsequent build up of water on shore in these zones. A hydraulic gradient results between areas of low waves, (low water level on shore), and high waves, (high water level on shore), and alongshore movement of water occurs in both directions away from areas with high water levels. Where two opposing alongshore currents meet they then flow out to sea as a rip current at the point of lowest wave height. Wave height differences as mentioned here can be the result of an uneven sea bed or edge waves.

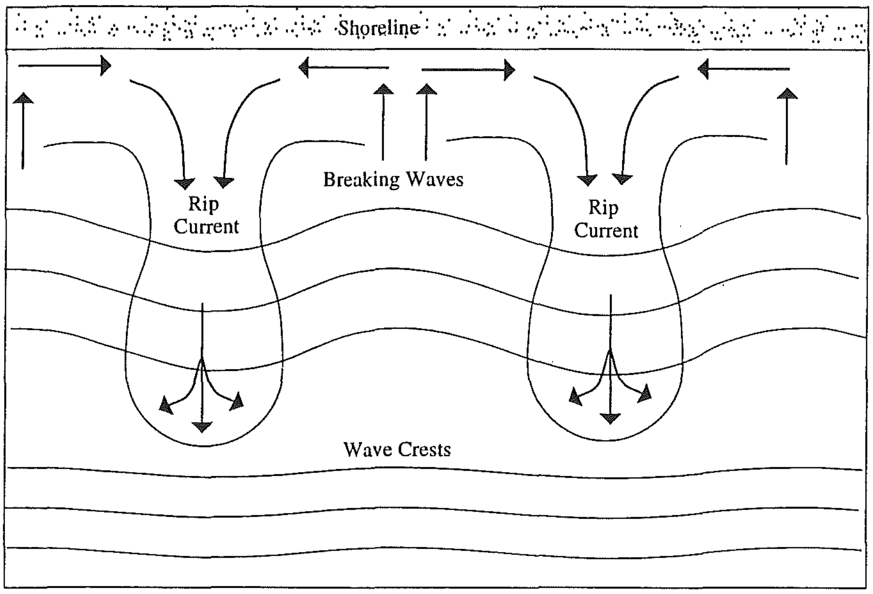

Figure 2.6 *Rip current circulation*

2.4.3 Tides

Tides are created due to the gravitational pull of celestial bodies on the earth. Pegasus Bay exhibits semidiurnal tides. An accurate tidal range for the open coast of Pegasus Bay has not been determined but estimates of 1.3m to 2.4m have been made (Cope, 1993). The changing tidal water levels serve to determine the vertical extent of wave action. At high tide waves can reach further up the shore while swash and wave action at low tide is restricted to the lower foreshore. Apart from the above factor tides have little influence on sediment transport. The currents generated by tides do not reach critical velocities capable of transporting sediment on the open coast. The main site where the tidal stream transports sediment is the Avon-Heathcote Estuary inlet and channels. Some sediment transport by tidal currents may also occur at the mouths of the Waimakariri and Ashley Rivers.

2.5 Nearshore Processes

The nearshore zone is extremely dynamic. It is the region which stretches from the first breaker line to the upper limit of the swash. Consequently the area changes in extent with tidal changes. This environment is discussed in the ensuing sections.

2.5.1 Swash Zone

Runup or swash is the movement of a wave up the beach slope once it has broken. The height of the runup determines the area of beach exposed to the depositional or erosional effects of the sea. The actual run up height can be influenced by a number of factors including breaker form, number of breakers, wave height, wave period, wave approach and the nature of the beach and nearshore profile. Wave height, period and approach and the beach profiles are discussed separately. The breaker forms for this study, (Figure 2.7), have been divided into the following categories:

spilling, plunging, spilling/plunging and surging

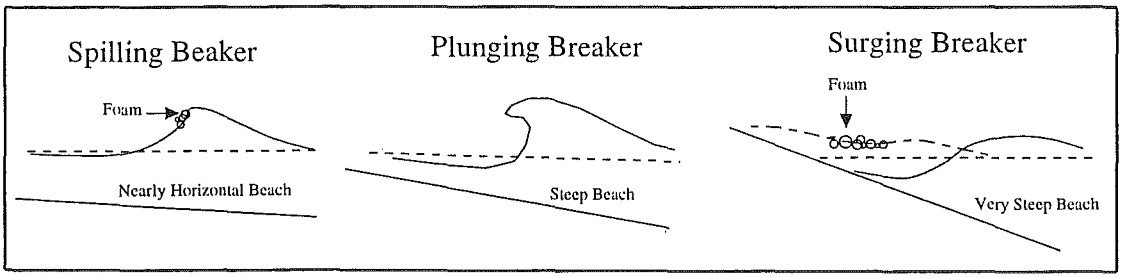

Figure 2.7 *Breaker types*

Spilling waves occur when a wave crest becomes unstable and flows down the front face of the wave. Characteristic of this breaker type is an irregular foamy water surface. Plunging breakers are also known as dumpers. The wave crest curls over the front face of the wave and falls to the base of the wave. A high splash and foam is evident. The crest of a surging wave remains unbroken while the base of the front of the wave advances up the shore. Foam is present at the shoreline. Spilling/plunging waves are a combination of the two types (Komar 1976).

The type of breaker can be related to the shore slope and wave steepness. Steep gradient beaches characteristically have high energy plunging breakers while spilling breakers are more common on gently sloping shores. Surging breakers normally occur on medium gradient beaches. As expected the most common form of breaker during the study period at Waikuku, a flat sandy beach, was the spilling breaker, (46%). At Amberley, a steeper mixed sand and gravel beach, 56% of breakers were observed to be of the spilling/plunging type. This corresponds to the theory that plunging breakers occur on steep beaches (Amberley) and spilling breakers are common on gently sloping beaches (Waikuku).

Run up widths are indicative of the breaker type. Plunging/spilling waves have more energy than spilling waves and the run up widths at Amberley and Waikuku reflect this. A maximum swash length of 25m for Amberley Beach and 20m for Waikuku were recorded during the study period. Similarly the average runup for Amberley was 9.6m and only 6.2m for Waikuku. Therefore steep beaches such as those found in the north of Pegasus Bay are subject to a more intense swash regime than the flatter beaches in southern and mid Pegasus Bay.

2.5.2 Offshore Bar

Storage in the nearshore zone further complicates the sediment budget. When a beach is in deficit the sediment may not be completely lost to the system. In times of erosion, beach sediment is often removed from the beach and deposited to form an offshore bar. This bar then tends to modify the process environment. Waves break when:

$$H/d = 0.78 \qquad \text{eq. 2.4}$$

where H is the deep water wave depth
and d is the depth of shallow water.

An offshore bar may build up so that waves that would normally break on the shore, break first in the shallow zone above the offshore bar. The wave energy at the shore is reduced and sediment can be moved onshore.

2.6 Concluding Remarks

The process environment of Pegasus Bay is not uniform throughout the entire region. Instead distinct divisions between the northern, middle and southern sectors can be made. This division is apparent in many of the process variables.

Southern Pegasus Bay does not show a seasonal trend in wave height whereas heights increase during the winter months in northern Pegasus Bay. This is due to the southerly swells being deflected in the south by Banks Peninsula.

Waves are steeper at Waikuku Beach than at Amberley Beach which corresponds to the preponderance of north-east seas in this region. The waves here are steeper because of the short period rather than the wave height and so are not indicative of the energy environment and can therefore not be used as an indicator of sediment transport. However there is a positive relationship between the steepness values and the state of the beach.

The wave angle frequencies reflect the topography of the surrounding area. Banks Peninsula reduces the number of southerly swells arriving at the shores of southern Pegasus Bay. Northern Pegasus Bay receives more southerly swells and less north-easterly seas as the propagating fetch to the north-east is restricted.

The wind environments are also different at various locations of Pegasus Bay. Strong offshore winds are not experienced in the south to the same extent as they are in the north due to the barrier the high dunes in this zone create. The winds in the north are stronger but can not transport as much sediment as there are less fine grained sands available for transport.

It is the interaction of these processes which drive the sediment budget. Northern Pegasus Bay has an extremely high energy environment compared with southern Pegasus Bay. This means that more sediment may be put into action although the differing sediment types (Chapter Five) must also be considered. Where this sediment is stored, its origins and the mechanisms by which it moves are discussed in the following three chapters.

Chapter Three
Sources of Sediment

3.1 Introduction

Sources of sediment serve to nourish the beaches of Pegasus Bay. It is important to understand the nature of these sources to be able to quantify their roles in the sediment budget.

This chapter examines and quantifies two of the sources in Pegasus Bay - rivers and the offshore source. It is important to note that the beach system, estuaries, lagoons, dunes and longshore transport can also be sources of sediment. However these features are discussed in Chapters Four and Five, as they are also sinks or account for transfers of sediment.

3.2 Rivers

> *'Fluvial erosion of the continents is by far the most important source of coastal sediment supplying over 90% of global marine sediment.'*
>
> (Hansom, 1988)

Hansom's statement highlights the importance of the river source to the sediment budget of beaches. Rivers have great potential to transport sediments to the coastal system. The impact a river has on the coast is dependent on the size of that river. Zenkovich (1967) described three classes of river size, large rivers, small isolated rivers and small closely spaced rivers. On a world scale New Zealand has no large rivers. Large rivers transport vast quantities of sediment to the coast and have huge impact on the coastal area. Deltas form at the mouths of these rivers changing the environment such that marine processes have very little impact and the fluvial processes dominate (Zenkovich, 1967).

Small rivers have little effect on the coast. The mouths are controlled by coastal processes such as waves tides and the rate of littoral drift (Zenkovich, 1967). A small river's mouth can be deflected by longshore transport and may even be dammed by the beach so that the water from the river reaches the sea through percolation.

> *'the morphology of a river mouth is not affected solely by runoff, but also by conditions in the sea and the size of the particles transported by the river. The greater the effect of marine factors, the greater must the load of a river be in volume or in grain size for it to leave its mark on the morphology of the coast.'*
>
> (Zenkovich, 1967)

The rivers of Pegasus Bay are small rivers. The Ashley and Waimakariri Rivers are the largest in the region and although they maintain their conveyance, the shifting nature of their mouths may be a testament to the influence of the marine environment. The Waipara and Kowai Rivers seldom have open access to the coast as the high energy coastal processes detailed in Chapter Two dominate this region. The Avon and Heathcote Rivers flow into an estuary and are therefore dominated more by tidal processes than other coastal processes. The following sections will examine the Pegasus Bay rivers and estimate the amount of sediment reaching the coastline.

Table 3.1 presents the sediment inputs of each of the rivers within Pegasus Bay. These figures have been obtained from secondary sources and are originally expressed as tonnes per year which is then converted to cubic metres in order to maintain continuity with other sediment measurements. The tonnes per year have been divided by 1.25 (bulk density) to convert tonnes per year to cubic metres per year as prescribed by Gibb and Adams (1982). The suspended yield represents the specific annual suspended sediment yield based on values obtained from Griffiths and Glasby (1985). The bedload range represents between 2% and 20% of the suspended yield giving the upper and lower limits of the amount of sediment delivered to the coast by this transport mechanism. Griffiths (1979) established that of the suspended load reaching the open coast of New Zealand, only 40% of the yield is contributed to the shoreline. The remainder, (mud and silt) is transported to the offshore. Therefore the totals present the calculated bedload and associated errors as well as the suspended load which reaches the coast.

Table 3.1 *Annual river yields of suspended sediment, bedload and total load to the coast in Pegasus Bay*

	Suspended Yield (t/yr)	Suspended Yield (m^3/yr)	Range of Bedload Upper (m^3/yr)	Lower (m^3/yr)	Suspended Load to the Coast (m^3/yr)	Total Load to the Coast (m^3/yr)
Avon and Heathcote Rivers	7,100	5,680			2,272	2,272
Wamakariri River	5,950,000	4,760,000	952,000	95,200	1,904,000	2,332,400 ± 428,400
Ashley River	1,160,000	928,000	185,600	18,560	371,200	454,720 ± 454,720
Kowai River	91,000	72,800	14560	1,456	29,120	35,672 ± 6,552
Waipara River	460,000	368,000	73,600	7,360	147,200	180,320 ± 33,120
TOTAL	7,668,100	6,128,800	1,225,760	122,576	2,453,792	3,005,384 ± 551,592

3.2.1 Avon and Heathcote Rivers

Both the Avon and Heathcote Rivers are located in the south of Pegasus Bay and travel through the urban centre of Christchurch. The Avon winds through a flat urban catchment 84km^2 in area and the Heathcote River has a catchment area of 105km^2 consisting of both flat urban areas as well as developed and undeveloped regions of the Port Hills. Consequently the sediment load of the Heathcote is almost twice that of the Avon. According to Hicks (1993b) the estimated suspended sediment yield of the Heathcote is 4,500 tonnes per year and the Avon's suspended sediment yield is estimated to be 2,600 tonnes per year. Suspended sediment was measured using an I.S.C.O. auto-sampler programmed to sample regularly every hour at Gloucester Street for the Avon and Buxton Terrace for the Heathcote River. Manual samples were also made during peak flows to build up a comprehensive data set. Bedload was also measured but was insignificant even during peak flows and so has not been regarded. Table 3.1 shows the suspended loads for the Avon and Heathcote Rivers.

The 40% of suspended yield that is transported to the coast (Griffiths 1979) for the Avon and Heathcote Rivers amounts to 2,727m^3.yr^{-1} (presented in Table 3.1). This value is probably an over estimate due to a high proportion of silt and mud content reflecting the fine sediments of the catchments, and the "sink" nature of the Avon-Heathcote Estuary.

The sediment from the Avon and Heathcote Rivers is not transported directly to the open coast. Instead the velocities of the rivers decrease as they enter the Avon-Heathcote Estuary resulting in sediment deposition. This sediment then works its way into the estuary channels and inlet before being scoured out on ebb tides or during flood episodes. The net deposition rate within the estuary is thought to be minimal, (discussed further in Chapter Four), and so it can be assumed that the sediment from the Avon and Heathcote Rivers eventually reaches the open coast. Therefore the Avon-Heathcote Estuary can be considered to supply the sea off Pegasus Bay with approximately 2,300m^3 of sediment per year. Due to the fine composition of this material very little would have the properties necessary to build up the beaches.

3.2.2 The Waimakariri River

The largest river with regards to water and sediment volume along the Pegasus Bay coastline is the Waimakariri River. Of all the rivers flowing into the bay this is also the most modified by human actions. Gravel extraction from the river bed affects the sediment yields while flood protection works constrain the river's channel. The catchment of the river is 3,564km^2 and is situated mainly within the Southern Alps. The Waimakariri is also the only Pegasus Bay river to originate near the main divide of the Southern Alps. The steeper regions of the upper Waimakariri are highly erodable and contribute vast quantities and sizes of sediment. Conversely the lower reaches of the Waimakariri are gently sloping and unconfined and the river loses much of its carrying capacity as it becomes braided and the velocity lessens. Recent views state that the bulk of the sediment in the lower Waimakariri is supplied by local bed scour and bank erosion and not from the upper catchment (Griffiths, 1979; Blakely and Mosely, 1987). The last 18km of the Waimakariri is gently sloping. The mean sediment size ranges from 28mm at the Gorge Bridge (the eastern edge of the Southern Alps), down to 9mm just east of the old Highway Bridge. These gravels are subangular to slightly rounded indicating a significant period of transportation.

The last 3 km of the Waimakariri River bed is sand (Deely 1992). The carrying capacity of the river at this point has dropped to levels such that no gravels are transported to the coast. Table 3.1 shows the Waimakariri contribution of sediment to the marine environment. This figure is originally derived from Griffiths and Glasby, (1985), who state that the sediment yield to the coast is $5.95 \times 10^6 t.yr^{-1}$ ($4,760,000m^3.yr^{-1}$) based on measured suspended sediment. After accounting for the bedload range and 60% of the suspended yield, (mud and silt), being lost from the system an average value of $2,332,400m^3.yr^{-1} \pm 428,400m^3.yr^{-1}$ is transported from the Waimakariri to the adjacent beaches.

It is important to note here that the Waimakariri River is the major contributor of sediment to the coastal system of Pegasus Bay. This river has undergone dramatic changes over the past fifty to sixty years with the dramatic shifting of the river mouth. Kirk (1979) estimated that 30% of the sand fraction was being trapped in Brooklands Lagoon. This rate has decreased dramatically since then as the lagoon reaches its saturation point. If the lagoon now only receives 10% of the Waimakariri's suspended sediment yield then only $190,400m^3.yr^{-1}$ of the $1,904,000m^3.yr^{-1}$ (Table 3.1) would not reach the coast. This is approximately $380,800m^3.yr^{-1}$ more reaching the coast than when the lagoon traps 30% of the yield.

3.2.3 The Ashley River

The Ashley River is the second largest river in Pegasus Bay in terms of sediment yield, water volume and catchment size. The Ashley catchment covers an area of $1,298km^2$ originating in the eastern part of the Southern Alps. The upper reaches of the river are steep and gravels are transported. The lower reaches across the plains are gently sloping and the carrying capacity and size of the material in the river decreases coastward. However the Ashley has been known at times to discharge pebbles during high flow events (Little, 1991).

The mouth of the Ashley River is narrow and velocities and potential carrying capacity at this point can be high. The narrow mouth may also be indicative of the dominance of coastal processes over fluvial processes. Griffiths and Glasby (1985) estimate that the Ashley River has a sediment yield of 1.16 million $t.yr^{-1}$ ($928,000m^3.yr^{-1}$). This value was established using regional prediction equations for yield and mean annual runoff of the river catchment. If 60% of this yield is mud and silt which is then flushed from the system and bedload equates to between 2% and 20% of the suspended yield, then the average annual contribution from the river to the adjacent beaches is about $454{,}720m^3 \pm 83{,}520m^3$ (Table 3.1).

3.2.4 The Kowai River

This river is the least researched river of the bay. The catchment itself is small, only $552km^2$ and originates near Mount Grey. The very size and virtual non-existence of flood risk account for little knowledge of the Kowai River. The gradient of the river is very steep so that large gravels can be transported. However as the river bed is normally dry sediment transport rarely occurs. Only during high precipitation events and spring snow melt does water flow along the river bed. The mouth of the Kowai is enclosed by a stable gravel barrier highlighting the influence of the marine processes at this point. Medium flows result in the ponding of water in a lagoon behind the barrier and only during high flows, (approximately once every year) is the barrier breached (J. Austin, Amberley Beach resident *pers. comm.* 1995). An average yearly figure of suspended sediment for the Kowai River has been estimated from regional prediction equations by Griffiths and Glasby (1985) to be about $91{,}000t.yr^{-1}$ ($72{,}800m^3.yr^{-1}$) The total contribution to the coast is calculated to be $35{,}672m^3.yr^{-1} \pm 6{,}552m^3.yr^{-1}$ (Table 3.1).

3.2.5 The Waipara River

The Waipara River enters Pegasus Bay approximately 2km south of Double Corner. This river is very similar in nature to the Kowai River. It extends for 64km from the foothills of the Southern Alps to the coastline encompassing a catchment of $741km^2$. As with the Kowai River the gradient is steep allowing for a greater capability to transport large sediments. An examination of flow velocities from January 1988 through to January 1995 (Canterbury Regional Council (C.R.C.) records) showed that for a significant number of days the river is capable of breaching the gravel barrier. However this occurs on an average of only twice a year. These occasions are during high intensity rainfall events or spring snow melt events. The more frequent opening to the sea, larger catchment and steeper gradient equate to more sediment reaching the coast from the Waipara River than the Kowai River. Based on regional prediction equations for sediment yield and mean annual runoff as well as basin mean rainfall estimated from isohyetal maps, Griffiths and Glasby (1985) estimated that the suspended sediment yield to the coast for the Waipara River is $460{,}000t.yr^{-1}$ ($368{,}000m^3.yr^{-1}$). This then corresponds to $180{,}320m^3 \pm 33{,}120m^3$ of sediment being contributed to adjacent beaches each year (Table 3.1).

3.2.6 Summary

The amount of sediment each river discharges is dependent on the catchments characteristics. Rainfall, vegetation, steepness and catchment size are all important variables. Each river contributes to its adjacent shoreline with the Waimakariri River having the most significant input. The Avon River and Heathcote have the least input into Pegasus Bay. From Table 3.1, it can be seen that an overall total of approximately $3{,}005{,}000m^3.yr^{-1} \pm 551{,}600m^3.yr^{-1}$ of material is estimated to be contributed to the beaches of Pegasus Bay from rivers.

3.3 Offshore Sources

The continental shelf is an important supply of sediment. The shelf break of Pegasus Bay lies between the 150m and 180m isobaths. The width of the shelf ranges from 40km to 85km wide (Carter and Herzer, 1979). In the south of Pegasus Bay at Christchurch, the shelf edge lies 85km from the coast while in the north of Pegasus Bay the shelf edge is only 55km from the coast (Figure 3.1). The Pegasus Canyon is an anomaly. It is a deep incision into the shelf. Located in the center of Pegasus Bay, it has significant ramifications to the sediment budget which will be discussed later in association with sediment sinks.

The Canterbury Continental Shelf is mantled with modern, relict and palimpsest terrigenous sediments (Herzer, 1977). Terrigenous sediment is described by

Carter (1975) as being sediment derived from the land through river, wind and coastal erosion. Furthermore he described palimpsest as being relict material which has been reworked, and while retaining some relict characteristics it is approaching equilibrium with the modern environment.

The limit of offshore and onshore sediment exchange is between a depth of 15m, (Kirk 1979) and 18m (R. McLean, Department of Geography and Oceanography, Australian Defence Force Academy, University of New South Wales, *pers. comm.* 1995). Around this depth there is a change in character of the bottom sediments from principally sand (> 90%) close to the shore, to predominantly sand (50% to 90%) with a non-calcareous mud overlay (33% to 67%) (Carter and Herzer, 1986). It is possible that this demarcation from sand (>90%) to sand with a mud overlay (50% to 90% sand and 33% to 67% silt) mark the onshore/offshore limit of exchange (Figure 3.1). As turbulence decreases and current velocity drops the mud and silt are filtered out and deposited on the shelf. The inner shelf from the shore to a depth of 30m is covered with a modern sand prism. This material progresses through to relict sand and mud on the outer shelf.

On the Canterbury Continental Shelf the main sediment transport is to the north-east in conjunction with the Southland Current, (Carter and Herzer, 1979). The inner continental shelf however has an onshore component induced by wind drift. Opposing the Southland drift is the north-east wind and wave currents that occur in the summer. North-easterlies can reach gale force and the subsequent currents in conjunction with an appropriate phase of the tide and wave surges, shift inner shelf sediments to the south west (Carter and Herzer, 1979).

In order for the modern sand prism material to be transported, bottom speed currents must reach approximately 35 $cm.sec^{-1}$ (Sternberg, 1971). The relict sand and mud is rarely transported as currents greater than 35 $cm.sec^{-1}$ seldom occur at this depth. Day to day currents rarely reach these speeds on the inner continental shelf and only the combination of tidal currents and storm induced currents permit the hydraulic regime to move fine sand or even coarser sediments at a depth greater than 30m (Carter and Herzer, 1979). Because bottom currents are difficult to measure it is even more difficult to quantify any possible sediment movements.

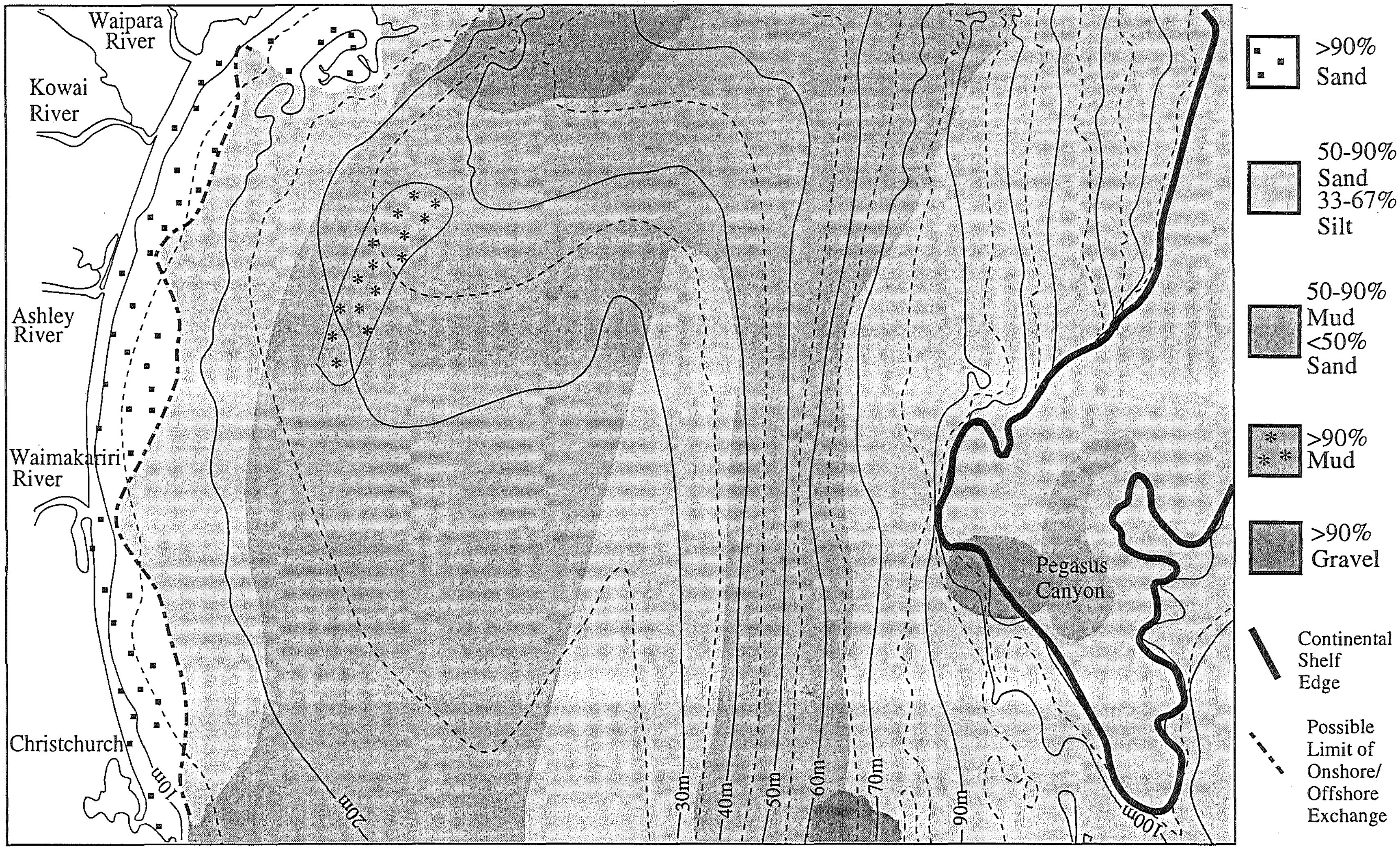

Figure 3.1 *Offshore sediment composition and possible limit of onshore /offshore exchange on the Canterbury Continental Shelf*
After: Carter and Herzer (1986)

It is also pertinent to note that there is no sediment of unknown origin on the beaches of Pegasus Bay. All the sediment can be attributed to local supply. This means that no sediment is transported onto the Pegasus Bay beaches from the south or the north indicating that sediment deposited on the shelf at depth from other sources is not then reworked onto the Pegasus Bay shores. For these reasons input to the beaches from the offshore zone is taken as zero for present purposes.

3.4 Concluding Remarks

As can be seen there are relatively few sources of sediment within Pegasus Bay detailed here. However the next chapter looks at the sinks of sediment within Pegasus Bay some of which double as sources depending on the state of the process environment at particular times. The six rivers of Pegasus Bay all have varying inputs depending on their catchment and flow characteristics. The Waimakariri River contributes the highest proportion of sediment to the coast. The Kowai and Waipara, though being closed off from the sea most of the time still make important contributions during high energy events when coarser material is transported into Pegasus Bay. The Ashley River also transports pebbles during high energy events. The Avon and Heathcote Rivers are more silt dominated due to their urban nature and have smaller effective sediment yields. An average total of about 3 million m^3 of sediment is contributed to the Pegasus Bay coastline each year from rivers.

The offshore environment is extremely complex. Modern, relict and palimpsest terrigenous material mantles the continental shelf. The inner shelf, (<30m deep), is mantled with a modern sand prism progressing through to relict sand and mud on the outer shelf. This material is available for transport onshore when bottom currents reach significant velocities over 35 $cm.sec^{-1}$. The deeper the material, the less likely it is to be transported.

The following chapter looks at the sinks of sediment within Pegasus Bay. Each one is discussed in detail and quantification is presented where possible. The relative importance of each feature to the sediment budget is also discussed.

Chapter Four
Sinks of Sediment

4.1 Introduction

Sinks of sediment are regions which receive material which has been removed from a coastal compartment. This chapter will examine each of the sinks present in Pegasus Bay individually. An attempt at quantification will be made for input into the derivation of the quantified sediment budget model for Pegasus Bay.

4.2 Estuaries and Lagoons

Estuaries and lagoons can hold vast quantities of sediment for long periods of time. These features are located where a river meets the sea. Estuaries are tidally dominated and lagoons are influenced more by fluvial processes. Despite these sometimes nebulous distinctions the two landforms are often similar and for sediment purposes shall be discussed together. The major estuaries and lagoons in Pegasus Bay are the Avon-Heathcote Estuary at the mouth of the Avon and Heathcote Rivers and Brooklands Lagoon at the mouth of the Waimakariri River. Sediment brought down from the catchment by the rivers is swept into the lagoon or estuary. As the flow velocity decreases below the sediment carrying velocity it is deposited. If the flow does not decrease below the threshold then the material can be flushed through or from the system.

There are four main processes which affect the transport of sediment in, out and within the estuarine system as follows:

(i) tidally induced flow into the estuary
(ii) longshore currents
(iii) fresh water runoff
(iv) wave dynamics at the inlet

The sea upon entering an estuary on the rising tide then attempts to scour the sediment out on the falling tide. Consequently high seas and or spring tides can have a major impact on the sediment budget as more water enters and leaves at higher velocities. This scouring effect is generally restricted to the channels where flow velocities are the highest. When the depositional rate exceeds the scour rate then sedimentation occurs, and when this is the case an estuary is deemed to be a point sink of sediment.

A lagoon is usually non-tidal and any rise and fall of water is controlled by river processes. These processes also control sedimentation. In this case flooding down the river plays an important role in calculating a sediment budget. Flood flows scour sediment from the feature.

Lagoons store sediment but often this sediment is not directly from the coastal zone. Instead lagoons trap the sediment before it reaches the coast. In this regards the feature is not a sink of the coastal budget unless it is through overwash or wind blown sediments from the beach system. The sediments stored by the lagoon are transported to the coast during flood episodes in which case the landform is a source rather than a sink.

4.2.1 The Avon-Heathcote Estuary

The Avon-Heathcote Estuary has two major fluvial contributors, the Avon and Heathcote Rivers. As recently as two thousand years ago the Estuary did not exist in its present form and position (Figure 4.1) (Brown and Weeber 1992). The Avon and Heathcote had separate mouths each with its own small estuary (Brown and Weeber, 1992; Owen, 1992; Hicks, 1993b). The Avon River mouth flowed out to the coast further north than its present site. The South Brighton Spit slowly grew as sediment from the Waimakariri and Ashley Rivers drifted south (Hicks, 1993b). It is thought that about 1,000 years before present the Avon's estuary occupied the area now known as Travis Swamp (Brown and Weeber). Approximately 500 years later the swamp had infilled and the spit grown such that the Avon and Heathcote mouths were both enclosed to form the Avon-Heathcote Estuary as it can be seen today (Figure 4.1). Since this time the major changes in the area have been to the spit tip which has demonstrated fluctuations since the 1940s (Kirk 1979). The estuary as it stands today covers an area of approximately 880 hectares.

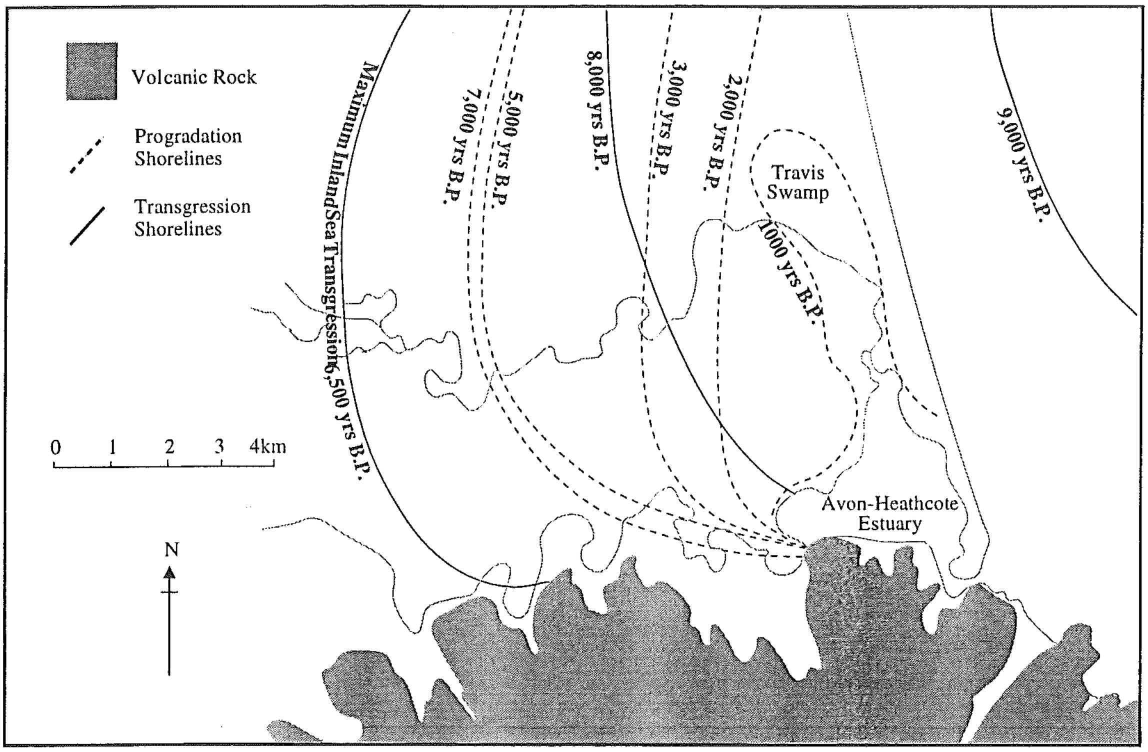

Figure 4.1 Postglacial marine and progradational shorelines

After: Brown and Weeber 1992 p14

The Avon-Heathcote Estuary can be classified as a "single spit barrier enclosed estuary" under the Hume and Herdendorf (1988) classification of New Zealand estuaries. This type of estuary is characterised by the following criterion:

1. Spit forms enclosure
2. Unstable inlet, narrow gorge, with flood and ebb tide shoals
3. Extensive intertidal area
4. Small inlet width to mean width ratio
5. Low freshwater inflow
6. Tide dominated hydrology
7. Well mixed except in head waters

The Avon-Heathcote Estuary has all of the above feature and the most significant of these to the sediment budget are the ebb and flood tide shoals. The ebb tide delta is a consistent feature at the inlet of the estuary indicating the propensity for sediment transport out of the estuary.

The Avon-Heathcote Estuary is an extremely dynamic feature. It is influenced by two rivers, coastal processes and human activity. Its fragile nature can lead to dramatic responses to changes in its regulating features. The urbanisation of the Avon and Heathcote catchments, in particular the urbanisation of the Port Hills has lead to an increase in sediment yield to the Heathcote River. Market gardening on the lower slopes of hill tributaries has also lead to loess being washed into the Heathcote River (Findlay and Kirk 1988). The Horotane Valley, which is an extensive market garden area, has a stream laden with sediment during the winter months. This stream feeds into the Heathcote River.

At the present time the Avon-Heathcote Estuary does not appear to be accumulating significant amounts of sediment. Between the 1920s and 1950s a huge amount of silt was washed from the urbanising Christchurch area to the estuary's contributing rivers. This silt was then built up in the rivers to such an extent that areas of the Avon which had been 3m to 6m deep had become only 80mm to 100mms deep (Deely 1992). This sediment was trapped in the rivers and subsequently cleared by a river sweeper which in turn led to a layer of mud 250mms deep being deposited in the Estuary. New areas of Christchurch being urbanised decreased in the 1960s and the rate of accumulation dropped from 60mm to 120mms per year to only 5mms per year. Hicks (1993b) disagrees with Deely (1992) and contests that the 250mm layer of silt and mud was deposited over a longer time frame from the 1880s to the 1950s corresponding to a deposition rate of only 20mm to 40mms per year. This he states, agrees more with anecdotal evidence of the rates of deposition in the estuary.

These significantly different rates of deposition and corresponding sediment yields demonstrate the importance and uncertainty of quantification for both factors. Since the 1960s, deposition within the estuary has decreased as have the sediment yields of the Avon and Heathcote Rivers. Not only do the deposition rates vary with sediment yield but so too does the shape of the estuary especially the inlet and spit area. The spit was relatively stable until the early 1900s after which time it fluctuated greatly, (Figure 4.2), corresponding to the rapid urbanisation of Christchurch (Findlay and Kirk, 1988).

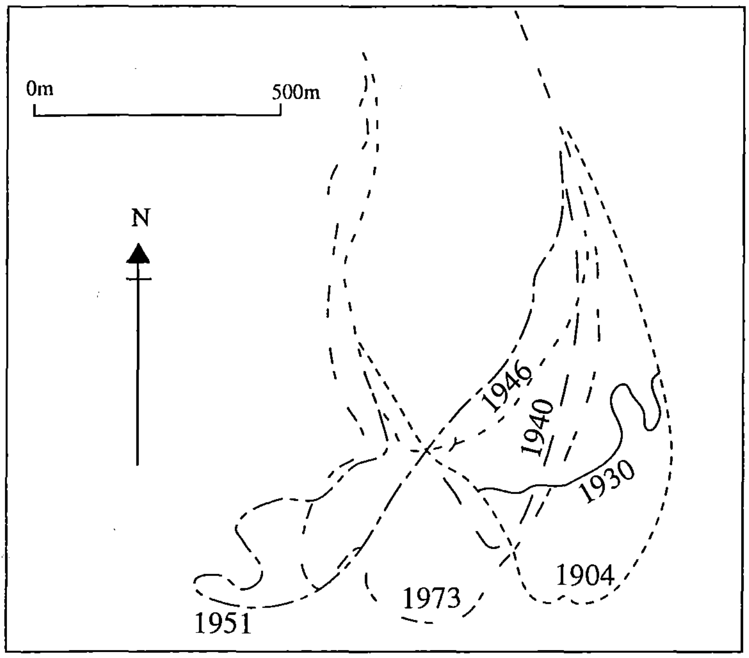

Figure 4.2 *Changes to the South Brighton Spit*

Source: Findlay and Kirk, (1988) p108

Since 1962 there has been a lowering of the mud flats in the Avon-Heathcote Estuary (Hicks 1993b). This value varies spatially over the Estuary from 2mm to 6mm per year. Compounded with the lateral shifting of tidal channels and bars the result of this activity has been a barely detectable gain of sediment at a rate less than 1mm per year.

Current estimates of the sediment yields from the Avon and Heathcote Rivers to the estuary are potentially at $2{,}600 t.yr^{-1}$ ($2{,}080 m^3.yr^{-1}$) and $4{,}500 t.yr^{-1}$ ($3{,}600 m^3.yr^{-1}$) respectively. Furthermore the city outfall drain yields $170 t.yr^{-1}$ ($136 m^3.yr^{-1}$) (Hicks 1993b). These values represent a potential value for net sedimentation within the estuary of 1mm per year. It therefore follows that based on a 1mm per year sedimentation rate, the Avon-Heathcote Estuary is a sediment sink. It is trapping all the sediment from the rivers and some sediment from the coastal zone to achieve this sedimentation rate. These conclusions are tentative, based on a <1mm which corresponds to a sedimentation rate of $<5,800m^3.yr^{-1}$.

4.2.2 Brooklands Lagoon

Brooklands Lagoon is located to the south of the mouth of the Waimakariri River. It extends through the old channel of the Waimakariri when the river's opening was to the south of its present position. The Styx River and the Waimakariri River both feed into Brooklands Lagoon (Figure 4.3). Brooklands Lagoon is smaller than the Avon-Heathcote Estuary and covers approximately 270 hectares. It is 4.5kms long and 0.8kms at its widest point (Owen 1992). Brooklands Lagoon and the Waimakariri River mouth have changed dramatically over the past 150 years and have in recent years attained a semi-stable state. Flooding of the Waimakariri River, longshore drift and artificial flood protection works within the Waimakariri itself have led to the maintenance of the present day location and configuration of the Waimakariri River mouth and Brooklands Lagoon Spit. Before the Waimakariri River mouth shifted north to its present position after 1935, the now well vegetated sand dunes of Brooklands Spit were a series of shifting sand bars and lagoon mouths (Owen 1992). The Styx River has in the past 25 years been constantly shifting in its lower course. This perhaps reflects its attempt to maintain its channel morphology in the face of a shallowing lagoon (Hicks and Duncan, 1993).

The Brooklands Lagoon sand spit is eroding at its distal end which also the true right bank of the Waimakariri River mouth. The spit itself is approximately 4kms long. Investigations during the study period showed that the dune at the north end of the spit eroded 2.1m horizontally for the two month period from the 17th of March to the 15th of May. Hicks and Duncan (1993) and Boyle (1984), state the Brooklands Lagoon spit has been eroding since the 1970s on the Brooklands Lagoon side along its entire length. One reason for this could be the growth of Pinus Radiata on the spit preventing the deposition of wind blown sand borne on the north-east winds common in this area. Any sand eroded from this shore is not replaced. Another possibility is that the Styx River is building a delta at its mouth and in doing so is forcing the tidal channel up against the spit. Tidal currents flowing along the channel are scouring the shoreward channel margin.

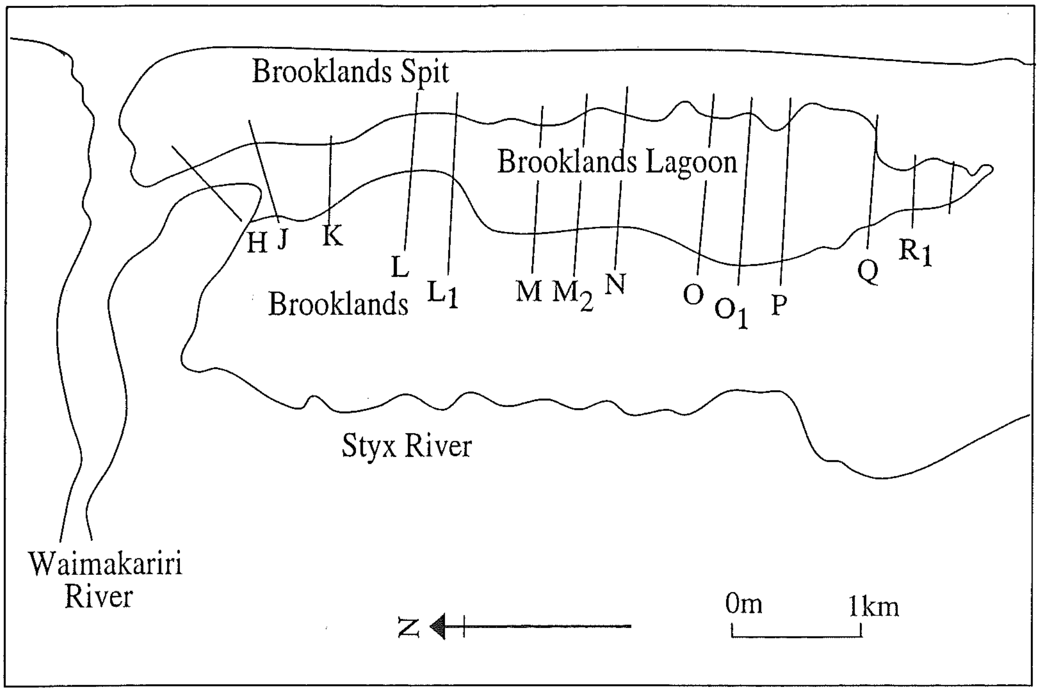

Figure 4.3 *Brooklands Lagoon showing locations of cross-sections*

After: Hicks and Duncan (1993) p11

Figure 4.3 locates cross-sections that have been surveyed through Brooklands Lagoon. Surveys have been recorded in 1932, 1969 and 1977, with partial surveys at the mouth of the lagoon in 1973,1978 and 1984. Data presented by Hicks and Duncan (1993) and Knox *et al.* (1978) demonstrate the considerable deposition which occurred between 1932 and 1969. During this time there was an average of almost 1m of deposition in the old Waimakariri channel. This results in an estimated 1.4 million m^3 of deposition over this period (Figure 4.4). It can be assumed that the most rapid period of deposition was shortly after the mouth changed position in the 1940s. However this rate of deposition has not continued since 1969 and in places erosion has occurred. Local migration of the river mouth has lead to erosion and deposition at sections H and J, (Figure 4.3), which have greatly influenced the overall trend (Figure 4.4). The deposition trend shown in Figure 4.4 is for the entire lagoon and is significantly lower in recent years due to erosion at cross sections H and J. Despite these falls in sedimentation rates it is locally believed that infilling is still occurring but at a lesser rate (L. King, Waikuku Beach resident, *pers. comm.* 1995). Sediment is deposited into the lagoon during flood flows of the Waimakariri but is mostly a fine layer of mud and is easily transported out via suspension in subsequent moderate flow events. Kirk (1979) estimated that of the 1.3 million $m^3.yr^{-1}$ of sand thought to be transported to the coast by the Waimakariri, $340,000m^3.yr^{-1}$ was trapped in Brooklands Lagoon.

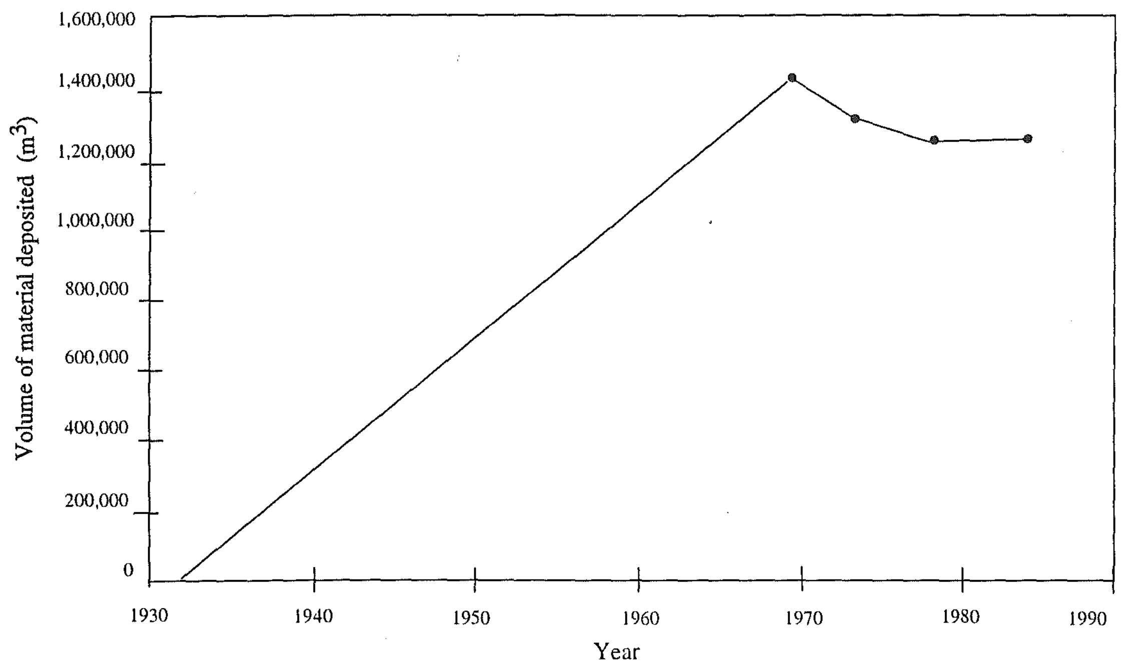

Figure 4.4 *Brooklands Lagoon volume changes between 1932 and 1984 as determined by cross-section changes*

Source: Hicks and Duncan (1993) p11

The rate of deposition in Brooklands has decreased dramatically in past years. Hicks and Duncan (1993) conclude that future average rates of deposition are likely to be no more than a few millimetres per year and most of this will be deposited at the Spencerville end (south) of the lagoon as the shallow flats are gradually converted to marsh. Furthermore they state that as the spit continues to vegetate, wind blown coastal sand and/or storm wash over will also continue to decrease. It therefore appears that Brooklands Lagoon has reached near saturation point for the amount of sediment it can store. A $5mm.yr^{-1}$ deposition rate corresponds to only 1,350$m^3.yr^{-1}$ being deposited in the lagoon so that sediment from the Waimakariri is now likely to reach the coast rather than being deposited in Brooklands Lagoon and Spit. Kirk (1979) stated that 390,000m^3 of the Waimakariri's sediment yield was being deposited in the lagoon. This is a 289% reduction in the amount of sediment deposited in Brooklands Lagoon. The same order of reduction can be assumed for Brooklands Spit. This substantially alters the input to the beach system from the Waimakariri River. Post 1935 30% of the yield was deposited in Brooklands Lagoon (Kirk 1979). This figure has dropped to less than 1% of the Waimakariri's yield. Now almost 100% of the yield is reaching the open coast. This increase in sediment supply may have significant ramifications on Pegasus Bay beaches with an increase in deposition at adjacent sites. The Styx River contributes little sediment. Its present yield is 3,000 to 3,900 m^3/yr of which most is trapped upstream of the tidal gates. It is likely that this sediment will be contained (at least in the short term) in Brooklands Lagoon.

4.3 The Beach System

As shown in Figure 1.4, the beach can divided into two regions, the foreshore and the backshore. The foreshore extends from mean high water springs to mean low water springs and is the zone where most sediment transport occurs. The backshore is often more stable as it is less affected by wave action. The shore can be both a sink and a source of sediment, although the time frame is often too short or transitory in budget model terms as such models normally cover time frames of years. A shore can build up or lose sediment over as short a period as one tidal cycle. Such short term fluctuations are often disregarded but play an important role in the dynamic movement of sediment within and through a coastal compartment.

Within the field area of Pegasus Bay, twenty-four profile sites were established (Figure 1.1). Detailed descriptions of their locations are given in Appendix 2. Of the twenty-four sites, twenty-one are sites that have been established by the

Canterbury Regional Council (C.R.C.). Three further sites were installed for this study in order to provide a more detailed coverage of the more unknown northern sector of Pegasus Bay. The sites in southern Pegasus Bay from South Brighton Spit to Brooklands Lagoon were established in 1990 and have been surveyed twice yearly, once in summer and once in winter by staff at C.R.C. Profiles in the northern sector, from Pines Beach to Teviotdale have been surveyed once a year during summer, since November 1991 when the sites were established. The exceptions are South Leithfield, Newcombes Road and Double Corner where monitoring began this year when the profiles were established.

An examination of these profiles was carried out to investigate the sediment volume and profile form and position changes that have occurred during the study period and since the C.R.C. began monitoring. The profiles were surveyed using a variety of methods depending on the availability and demands on the Geography Department survey equipment. During the study a total station, compass theodolite, quickset level and dumpy level were used at different times. The profile data was reduced using a computer spreadsheet and is displayed (Figure 4.5 to 4.13 and Appendix 2) using graphpro on the Archimedes computer. Distances along the horizontal axis begins at zero, representing the benchmark as designated by the C.R.C. Not all of the profiles displayed start at zero as often the benchmark is located behind the beach system. The vertical axis shows the height above mean low water level as determined by C.R.C. and is given the value of zero. This allows for ease of calculation of the beach volume, which is the area under the graph, as well as a clear concise display which is easily interpreted. Beach volumes, also presented in Figures 4.5 to 4.13 are measured in cubic metres above the mean low water level.

Large quantities of data have been processed such that forty-five profile graphs were produced. A selection of these graphs have been chosen as representative of each region within Pegasus Bay. The following is a brief synopsis for the various localities within Pegasus Bay. The bay has been divided into eight sectors as shown in Table 4.1.

Table 4.1 *Names of profiles and sector divisions of Pegasus Bay adapted for this study*

Sector	Profile
South Brighton Spit	South of Pukeko Street Plover Street Caspian Street
Christchurch City	Beatty Street North of Rodney Street Rawiti Street
Bottle Lake Region	Larnach Street South Bottle Lake Forest Heyders Road
Brooklands Spit	Brooklands C1891 Brooklands C1972 Brooklands C2070
Mid Pegasus Bay	Pines Beach Woodend Beach Waikuku Beach
Leithfield Region	Ashworths Ponds South Leithfield Leithfield Beach
Amberley Region	Kowai River Newcombes Road Amberley Beach
Waipara River Region	Amberley Golf Club Teviotdale Double Corner

The beach volumes from the the low tide mark to the dune toe above the mean low water level for each region have been calculated and are presented in Table 4.2. Each profile site has been taken as representing one half of the distance to the next profile site so as a complete estimate for the total length of shore is built up. The volumes are also presented in unit metres per length of the coastline to give a comparison of the average beach volume at a specific location in a sector. The beach system contains a total of $18.7\times10^6 m^3$ of sediment. The following sections look at the individual sectors and their observed changes.

Table 4.2 *Beach volumes within Pegasus Bay*

REGION	Length of Region (Km)	Volume of Region (m^3)	Volume / metre (m^3/m)
South Brighton Spit	3.3	770,170	233
Christchurch City	4.5	1,152,700	256
Bottle Lake Region	7.8	2,121,200	272
Brooklands Spit	2.9	436,170	150
Mid Pegasus Bay	13.0	9,022,000	694
Leithfield Region	9.8	3,975,300	406
Amberley Region	4.0	745,600	186
Waipara Region	4.4	480,800	109
TOTAL	49.7	18,703,940	

4.3.1 South Brighton Spit

The beaches on South Brighton Spit are composed of sand. The beach area extends for approximately 150m from the dune base to mean low water level. Within this area there are three profile sites which have been surveyed during the study period. The Caspian Street site is the most stable of all sites as it is located near the proximal end of the spit. This is reflected in Figure 4.5a which shows the volume changes for this profile. The average volume of the beach is $288m^3.m^{-1}$. The deviations from the mean which are the most significant are a $40m^3.m^{-1}$ increase in May 1995 and a $32m^3.m^{-1}$ decrease in September 1992. The latter is probably a direct result of the storms during July and August 1992.

Fluctuations closer to the end of the spit are much more pronounced. This can be seen in the volume and profile changes of South Pukeko Street (Figure 4.5b and c). The volumes have a range of $197m^3.m^{-1}$ varying about an average volume of $188m^3.m^{-1}$. It is also interesting to note here that the two highest volumes of $302m^3.m^{-1}$ and $290m^3.m^{-1}$ occurred in May 1990 and January 1992 respectively. The May profile is 24m longer than the January profile which equates to only $12m^3.m^{-1}$ difference. This is a relatively small difference in volumes considering the large horizontal change. Examination of the profiles

(Figure 4.5c and d), shows that the January 1992 profile has two pronounced berms characteristic of a summer profile. These features store large volumes of sediment and account for the apparent volume discrepancies. Furthermore the summer profiles at this site exhibit well defined berms. This highlights the need to look at the beach in three dimensions not just the two dimensions given by profile line graph.

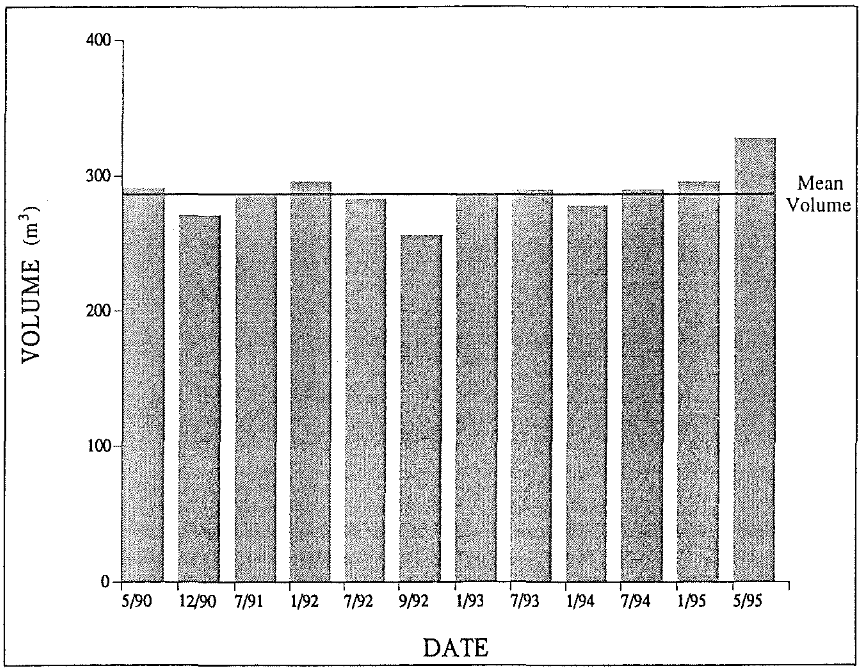

Figure 4.5(a) *Beach volumes at Caspian Street*

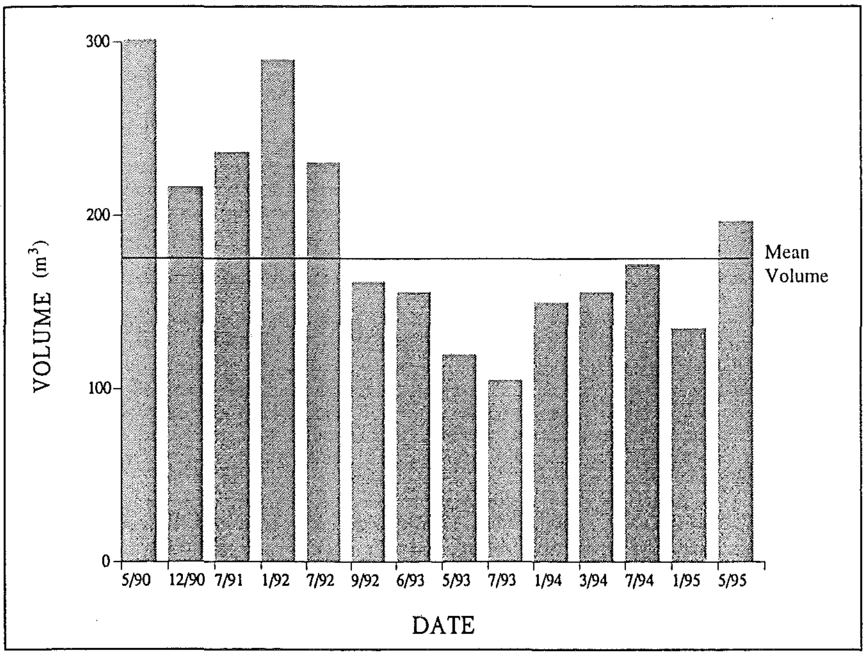

Figure 4.5(b) *Beach volumes at Pukeko Street*

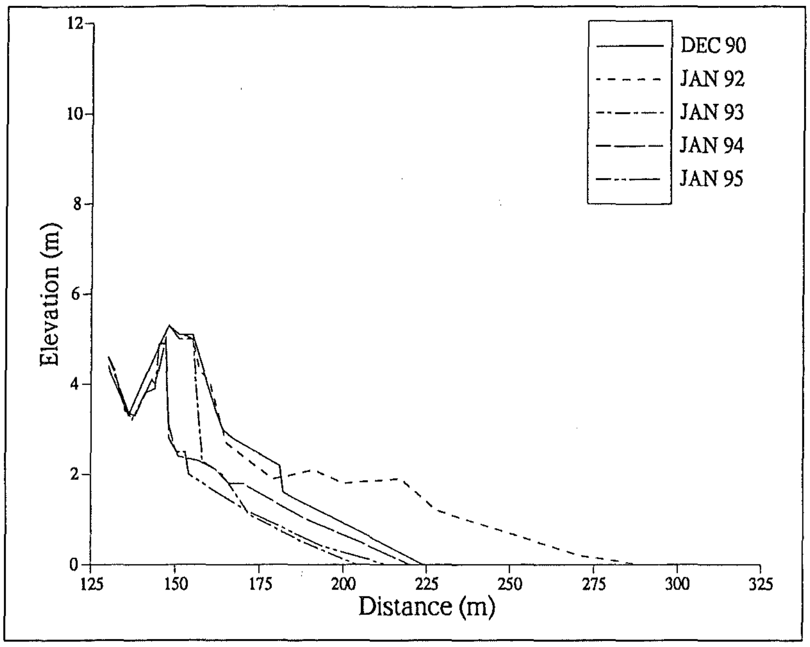

Figure 4.5(c) *Summer beach profiles at South Pukeko Street*

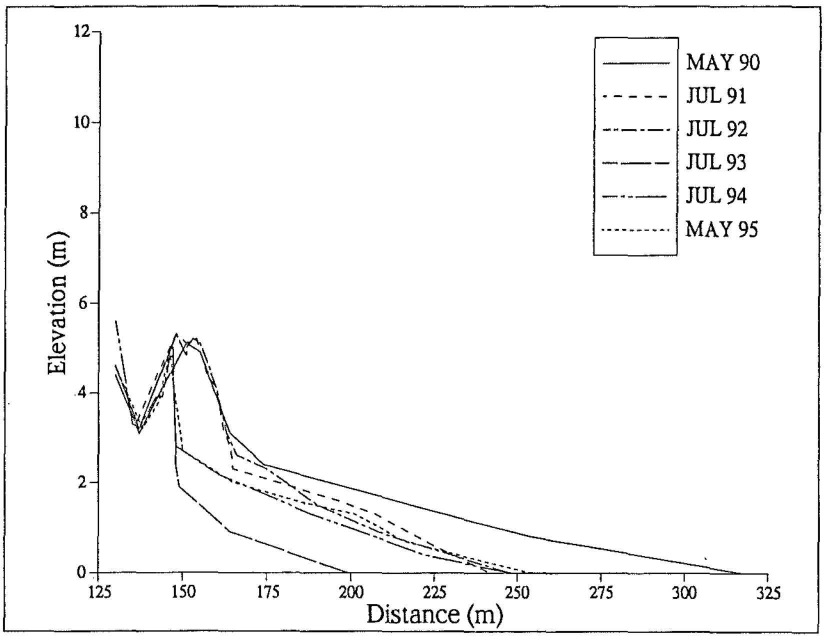

Figure 4.5(d) *Winter beach profiles at South Pukeko Street*

4.3.2 Christchurch City

The Christchurch City beaches are similar to the South Brighton Spit beaches. The beach widths are around 100m from the dune to low water. The average slope of the foreshore is less than 1°. These sites all exhibit reasonably consistent trends and for this reason only the Beatty Street site will be illustrated (Figure 4.6). The changes in volume for these beaches since 1990 are slight with a range of $64m^3.m^{-1}$ for Beatty Street (Figure 4.6a) as compared with the $197m^3.m^{-1}$ volume range for south of Pukeko Street. Figure 4.6b and c show the difference between the summer and winter profiles from 1990 to the present. The most noticeable difference between the summer and winter profiles is the beach widths which are more varied in the winter profiles. The beach width is the distance from the dune toe to the low water mark. This is also reflected in a greater variability from the average beach volume in the winter. The range in winter is $44m^3.m^{-1}$ and only $25m^3.m^{-1}$ in summer.

Perhaps one of the most significant factors is that all three beaches experienced maximum volumes in January 1991 and a minimum in September 1992. These can be attributed to an accretionary phase leading up to the January 1991 survey which resulted in a $27m^3.m^{-1}$ increase in volume above the average at Beatty Street. In 1992 two major storms affected the coast which lead to a $37m^3.m^{-1}$ drop in volume below the average of $362m^3.m^{-1}$. The uniformity of volume changes indicates that the processes acting on these three sites are very similar.

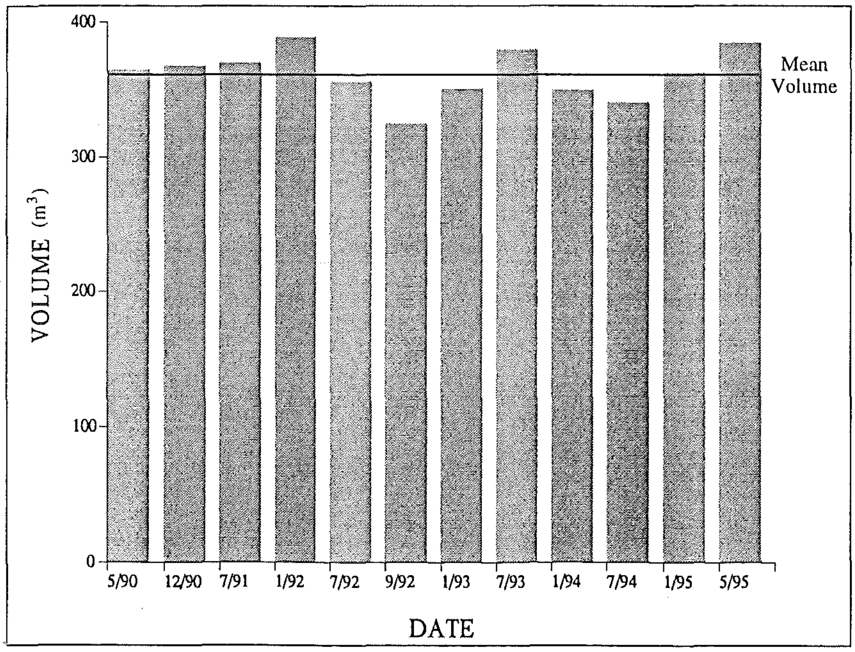

Figure 4.6(a) *Beach volumes at Beatty Street*

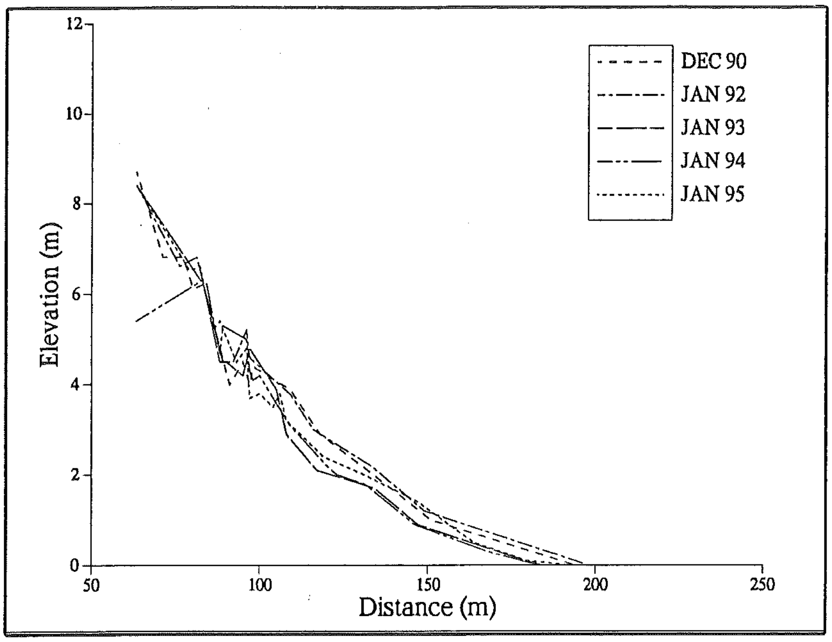

Figure 4.6(b) *Summer beach profiles at Beatty Street*

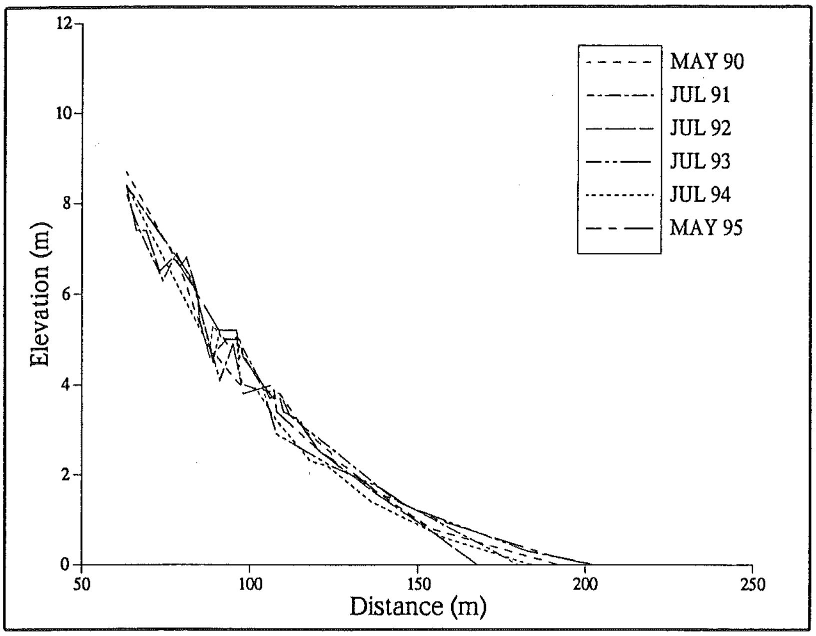

Figure 4.6(c) *Winter beach profiles at Beatty Street*

4.3.3 Bottle Lake

The South Bottle Lake region is one of the larger areas in Pegasus Bay, extending from Waimariri Beach north to Spencerville. However these beaches do not exhibit the same characteristics as the Christchurch City shores. Instead beach volumes in this zone fluctuate more about the mean volume of $134m^3.m^{-1}$ (Figure 4.7 a). Maximum volumes are evident in January surveys and the minimum is again in September 1992. For example a deficit of $52m^3.m^{-1}$ below the mean volume at the Heyders Road site. This is particularly significant compared to the beach width which varies about 80m in length (Figure 4.7b and c). In September 1992 the profile width was only 64m long and from Figure 4.7b and c, it can be seen that there is a general trend, that has not shown up in the other profile regions, for the summer beaches to be wider and flatter than those in the winter. Only one winter survey, July 1993, is wider than the average beach width of 85m and none of the summer surveys drop below the average beach width. The volumes however do not follow this trend and fluctuate greatly about the mean with a range of $91m^3.m^{-1}$ when at Heyders Road.

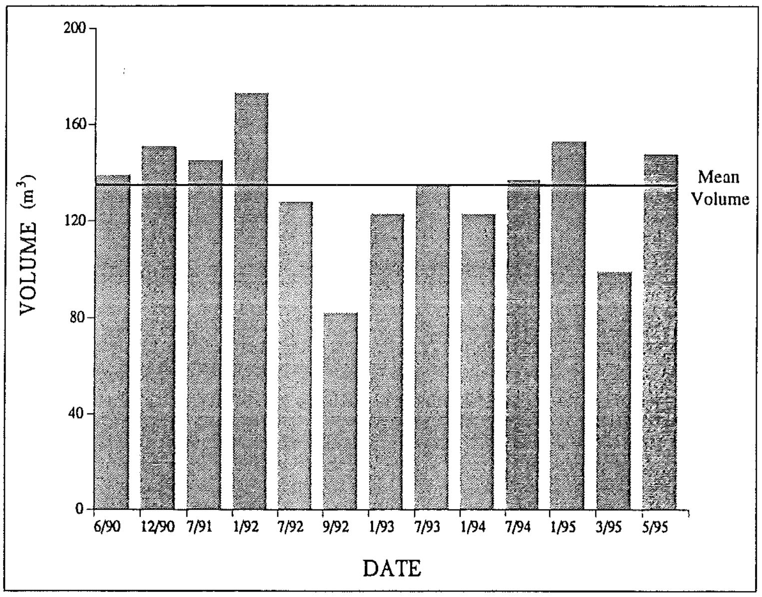

Figure 4.7(a) *Beach profile volumes for Heyders Road*

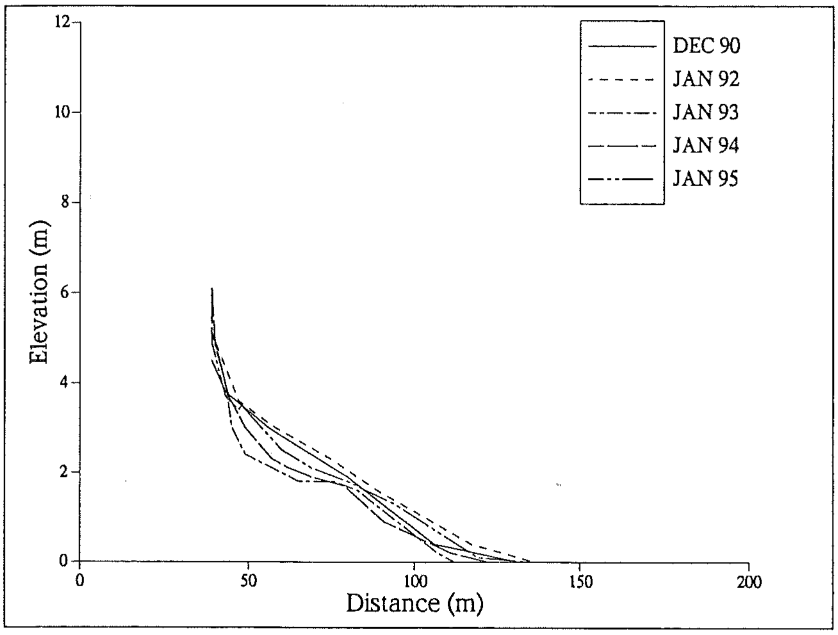

Figure 4.7(b) *Summer beach profiles at Heyders Road*

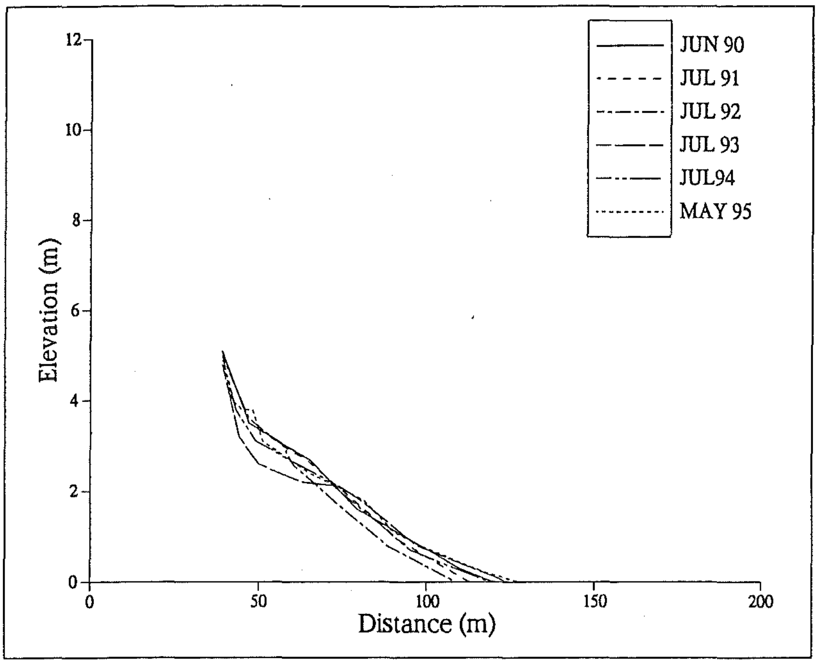

Figure 4.7 (c) *Winter beach profiles at Heyders Road*

4.3.4 Brooklands Spit

The Brooklands spit sites are the most northern of those examined in southern Pegasus Bay. The sites are located along Brooklands Spit (Appendix 2). Unlike South Brighton Spit the most variable site is not the one closest to the spit tip. Instead the site which exhibits the greatest fluctuations, C1972, is located in the middle of the spit. As with the Bottle Lake region and Christchurch City profiles, maximum volumes occurred in January. In this sector however the maximums were in 1995 although a number of accretionary phases can be identified, for example June 1990 to July 1991, September 1992 to July 1993 and July 1994 to January 1995 (Figure 4.8a), The 1992 storm impact in this area is shown by a $43m^3.m^{-1}$ deficit from the average being evident in the September 1992 survey. Figures 4.8b and c show that once again summer profiles are longer than their winter counterparts. Here it is pertinent to note the differences in profile form. The increased widths and therefore volumes can be attributed to flattening of the profile near the mean low water level mark during the summer. This flat low tide shelf is a response to the processes acting at this time coupled with the steepening of the upper foreshore.

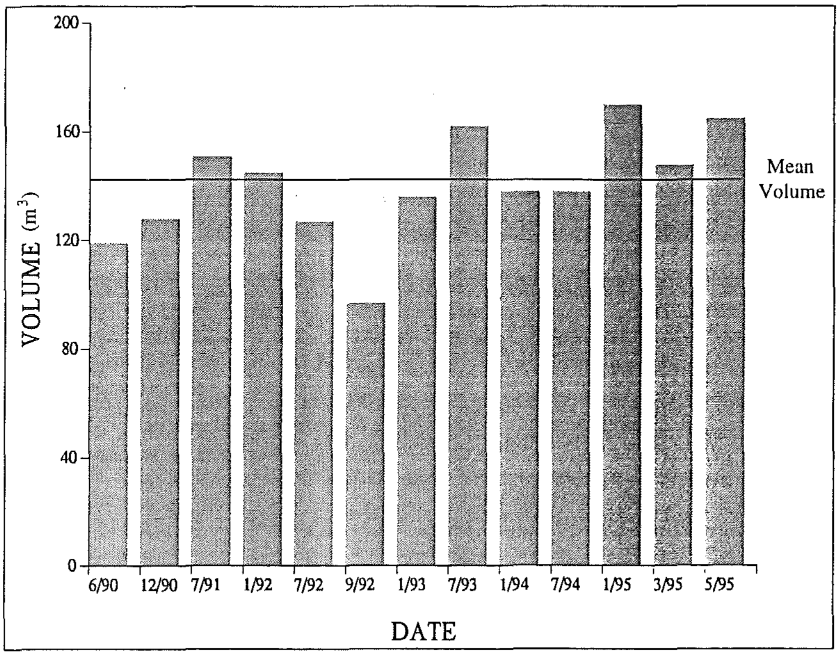

Figure 4.8(a) *Beach profile volumes for C1891*

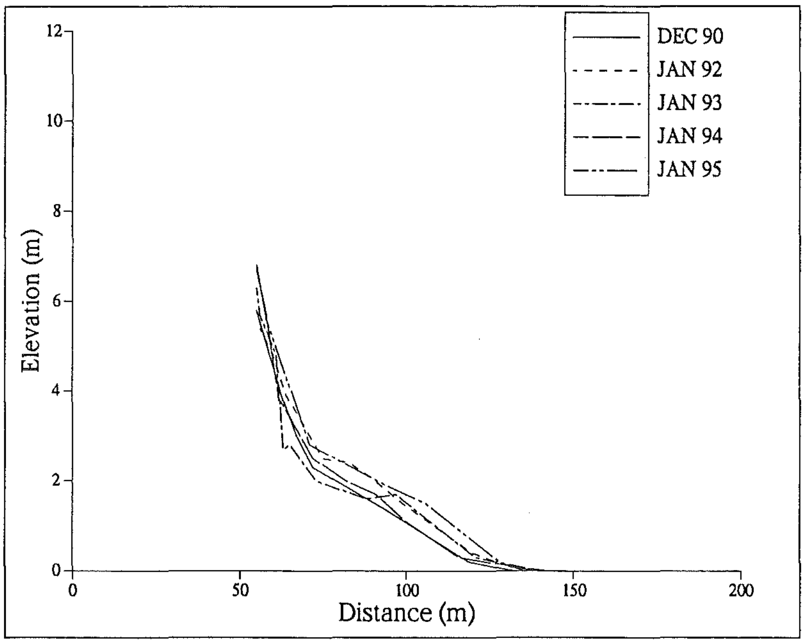

Figure 4.8(b) *Summer beach profiles at C1891*

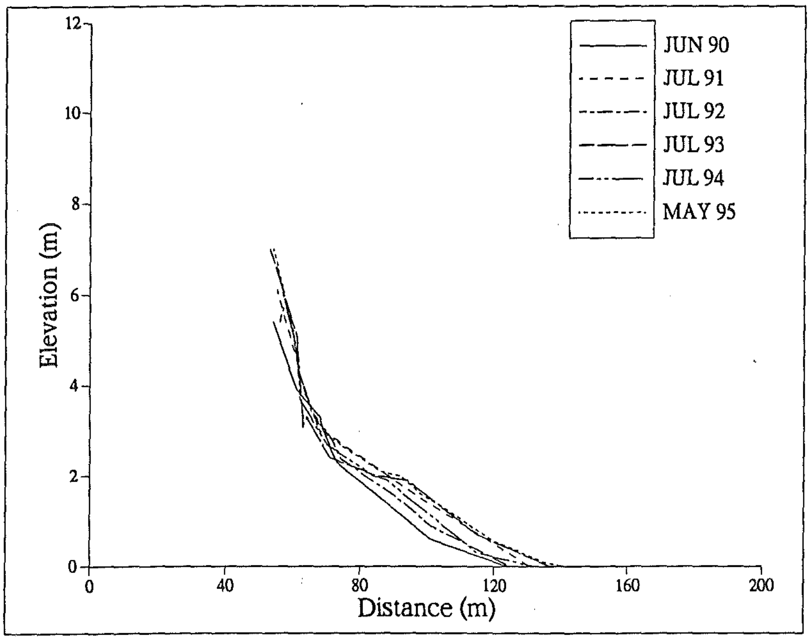

Figure 4.8(c) *Winter beach profiles at C1891*

4.3.5 Mid Pegasus Bay

The three beach profile sites in the Mid Pegasus Bay region are located at the main access points to the beach. Subsequently they are high use areas and this factor is reflected in their profiles and volume data. The beaches are wider than those on Brooklands Spit ranging from around 100 to 200m. There is a trend for the beaches to become progressively shorter with distance from the Waimakariri River. For this reason Woodend Beach is displayed, being representative of the region as it lies in the centre. Figure 4.9a shows the volume changes for Woodend. Low volumes occurred in December 1991 and in May 1995, which is consistent with the other two profiles in the region. Volumes vary significantly with a range of $94m^3.m^{-1}$ varying about a mean of $328m^3.m^{-1}$ at Woodend Beach.

The profile of Pines Beach surveyed during 1995 (Figure 4.9b), has been selected to demonstrate the effects of human use. In January 1995 the dune adjacent to the surf club house and pictured in the profile (at 1), had been trampled by holiday makers. The March and May profiles indicate that the dune rebuilt itself. An important feature is the height of the upper foreshore in

January 1995 corresponding with a maximum volume for this period, demonstrating that the bulk lost from the dune had been displaced to the upper foreshore and is not lost from the beach system.

It is important to note that at the time of the April 1995 survey when the Waikuku profile volume was lower than average, pebble size gravels, 4mm to 64mm in diameter lay exposed on the beach. This gravel is probably indicative of a past hydraulic regime when the Ashley River regularly supplied gravel to the Pegasus Bay coastline.

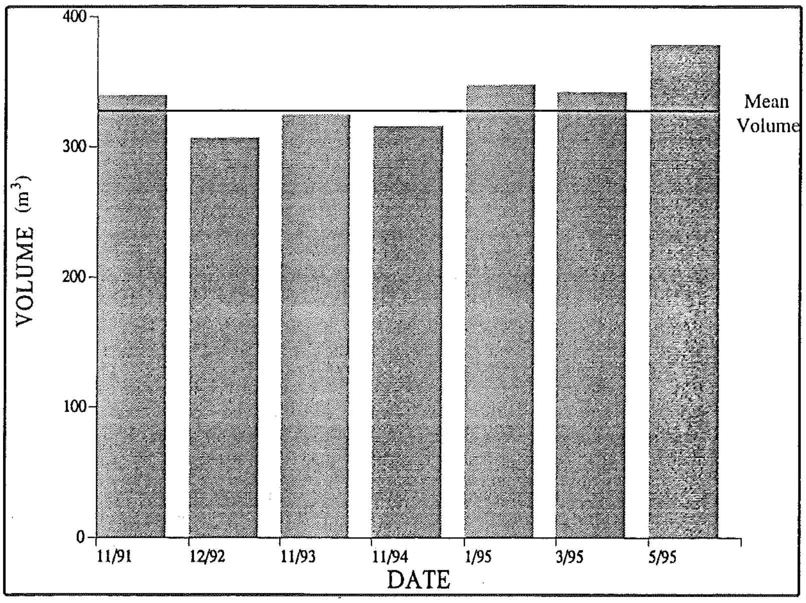

Figure 4.9(a) *Beach profile volumes for Woodend Beach*

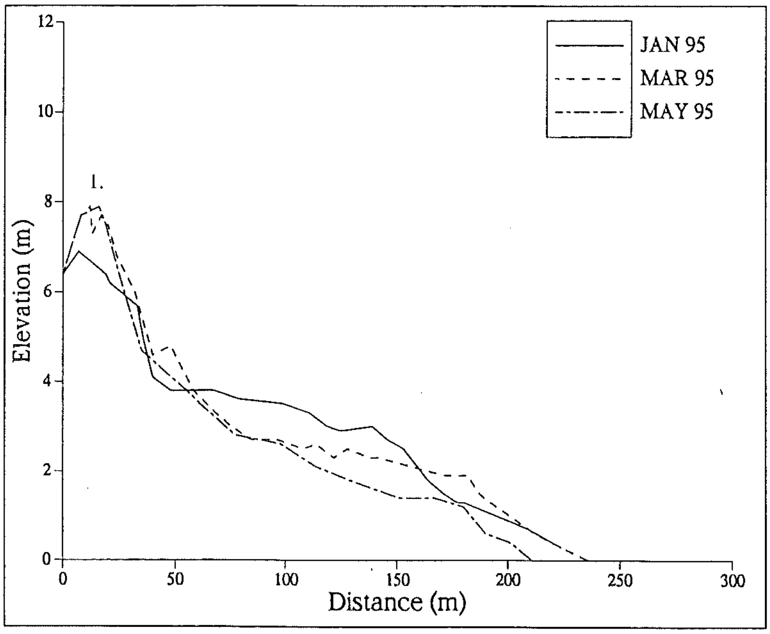

Figure 4.9(b) *1995 beach profiles at Pines Beach*

4.3.6 Leithfield

Present within the Leithfield region is the demarcation from sand beaches to mixed sand and gravel beaches. Consequently the beaches in this zone display differences in their characteristics. During the study period the Ashworths profile was predominantly sand with small pockets of gravel and shells in shallow lenses. In the past this beach has had a more gravel laden foreshore (H. Connor, University of Canterbury *pers. comm.* 1995). The gravel found here, as with the Waikuku Profile, reflects the past hydraulic regime of the Ashley River. The Ashworths profile is the widest of Pegasus Bay, being almost 300m from the base of the dune to mean low water level. The lower foreshore is the steepest region of the beach and extends approximately 80m (Figure 4.10a and b). Despite this the Ashworths profile volumes fluctuate greatly (Figure 4.10c). Only South Pukeko Street on the South Brighton Spit has a greater range of volumes than Ashworths Ponds. Volumes at this site fluctuate 176m^3.m^{-1} about 509m^3.m^{-1}. These large variations from the mean are reflected in the profiles (Figure 4.10a and b). The major variation is on the long undulating flat of the backshore. The primary process causing these changes is wind redistribution of sand. An embryo dune, seen at the 170m mark on the November 1991 profile (Figure 4.10b), is the most comprehensive example of this. Smaller scale embryo dune growth was observed during the study period and is visible in the profile graphs (Figure 4.10a and b).

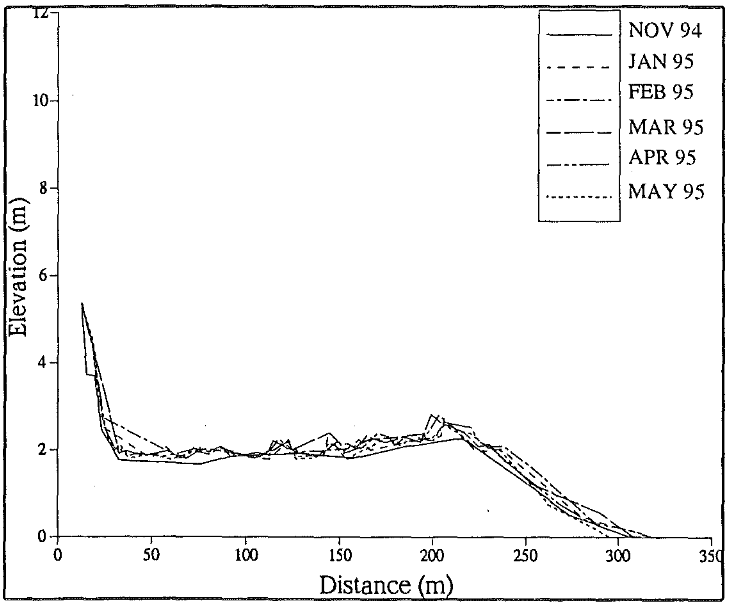

Figure 4.10(a) *1995 beach profiles at Ashworths Ponds*

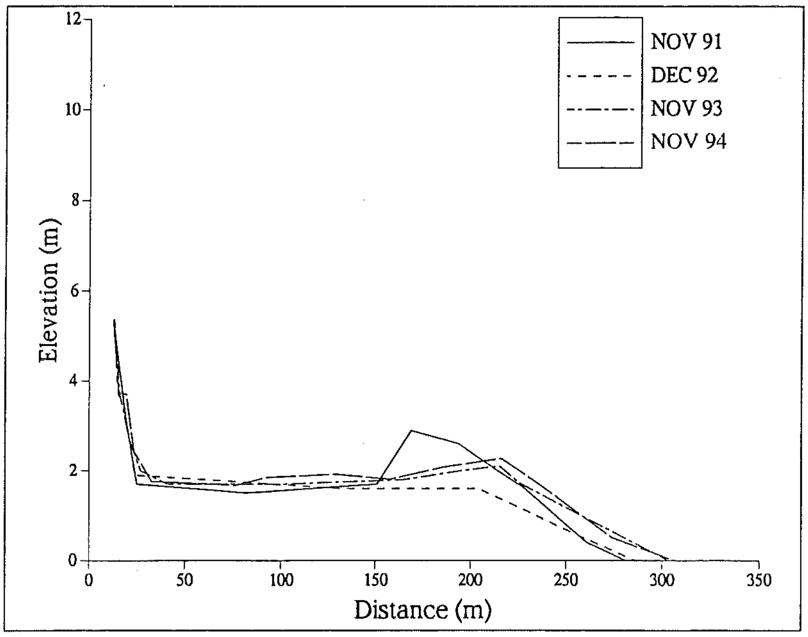

Figure 4.10(b) *Past beach profiles at Ashworths Ponds*

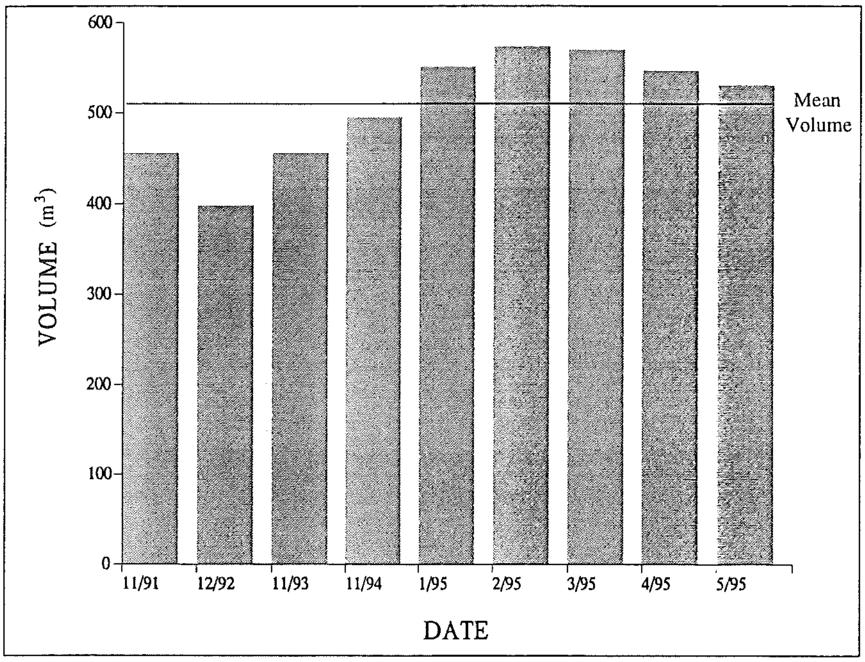

Figure 4.10(c) *Beach profile volumes for Ashworths Ponds*

South Leithfield is approximately 2kms north of Ashworths Ponds, between which the barrier separating sand and mixed sand and gravel sediments lies. South Leithfield is characterised by a sand and gravel foreshore of which the sand fraction is more dominant. This site was first surveyed in 1995 and followed the same growth and decay patterns as Ashworths during this time and so is not illustrated here. However the Leithfield Beach profile is located further away from the transition zone and is correspondingly more stable. The volume range is only 48 $m^3.m^{-1}$ about an average volume of $175m^3.m^{-1}$ (Figure 4.11a). Despite this small range in volume for the profile, the form alters dramatically as is shown in Figure 4.11c.

The lowest volume occurred in May 1992 corresponding to a short steep foreshore. In contrast to this is the highest volume of $192m^3.m^{-1}$ in September 1992 only four months later. This is due to human activity involving the bulldozing of flood protection banks and the introduction of sediment to the system from elsewhere. This flood protection bank is evident in subsequent profiles and there has not been a dramatic drop in volume since its instalment. The volume fluctuations, (Figure 4.11(a)) in early 1995 do not correspond to those at South Leithfield and Ashworths but rather reflect the changes in form specific to this profile (Figure 4.11c). These changes in form could be the result of the development and decay of cusps characteristic of some mixed sand and gravel beaches including this beach (Nolan 1993).

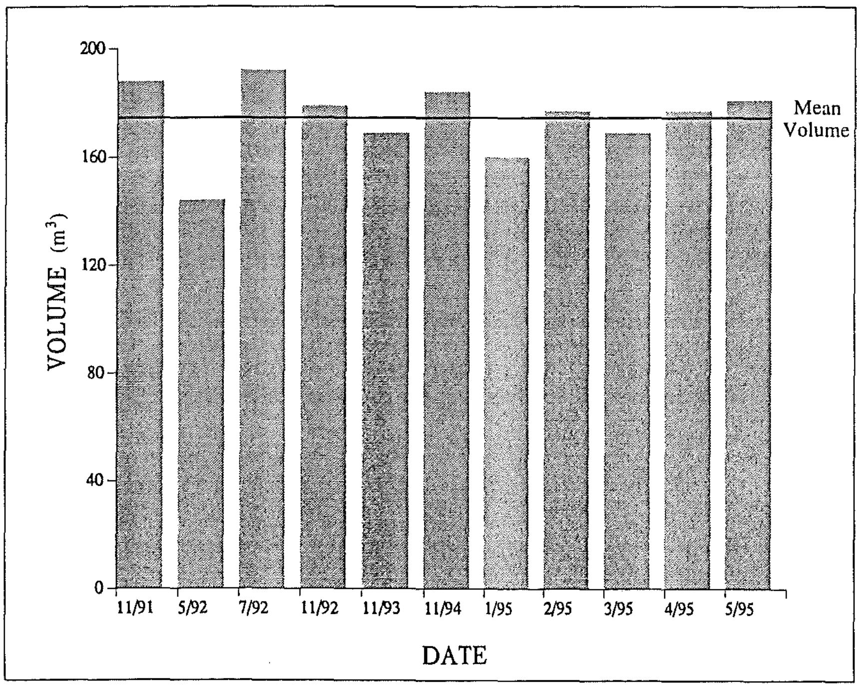

Figure 4.11(a) *Beach profile volumes for Leithfield Beach*

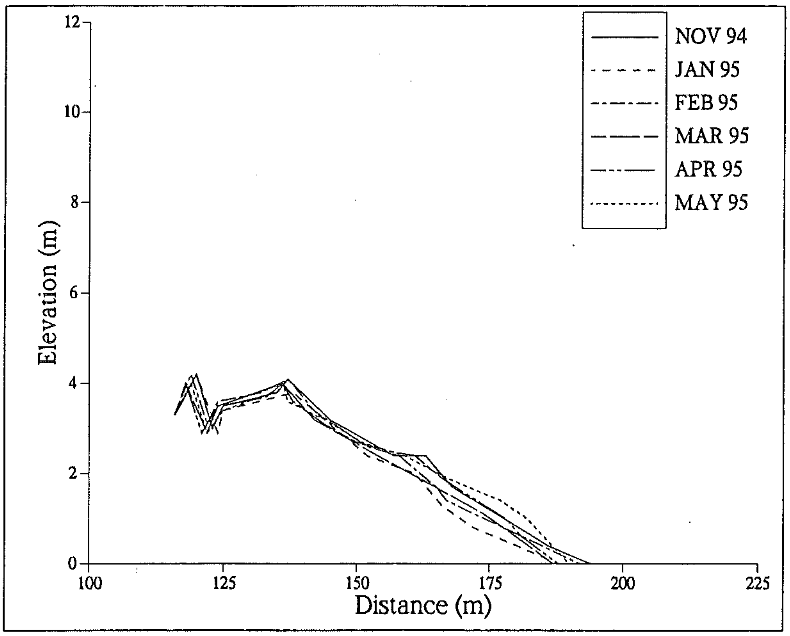

Figure 4.11(b) *1995 beach profiles at Leithfield Beach*

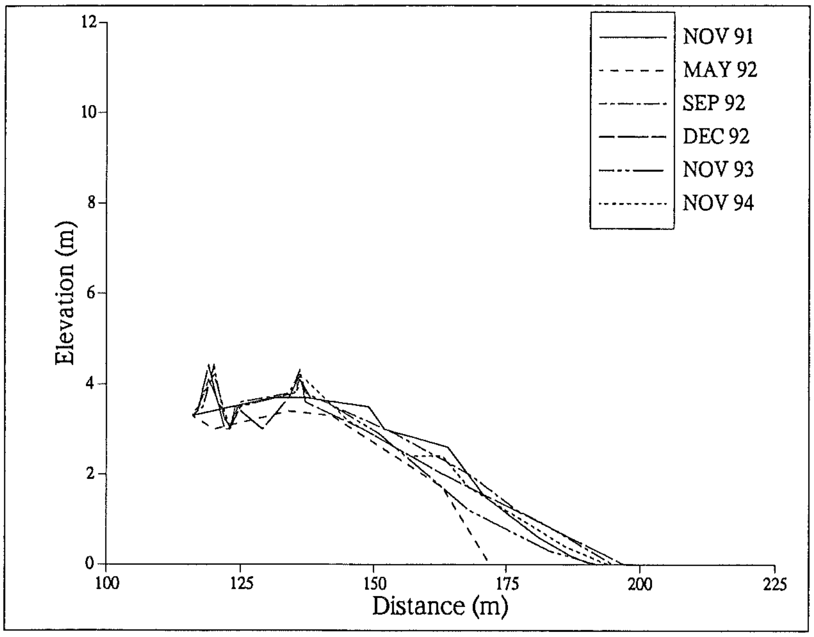

Figure 4.11(c) *Past beach profiles at Leithfield Beach*

4.3.7 Amberley

All of the Amberley beaches have mixed sand and gravel sediments with a gravel ridge backing the shore instead of the sand dunes seen in southern and mid Pegasus Bay. The beaches in this zone are much narrower than the sandy southern beaches (Figure 4.12a and b). The active foreshore zone is limited to approximately 50m. The foreshore is also a lot steeper (4° to 8°) in this region and this consequently affects the processes which act on it as outlined in Chapter

Two. This active region exhibits different sand and gravel compositions over extremely short time scales. Despite these composition changes the range of volume changes are small. The range for Amberley Beach (Figure 4.12c) is only $39m^3.m^{-1}$. This smaller volume range is a response of the narrow beach width.

The Kowai River profile is located adjacent to the south bank of the river and is influenced by the river during major flood events. However examination of profile records shows that no event has impacted upon the profile since 1991 when records began. The Amberley Beach profiles (Figure 4.12a and b) present changes in the form of the profile. Width and steepness of the beach are relatively uniform. Fluctuations in form were noted in the field as observed changes in the position and shape of beach cusps. The position of the cusp on the shore can be related to the volume. An accretionary phase results in the cusp being built up down the shore towards the sea. An erosionary phase corresponds with the cusp being eroded low on the foreshore so that it only appears further up the beach slope on the profile graph (Figure 12a and b).

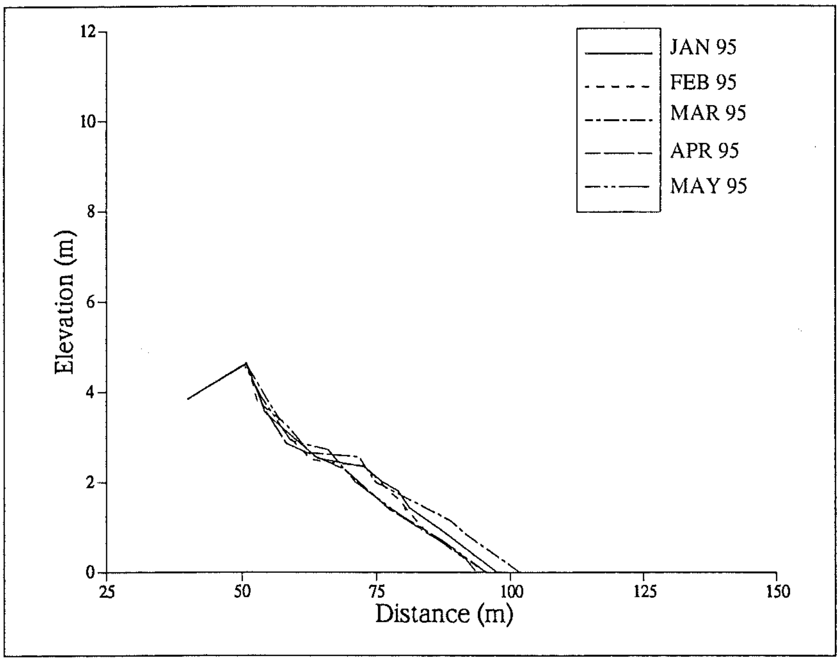

Figure 4.12(a) *1995 beach profiles at Amberley Beach*

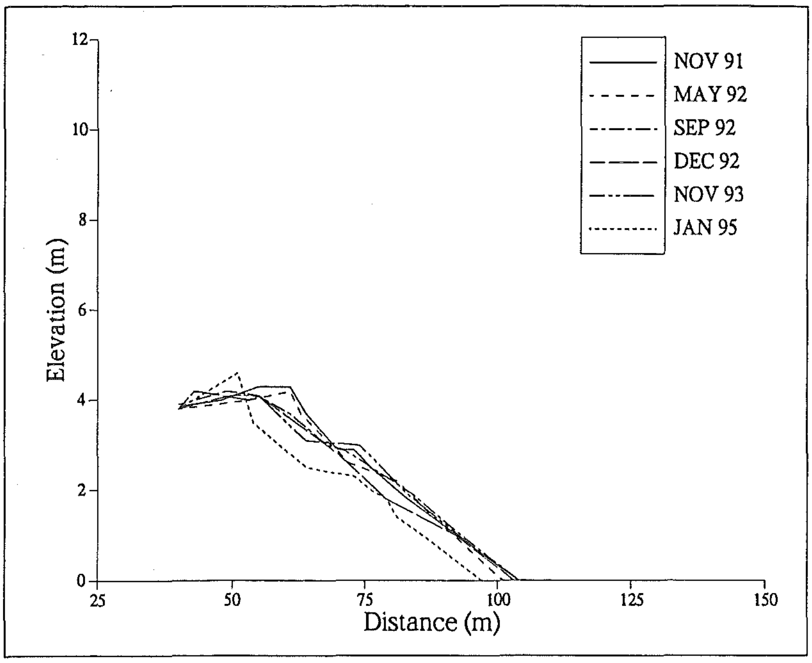

Figure 4.12(b) *Past beach profiles for Amberley Beach*

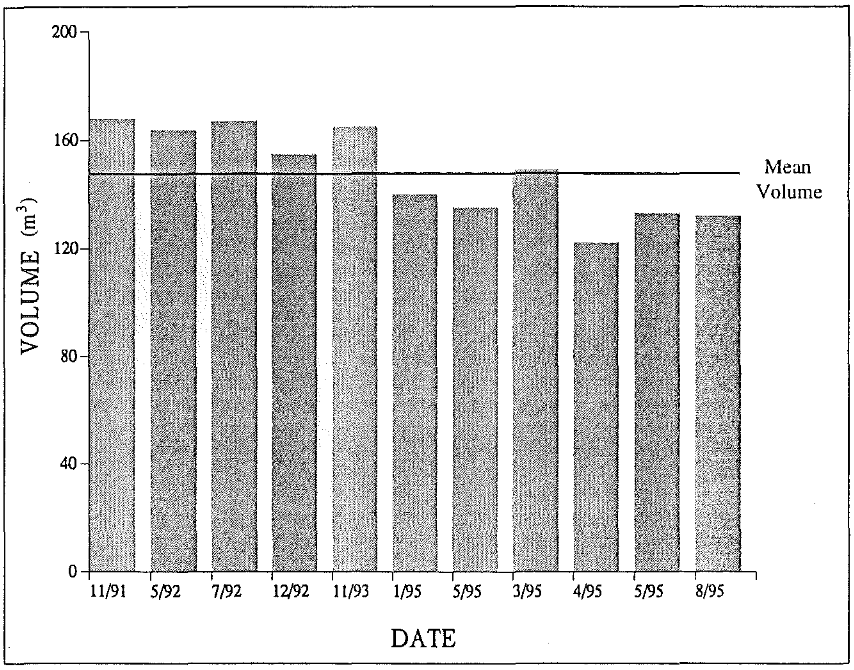

Figure 4.12(c) *Beach profile volumes for Amberley Beach*

4.3.8 Waipara River

The beaches in the Waipara River sector are mixed sand and gravel and are much narrower than the other mixed sand and gravel beaches in Pegasus Bay. The active foreshore width is less than 40m at times (Figure 4.13a and b). The steepness of the beaches in this zone is very similar to those in the Amberley region (between 4° and 8°) but the slope angle decreases to between 3° and 6° at Double Corner.

The composition of the beaches also varies in the same manner as at Amberley. The main difference between the two sectors is the degree to which cusps grow and decay. This effect is more pronounced in this northernmost region. Disregarding the Kowai River site (Amberley Region) for which other considerations are involved, the Waipara River region exhibits greater volume fluctuations than the Amberley region. Figure 4.13c shows the volumes for the Teviotdale site. The range is $45m^3.m^{-1}$ oscillating about a mean of $135m^3.m^{-1}$. From observations when a cusp is positioned high on the shore and there is a greater sand composition evident on the lower foreshore, the profile is in surplus. If the cusp is located closer to mean low water level and the lower foreshore is predominantly gravel then the profile is in deficit.

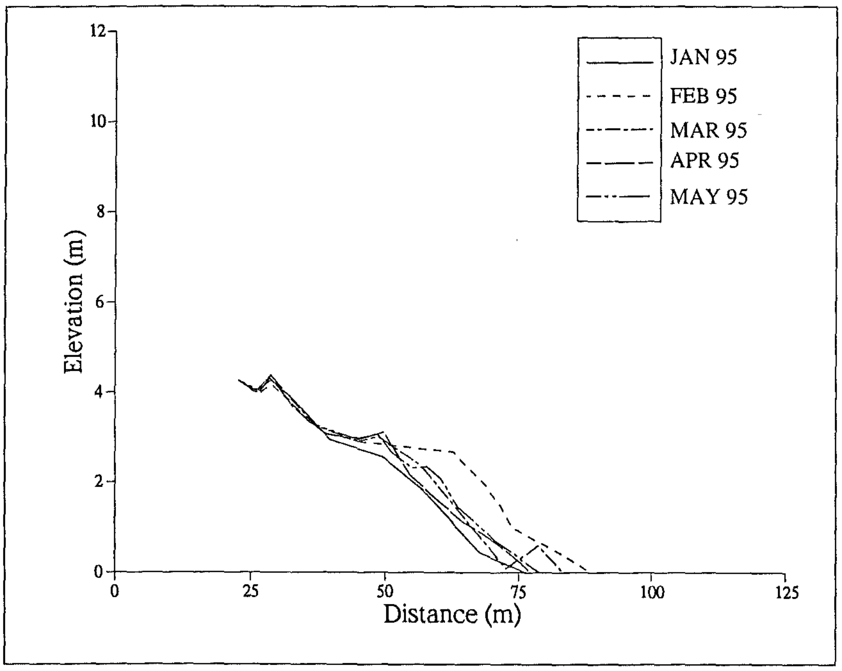

Figure 4.13(a) *1995 beach profiles at Teviotdale*

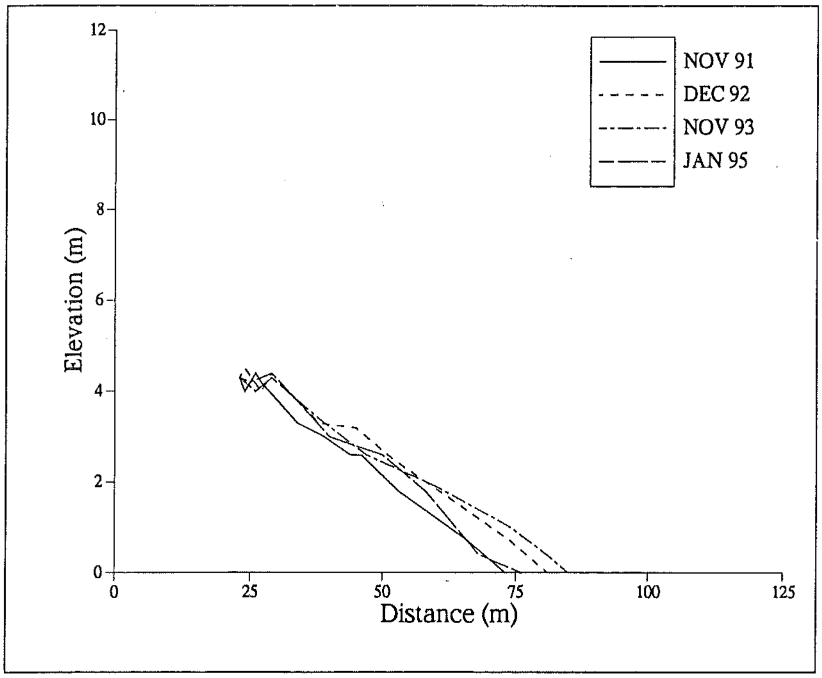

Figure 4.13(b) *Past beach profiles at Teviotdale*

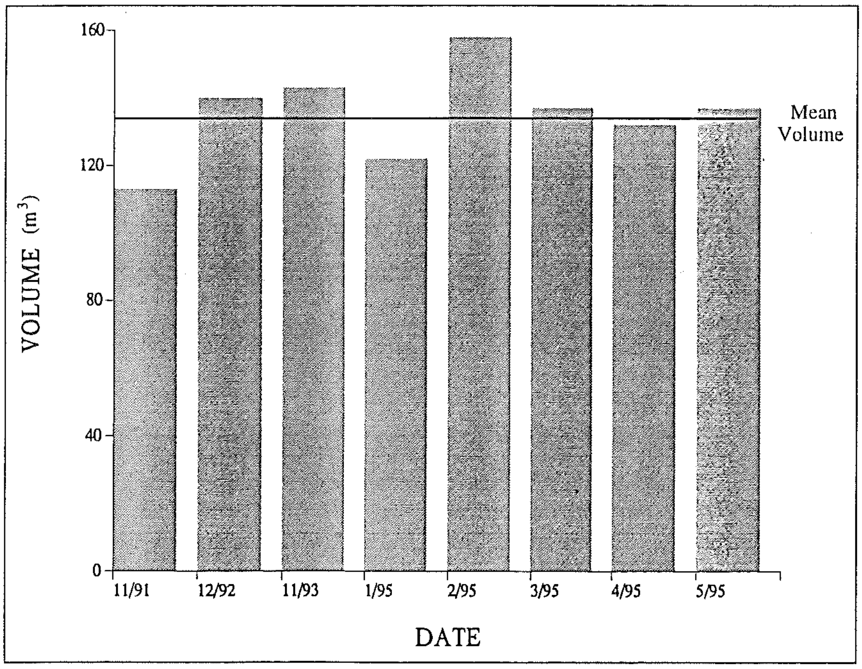

Figure 4.13(c) *Beach profile volumes for Teviotdale*

4.4 Dunes / Beach Ridges

Dunes are a feature that fit into both sources and sinks of sediment. During times of beach deficit, dunes become an important source of material. As a beach is eroded the dune supplies sand to replenish the beach system. In times of shore surplus the dune becomes a sink of sediment.

This section quantifies the amount of sediment which is present in the sand dunes and gravel ridges of Pegasus Bay. In order to quantify whether or not dune volumes are acting as a source or a sink a base volume must exist against which the present volume can be compared. Data for Pegasus Bay are limited to the past four to five years and so a comparison is not realistic. However the volumes presented in this section can be used as a base volume for future studies.

The method of calculation of dune volumes is as follows. Using the profile survey data collected by the C.R.C., an average dune volume was established for each site. This was then extrapolated along the coastline to half the distance to the next profile site to give coverage for all of Pegasus Bay. Unfortunately there are limitations in the accuracy of the data as it does not account for any significant high, low, wide or narrow points. However it is probable that these will probably cancel each other out. For ease of interpretation the volume values for the sectors of the coastline are shown in Table 4.3. The final column of Table 4.3 gives a volume per metre length of the shoreline to give an idea of the average bulk of the dunes or ridges for the region.

Table 4.3 *Dune volumes within Pegasus Bay*

REGION	Length of Region (Km)	Volume of Region (m^3)	Volume / metre (m^3/m)
South Brighton Spit	3.3	1,743,395	528
Christchurch City	4.5	1,694,905	377
Bottle Lake Region	7.8	3,918,290	502
Brooklands Spit	2.9	758,185	261
Mid Pegasus Bay	13.0	7,281,900	560
Leithfield Region	9.8	1,923,004	196
Amberley Region	4.0	402,785	101
Waipara Region	4.4	671,210	153
TOTAL	49.7	18,393,674	

From these values several trends can be drawn. The South Brighton Spit, Bottle

Lake and Mid Pegasus Bay regions have the greatest bulk per metre of beach in dunes. Christchurch City is a significant low point ($377m^3.m^{-1}$) between South Brighton Spit and Bottle Lake region. This can be attributed to the close proximity of infrastructure behind the dunes preventing them from growing. South Brighton Spit is urbanised but the housing and infrastructure are set further back than along the Christchurch City stretch allowing dune growth. This is also the case for the Bottle Lake region which is largely unpopulated. Brooklands Spit has a low value, $261m^3.m^{-1}$, which corresponds to the constrained width and relative age of this feature, especially considering that $758,185m^3$ has been deposited above sea level since the 1940s. The mid Pegasus Bay region has large expansive dunes generally undisturbed by settlements resulting in a value of $560m^3.m^{-1}$ of beach.
There is a marked drop in dune volumes in the Leithfield region corresponding to a change from sand dunes to gravel ridges. Amberley region experiences the lowest beach ridge volumes being an average of only $101m^3.m^{-1}$. This can be linked to the low points about the Kowai River and Amberley Beach which has been noted as subject to inundation through low points such as during the August 1992 storm. The Amberley Beach settlement is close behind the gravel ridge and acts in a similar constraining way to that of the Christchurch City dunes unlike the unrestrained gravel ridges of the Waipara region which attain volumes of $153m^3.m^{-1}$.

Sand dunes are wider and broader and therefore have more bulk than their narrow gravel counterparts. A total volume of approximately 18.4×10^6 m^3 has been calculated for the sand dunes and gravel ridges of Pegasus Bay.

4.5 Offshore Sink

The continental shelf and its sediment characteristics have been described in detail in Chapter Three. This section will look at the sediment that has been deposited on the shelf. The most difficult factor in calculating rates of sediment deposition offshore is the time span over which the sediment has been deposited.

As mentioned in Chapter Three there is a differentiation between modern, palimpsest and relict terrigenous material which represent different hydraulic regimes on a geological time scale beyond the scope of this budget. However certain interesting features can be gleaned from studying the material which has been deposited.

The Canterbury Continental Shelf is mantled with a modern sand prism on the inner shelf and relict terrigenous sands and gravels on the middle and outer shelf (Carter 1975). This is indicative of a zone where modern sedimentation is low. Sedimentation is dependent on the hydraulic regime and sediment supply which are in turn dependent on climate and tectonism as well as the nature of the source area and coastline. The broad Canterbury Continental Shelf receives low volumes of sediment due to the low sediment yields carried by the rivers. However the Waimakariri River has one of the highest sediment yields of all New Zealand rivers, so the transportation of this sediment once it reaches the coast is important.

The modern hydraulic regime as stated in Carter (1975) has tidal, oceanic and storm driven components. These influence the dispersal of modern terrigenous sediments. Mud is one fraction of modern terrigenous material that is relatively sparse on the Canterbury Continental Shelf. It is thought that the Southland Current may act to carry suspended sediment out into deeper water via submarine canyons such as the Pegasus Canyon, where it is lost from the system. Mud also accumulates on the down current side of large promontories such as Banks Peninsula.

Carter and Herzer (1979), conclude that most of the transport of sediment on the Continental Shelf is in a north-east, landward direction. The lack of sediment on the middle and outer continental shelves would indicate that the continental shelf is not a significant sink of sediment. Instead it is a transitory area from which sediment can be worked back onshore.

4.6 Concluding Remarks

This chapter has outlined and quantified the many sinks of sediment within Pegasus Bay. The history behind the Avon-Heathcote Estuary and Brooklands Lagoon is presented as well as a possible sedimentation rate for each.

Following this is an introduction to the twenty-four profile sites along Pegasus Bay. They have been divided into eight categories and representative profile graphs and volume graphs are presented. The volume for each site is also shown. By calculating the dune volumes and beach volumes at each specific site and extrapolating the data, dune volumes for the length of the coastline have been derived. This results in a total volume of 18.7 million m^3 of sediment located in the beach system and 18.4 million m^3 of sediment being stored in the dune/gravel ridge systems of Pegasus Bay. Finally the offshore sink is examined. Despite a lack of quantifiable data it is likely that the Canterbury Continental Shelf is not a significant sink.

Now that the sinks and sources within Pegasus Bay have been examined and quantified, transfers between the two can be looked at. The ensuing chapter details the movements of the sediment within Pegasus Bay and the importance of these transfers to the estimation of a sediment budget for Pegasus Bay.

Chapter Five
Transfers of Sediment

5.1 Introduction

Coastal systems are usually in a state of flux. Sediment is constantly moving from one location to another at varying spatial scales. The sediment is moved by both oceanic and aeolian processes. The amount of material moved and its destination are determined by the sediment characteristics and the process environment. This chapter will first examine the sediment characteristics of the Pegasus Bay beaches. The two current driven mechanisms of transporting sediment, longshore drift and onshore/offshore cycling will also be examined. Despite aeolian processes being a transport mechanism, the significance of this sediment dispersal method in Pegasus Bay has not been investigated to date. Therefore no reliable quantification of this type of sediment transfer has been possible.

5.2 Sediment Characteristics

5.2.1 Sediment Analysis Methodology

In order to study the sediment in Pegasus Bay, samples were taken from each profile site as well as additional sites of interest such as south of the Ashley River and the tip of Brooklands Spit. At each site three samples were taken, one each from the lower foreshore, upper foreshore and the backshore. Lower foreshore samples were collected at or near the low tide mark, backshore samples from within 5m of the dune or beach ridge and the upper foreshore samples at or below the high tide mark. The samples taken from the mixed sand and gravel beaches of northern Pegasus Bay weighed approximately 5kg and those from the southern sandy beaches weighed around 200g. Each sample was taken from the surface to a depth of about 10cm to reflect the most recent sediment transport mechanisms. A greater depth would not be indicative of the current processes acting at each site.

The sand fractions of the northern Pegasus Bay samples and the sand samples from southern Pegasus Bay were further analysed using a Rapid Sediment Analyser, (R.S.A.), in the University of Canterbury Geography Department's laboratory to produce sediment textural statistics.

The R.S.A. determines the weight percentage of sand size divisions of the total sample weight by calculating the settling velocity of each particle size falling through a two metre column of water. Computer analysis of the data determines statistical measures of mean grain size, sorting, skewness, and kurtosis using the method of moments and the graphical method based on interval mid points. A quarter phi scale is used resulting in a high degree of accuracy.

The mean grain size can be used to indicate the magnitude of the force, (water or wind), that is required move the beach sediment grains (Pethick 1984). The larger the grain size the stronger the force must be to move the sediment particles. The verbal classifications depicted in Table 5.1 apply to the grain sizes displayed in Table 5.5:

Table 5.1 *Verbal classifications of mean grain size parameters*

very fine sands	3.00ϕ to 4.00ϕ
fine sands	2.00ϕ to 3.00ϕ
medium sands	1.00ϕ to 2.00ϕ
coarse sands	0.00ϕ to 1.00ϕ

(Folk and Ward 1957)

Sorting is a measure of the standard deviation of the grain sizes of the sample. This variable signifies the range of forces that have combined to produce the sediment sample based on the size range of that sample. A large standard deviation is indicative of poor sorting which equates to minimal selection during the transportation and deposition of the sediments. There is also a large range of sediment sizes within the sample. Good sorting denotes the converse. The particle size range is small and selection during transportation and deposition is high (Pethick 1984). The verbal classification for sorting identifies with the following parameters shown in Table 5.2.

Table 5.2 *Verbal classifications of the sorting co-efficient*

very well sorted	< 0.35ϕ
well sorted	0.35ϕ to 0.50ϕ
moderately well sorted	0.50ϕ to 0.70ϕ
moderately sorted	0.70ϕ to 1.00ϕ
poorly sorted	> 1.00ϕ

(Folk and Ward 1957)

The history of a sample is reflected by its skewness. This is a dimensionless variable. Positive skewness corresponds to an excess of fine grain sizes in relation to the sample mean grain size. Such a skew may result from selective removal of coarse material or selective deposition of fines. An excess of coarse grains in a sample is represented by negative skewness. Symmetrical skews are indicative of a normal distribution with equal variation either side of the mean grain size (Pethick 1984). Skewness is classified into the verbal classifications shown in Table 5.3.

Table 5.3 *Verbal classifications of skewness*

strongly fine skewed	0.30 to 1.00
fine skewed	0.10 to 0.30
near symmetrical	-0.10 to 0.10
coarse skewed	-0.30 to -0.10
strongly coarse skewed	-1.00 to -0.30

(Folk and Ward 1957)

Kurtosis reflects the distribution of the sediment sample about the mean. The kurtosis of a sample is indicative of the sorting (Pethick 1984) so that the verbal classifications apply to the kurtosis categories as depicted in Table 5.4.

Table 5.4 *Verbal classifications of kurtosis*

extremely leptokurtic	> 3.00
very leptokurtic	1.50 to 3.00
leptokurtic	1.11 to 1.50
mesokurtic	0.90 to 1.11
platykurtic	0.67 to 0.90
very platykurtic	< 0.67

(Folk and Ward 1957)

These measures can supply a greater understanding of the sediments that form the beaches of Pegasus Bay through the establishment of a history of the sample. The bay has been divided into three sections, for ease of display, analysis and description, based on the coastal process environment of each discussed in Chapter Two.

5.2.2 Southern Pegasus Bay

Southern Pegasus Bay beaches are made up of fine, very well sorted sands, (Table 5.5) although the lower foreshore sample at the Larnach Street profile had a medium mean grain size with a skew towards the fine range of the sample. The fine well sorted sands signify that the forces at work in this region are selective and do not require high energy processes to transport the sediments.

The skewness ranges from near symmetrical (18%), through to strongly fine skewed (10%). The majority of samples (72%), are fine skewed. The predominant fine skew represents selective removal of coarse grains or more probably the selective deposition of fine grains. The samples' kurtosis ranges from mesokurtic, (87%), through to very leptokurtic, (3%), reiterating that the sample is well sorted.

Table 5.5 *Summary of sediment textural analysis statistics where a is the foreshore sample, b is the midshore sample and c is the backshore sample*

Sample Location	Mean size (ϕ)	Sorting (ϕ)	Skewness	Kurtosis	Sample Location	Mean size (ϕ)	Sorting (ϕ)	Skewness	Kurtosis
Pukeko Street a	2.09	0.29	0.69	2.99	Pines Beach a	2.35	0.39	0.55	3.75
b	2.20	0.32	-0.17	3.24	b	2.41	0.22	-0.05	3.29
c	2.44	0.24	-0.42	3.89	c	2.45	0.29	-0.50	4.18
Plover Street a	2.24	0.32	-0.45	4.09	Woodend Beach a	2.45	0.33	-1.43	6.67
b	2.38	0.22	0.52	2.44	b	2.32	0.25	0.18	3.27
c	2.37	0.34	-1.21	5.71	c	2.33	0.24	0.58	2.75
Caspian Street a	2.29	0.34	-0.94	5.15	Waikuku Beach a	2.06	0.47	-0.39	3.08
b	2.31	0.27	-0.69	5.12	b	2.23	0.35	-0.76	5.20
c	2.33	0.30	-1.17	6.93	c	1.99	0.48	-2.02	11.25
Beatty Street a	2.23	0.34	-0.26	3.53	South Ashley a	2.25	0.33	-0.59	4.08
b	2.23	0.30	-0.28	3.59	b	1.98	0.32	-0.84	9.03
c	2.14	0.29	0.14	4.55	c	2.44	0.30	1.22	4.08
North Rodney a	2.16	0.32	0.25	2.80	Ashworths a	2.36	0.39	-1.30	5.51
b	2.22	0.28	-0.33	4.21	b	2.07	0.50	-1.23	4.20
c	2.31	0.30	-1.23	6.89	c	2.40	0.34	-1.34	6.38
Rawiti Street a	2.12	0.34	0.18	3.02	South Leithfield a	1.97	0.84	-1.12	3.22
b	2.20	0.27	-0.09	4.33	b	1.85	0.42	-2.20	13.54
c	2.22	0.28	0.01	3.68	c	1.83	0.42	-0.14	3.55
Larnach Street a	1.92	0.31	0.80	3.23	Leithfield Beach a	2.43	0.49	-2.90	12.93
b	2.18	0.34	-1.01	5.02	b	1.74	0.30	-0.04	4.29
c	2.17	0.31	-0.36	4.47	c	0.68	0.54	0.39	2.68
Bottle Lake a	2.23	0.32	-0.17	3.73	Kowai River a	1.66	1.00	-1.01	5.52
b	2.13	0.23	0.38	2.91	b	0.79	0.83	0.09	1.72
c	2.21	0.25	0.82	4.75	c	0.72	0.68	0.45	2.09
Heyders Road a	2.05	0.32	0.30	3.02	Newcombes Road a	0.74	0.98	0.54	1.99
b	2.20	0.32	1.35	7.95	b	0.51	0.80	0.95	2.76
c	2.10	0.29	-0.44	5.53	c	1.55	0.57	-0.60	3.84
C1891 a	2.19	0.38	1.03	5.33	Amberley Beach a	1.38	0.96	-0.34	1.87
b	2.09	0.30	1.36	7.51	b	0.82	0.82	0.19	1.97
c	2.22	0.30	1.50	8.00	c	1.32	0.53	0.29	3.87
C1972 a	2.23	0.28	0.39	2.88	Amberley Golf a	1.28	0.78	-0.54	2.17
b	2.05	0.27	0.87	3.56	b	0.64	0.76	0.02	2.34
c	2.24	0.24	0.43	3.33	c	0.94	0.51	-0.39	2.97
C2070 a	2.22	0.40	-0.30	6.93	Teviotdale a	1.68	1.10	-0.58	1.71
b	2.14	0.43	1.81	9.47	b	1.48	0.54	-0.54	5.50
c	2.15	0.26	0.31	3.59	c	0.59	0.45	0.39	2.51
Brookland Spit a	2.19	0.39	-0.82	6.62	Double Corner a	1.98	0.97	-1.56	4.74
b	2.05	0.34	0.54	5.34	b	2.65	0.19	-0.38	2.49
c	2.27	0.25	-0.34	6.06	c	1.81	0.60	-1.11	4.28

5.2.3 Mid Pegasus Bay

The sands of mid Pegasus Bay, (Table 5.5), are fine and well sorted. The process environment and therefore the forces at work are similar to those of southern Pegasus Bay. The backshore sample at Pines Beach was coarse skewed while the other samples were near symmetrical or fine skewed except for the backshore south of the Ashley River which was strongly fine skewed. This indicates that a wide range of forces are depositing or removing the sediments. Once again the kurtosis ranged from mesokurtic through to very leptokurtic. The beaches furtherest away from a river source, Waikuku and Woodend, had mesokurtic samples while those closer to the Ashley and Waimakariri Rivers, Pines and South Ashley, exhibit leptokurtic tendencies.

5.2.4 Northern Pegasus Bay

The northern Pegasus Bay mixed sand and gravel beach sediment composition is shown in Table 5.6. Four size fractions, according to the Wentworth classification, of cobbles, pebbles, granules and sand, are utilised. The percentage make up of each category was calculated by dry sieving the total sample and then weighing each fraction. It is important therefore to note that these figures are based on weights and not volumes. The values presented in Table 5.6 are an average of the foreshore, midshore and backshore samples for each site.

Table 5.6 *Sediment composition of northern Pegasus Bay profile sites*

Location	Sand < 2 mm (%)	Granules 2 - 4 mm (%)	Pebbles 4 - 64 mm (%)	Cobbles > 64 mm (%)
Ashworths	99.3	0.3	0.3	0
South Leithfield	91	1	1	7
Leithfield Beach	81	1	18	0
Kowai River	29.6	11.6	58.6	0
Newcombes Road	53	7	31	9
Amberley Beach	24.3	40	32.3	3.3
Amberley Golf Club	37.5	7.3	43.3	12
Teviotdale	85	3	12	0
Double Corner	90	1	9	0

The Ashworths Ponds sample is almost entirely sand (99.3%). The granules and pebbles reflect either the past beach make up when it was a mixed sand and gravel beach or they have been erratically deposited. When both the Waipara and Kowai Rivers actively transport material to the coast the beaches exhibit a mixed sediment character (Shulmeister and Kirk 1993). Since the last time this occurred sand has accreted and built up substantial dunes.

South Leithfield and Leithfield beaches are near the contemporary transition zone from sand to mixed sand and gravel. Consequently the sand fractions are high, (91% and 81% respectively). The gravel at these locations is scattered across the surface and is not as well sorted as the beaches north of this area.

The Kowai River site has one of the lowest percentages of sand and the highest percentage of pebbles. This site is adjacent to the Kowai River which in times of flood transports gravels, (granules, pebbles and cobbles), to the coastal system. Examination of gravels showed that those located on the foreshore were much smaller (4mm to 10mm), rounder and smoother than the more angular shaped pebbles of the backshore. This is a likely indicator of the length of time the sediments have been in the coastal system. The angular gravels will have been deposited by the river. Rounded pebbles have been in the coastal zone to have lost their angularity. The predominance of rounded material indicates that the river mouth has not been open for some time.

Newcombes Road, Amberley Beach and Amberley Golf Club profile sites all lie between the Kowai and the Waipara Rivers. Interestingly the gravel fractions in this area are high. Of particular note is the cobbles found in each area, (9%, 3.3% and 12% respectively). All the cobbles found were thick and angular representing a short time in the coastal environment. These cobbles are derived from the Waipara and Kowai Rivers during flood events. The pebbles from Amberley and Amberley Golf Course were more angular than those from Newcombes Road. Amberley Beach, which had the least amount of sand had the highest proportion of granules, (40%). These granules are round and have spent a significant amount of time in the coastal system.

The sand fraction increases greatly at the Teviotdale, (85%) and Double Corner (90%) profile sites corresponding to the distance from the Waipara River source.

Angular pebbles were found at the Teviotdale site but those at Double Corner were round and smooth by comparison corresponding to the distance from the Waipara and Kowai source rivers.

As can be expected for mixed sand and gravel beaches, the sands are not as fine in northern Pegasus Bay, (Table 5.5), as they are in the rest of the bay. Only the Ashworths Ponds samples, the lower foreshore sample of Leithfield Beach and the two foreshore samples from Double Corner exhibited a fine mean grain size. The fine sand samples, (except the lower foreshore of Double Corner), were very well sorted which is indicative of a dominant process environment. These locations are on the outskirts of the high energy environment of the Amberley Beach area discussed in Chapter Two. The sand content of the beach samples within this high energy environment (Kowai River to Teviotdale) have a medium sand mean grain size, (47%), to coarse mean grain size, (53%). These were generally moderately sorted reflecting a greater variety of forces (magnitude of currents) acting on the sediment particles. The skewness tended to show no pattern between the samples or locations. The kurtosis of the samples however tended to reflect the sorting and so platykurtic samples were evident within the high energy zone.

5.2.5 Summary and Concluding Remarks

These statistical measures do not exactly explain the way in which the sample was formed or deposited. What is interesting to note here is that the high energy environment samples exhibit different statistical characteristics than those in lower energy environments. The northern sector of Pegasus Bay has a variety of processes transporting sediments unlike southern Pegasus Bay. Consequently the southern Pegasus Bay samples are well sorted, fine skewed and mesokurtic. Mid Pegasus Bay exhibits similar trends but exhibits a tendency towards leptokurtic samples. The northern Pegasus Bay samples have a variety of mean grain size, sorting , skewness and kurtosis values. This reflects the differing transport mechanisms based on the complexities of the process environment and the different agents acting on the coast.

5.3 Longshore Transport

The majority of waves do not approach perpendicular to the coast, but approach at an angle, α. The waves run up the beach on an angle equal to that of the wave approach and then under gravity the water returns normal to the shore. The result is a net displacement of wave energy, water and transported sediment alongshore in a direction away from the wave approach. When several waves run up the beach in this fashion a longshore current is set up.

Alongshore currents in the surf zone also have the potential to transport sediments along the shore, a process known as littoral drift. The direction of the current is dependent on the angle of approach and will vary over time accordingly. Gross littoral drift is the total volume of sediment that is transported within a given time frame, usually one year. Net littoral drift is more important to a sediment budget and is the difference between the volumes transported in each direction ie. the net displacement of sediment. For north-south oriented shoreline the equation for net littoral drift would be as follows:

$$Q^* = Q_n - Q_s \qquad \text{eq. 5.1}$$

Where Q^* is the net littoral drift, Q_n is the gross drift north and Q_s is the gross drift south. It is important to note that while longshore transport is a transfer of sediment, it can also act as a source or a sink for individual coastal compartments. If the littoral drift crosses over the control boundary into a specified budget area and is deposited within that area, it is a source of sediment. Conversely if the littoral drift transports sediment out of the budget compartment, it is a sink of sediment.

5.3.1 Inferred Sediment Transport Direction

Longshore transport direction may be determined if sorting is considered at the same time as mean grain size using the model developed by Sunamura and Horikawa (1972). This theory is based on the basic premise that both the sorting coefficient and the mean grain size decrease with distance from the source. Sunamura and Horikawa present the following criterion for the inference of transport direction:

(i) In the case of that grain size decreases and the degree of sorting unvaries with the increasing distance from a supply source, beach materials move in the direction of grain size reduction
(ii) In the case of that both grain size and sorting coefficient decrease with increasing distance from the source, longshore drift predominates in the direction of decrease of these parameters.
(iii) In the case of that grain size unchanges and sorting coefficient diminishes as the distance from the source is increased, the transport direction is the one in which the latter parameter decreases
(iv) In the case of that grain size increases and sorting coefficient reduces with the increase of distance from a source, material movement prevails in that direction of decrease of the latter parameter
(v) In the case except the above ones, the inference is the direction towards the source

These controlling factors are illustrated in Figure 5.1

A model incorporating this information for Pegasus Bay is presented in Figure 5.2 utilising samples from the lower foreshore. The figures graphed are based on the method of moments obtained through the R.S.A. The method of moments from the RSA gives values for mean grain size and sorting co-efficient.

This method is further enhanced by using 0.25ϕ intervals instead of the 0.5ϕ intervals used by Sunamura and Horikawa (1972). Each profile site has been graphed as a distance from Sumner Head and the river sources of sediment for the bay have also been located (Figure 5.2).

Inferred sediment transport directions in Pegasus Bay are indicated in Figure 5.2. Transport on the South Brighton Spit moves alongshore towards the Avon-Heathcote Estuary. North of the estuary along the Christchurch city coastline to Waimariri Beach, flow is in a northern direction towards the Waimakariri. This apparent anomaly is difficult to explain and may be a localised phenomena.

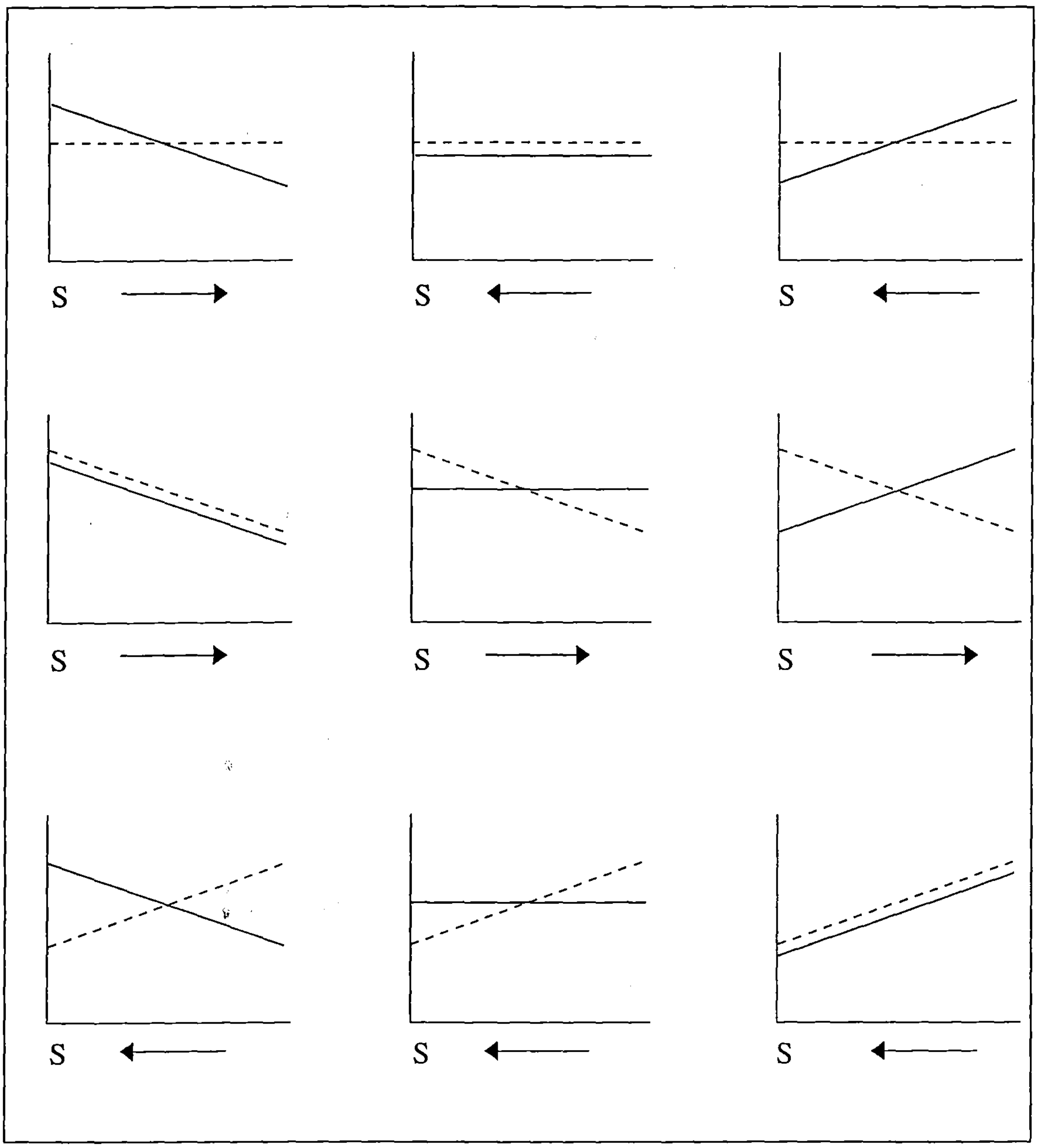

Figure 5.1 *Criterion for establishing longshore transport direction where S is the source of sediment*

Source: Sunamura and Horikawa (1972) p62

There is longshore transport in both directions from the Waimakariri as was established by Little (1991). The same is evident for the Ashley River where sediment is transported both north and south of the river. North of the Kowai the predominant direction is north. This may be attributed to the dominant high energy south east swells common in this area showing that coastal processes in this area dominate over riverine processes.

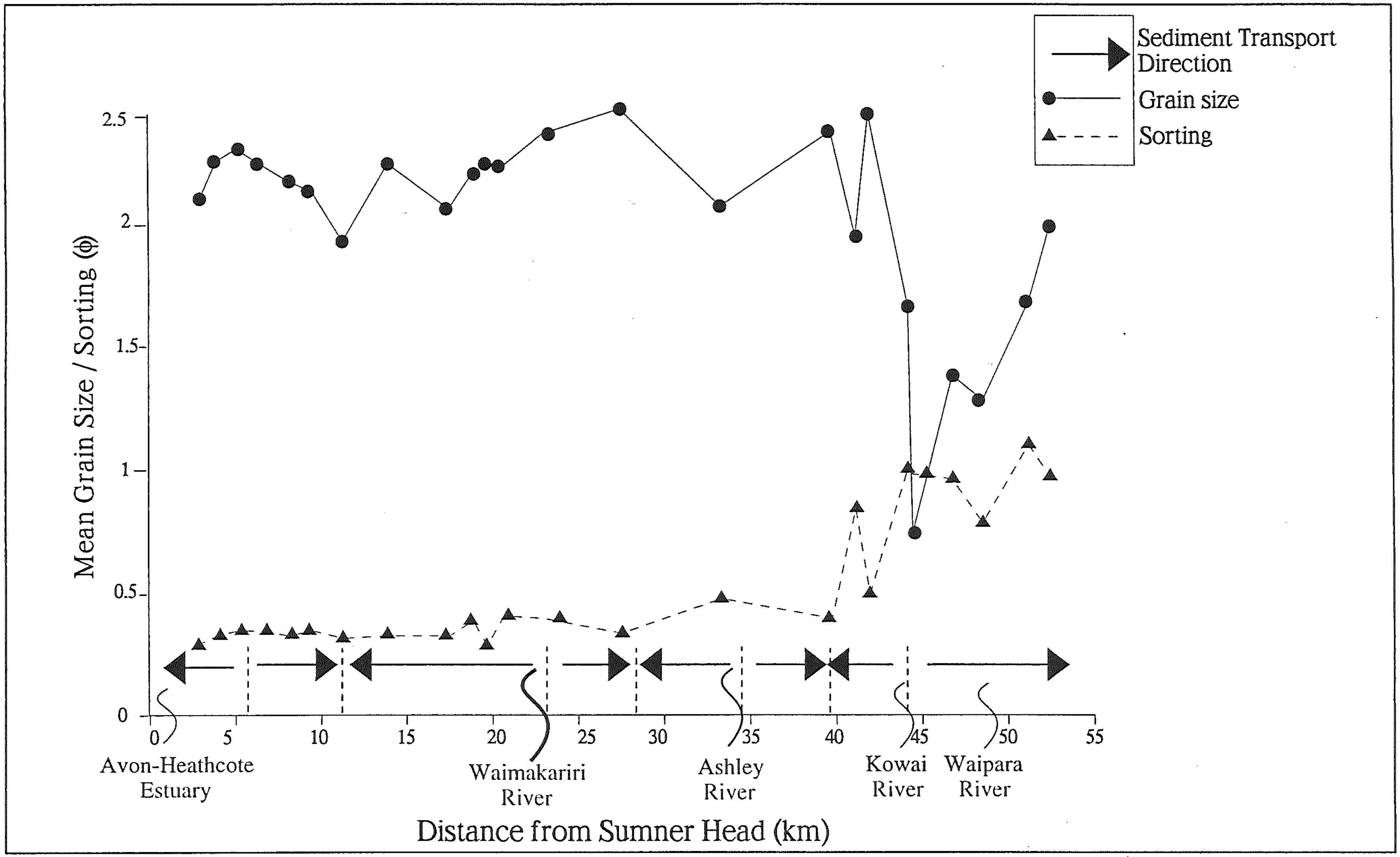

Figure 5.2 *Inferred longshore transport directions for Pegasus Bay*

5.3.2 Longshore Transport Calculated from Wave Observations

The potential volume of sediment moved alongshore can be calculated using the wave observation parameters. The figures obtained are therefore subject to the accuracy of the wave observation and are consequently only an approximation of the longshore transportation of sediment. The values have been calculated using the following data:

*Amberley Beach wave observations, February to June 1995 as detailed in Chapter Two,
*Waikuku Beach wave observations, February to June 1995 as detailed in Chapter Two,
*New Brighton Beach wave observations, August 1992 to July 1993 (Mawson in prep).

Further limitations to the calculations are that the Waikuku and Amberley wave observations do not cover a full year and may therefore not give an as accurate figure as the New Brighton data which does cover one full year.

The potential longshore transport was calculated using the longshore component of energy flux, (P_{ls}) as detailed in The Shore Protection Manual (C.E.R.C. 1984), as follows:

$$P_{ls} = \frac{\rho g}{16} H_b^2 C_{gb} \sin 2\alpha_b \qquad \text{eq. 5.2}$$

(C.E.R.C. 1984)

where: ρ = mass density of salt water (kg.m^{-3})
g = gravitational constant (m.s^{-1})
H_b = breaker height (m)
C_{gb} = group velocity of breakers (m.s^{-1})
α_b = breaker angle (°)

The group velocity of the breakers was calculated using:

$$C = \sqrt{gh} \qquad \text{eq. 5.3}$$

The potential longshore volume of sediment transported (Q*), can be established by substituting Eq. 5.2 into the following equation:

$$Q^* = \frac{k}{(\rho_s - \rho)\, g\, a'} P_{ls} \qquad \text{eq. 5.4}$$

(C.E.R.C. 1984)

where: k = constant (1290) (dimensionless)
ρ_s = mass density of sediment (kg.m^{-3})
a' = volume of solids / total volume (dimensionless)

so that:

$$Q^* = \frac{k}{(\rho_s - \rho)\, g\, a'} \frac{\rho g}{16} H_b^2 \sqrt{gh} \sin 2\alpha_b \qquad \text{eq. 5.5}$$

The volume for each wave angle has been calculated as to distinguish drift north from drift south (Eq. 5.1). The New Brighton value represents an entire years data and is expressed as such. Waikuku and Amberley volumes have also been presented as a yearly figure by extrapolation from the study period data. The volumes for net potential longshore transport are presented in Table 5.7.

The transport rates presented in Table 5.7 are highly subjectable to errors based on the breaker angle. The precise breaker angles have not been recorded for this study and instead sectors based on the L.E.O. method (Chapter Two) have been used. Only 1% of the wave angles used to calculate longshore drift did not arrive from sector 2 or 4. Therefore the error in the averaging of the breaker angle for these sectors can be applied to the longshore transport. This means that the maximum error of the breaker angle is 12.5° which then corresponds to a maximum error of 50% of the calculated potential longshore transport value (R. Kirk Geography Department Canterbury University *pers. comm.* 1995)

Table 5.7 *Potential north, south, gross and net longshore transport rates for three sites in Pegasus Bay*

Location	Q_{nth} ($m^3.yr^{-1}$)	Q_{sth} ($m^3.yr^{-1}$)	Q_g ($m^3.yr^{-1}$)	Q_n ($m^3.yr^{-1}$)
New Brighton	223,923 ±111,962	505,351 ±252,676	729,274	281,428 (south)
Waikuku Beach	56,502 ± 28,251	1,628,580 ±814,290	1,685,082	1,628,580 (south)
Amberley Beach	496,643 ±248,322	293,190 ±146,595	789,833	203,453 (north)

The net direction of longshore transport correlates to the directions established using the Sunamura and Horikawa (1972) model, (Figure 5.2) at the Waikuku and Amberley Beach sites but not for the New Brighton site. The large longshore sediment transport value for Waikuku Beach can in part be explained by examining the gross potential longshore transport from Table 5.7.

The Waikuku Beach value is over twice the Amberley and New Brighton values. This can be attributed to the higher percentage of waves arriving at oblique angles to the shore at this site (Chapter Two). Despite the high energy environment of Amberley Beach the gross longshore sediment transport is the lowest for the bay which is due to the large sediment sizes found at this site.

5.4 Onshore/Offshore Transport

When a beach is in an equilibrium state there is irregular movement of the material both onshore and offshore. This material does not remain in either site long enough to be deemed a source or a sink. Consequently the material cycling between the onshore and offshore regions is recognised as a transfer of sediment. The reason these transfers are often not calculated in a sediment budget model is their transitory nature and therefore the extremely difficult task of quantification. Further complicating the equation is the temporal factor. There are many occasions for beaches in Pegasus Bay when sediment cycles between the beach and the longshore bar. Although sediment is lost from the beach it is not lost from the coastal system. Instead it is cycling in the nearshore zone. Kirk (1979) estimates that the periodic onshore/offshore transfer of sand amounts to at least 1,600,000$m^3.yr^{-1}$ for the 16kms of beach from Sumner to the Waimakariri River. If this figure is consistent for the entire bay then 5,000,000$m^3.yr^{-1}$ is being transferred in the onshore/offshore zone.

For this study onshore/offshore exchange has been calculated from short term beach profile data. These short term volume changes have been taken as indicative of the onshore/offshore cycling. These values have then been averaged to give an annual average volume. To give entire coverage of the coastline each profile site has been taken as representative of half the distance to the next profile site. The eight regions described in Chapter Four have again been utilised. The results are presented in Table 5.8. The exchange volumes of each region have also been expressed as a volume per metre of beach to show the differences between each region.

Table 5.8 *Average annual onshore / offshore exchange volumes per region (m^3) and unit length of coastline (m^3/m)*

Location	Onshore Exchange (m^3)	($m^3.yr^{-1}$)	Offshore Exchange (m^3)	($m^3.yr^{-1}$)	Gross Exchange (m^3)	($m^3.yr^{-1}$)	Net Exchange (m^3)	($m^3.yr^{-1}$)
South Brighton Spit	722,340	219	466,260	141	1,188,600	360	256,080	77
Christchurch City	464,790	103	438,840	98	903,630	201	25,950	5
Bottle Lake Region	751,910	96	907,960	116	1,659,870	212	-156,050	-20
Brooklands Spit	196,950	68	382,700	132	579,650	200	-185,750	-64
Mid Pegasus Bay	3,770,050	290	3,450,290	265	7,220,340	555	319,760	25
Leithfield Region	1,107,450	113	687,530	70	1,794,980	183	419,920	43
Amberley Region	387,430	97	145,160	36	532,590	133	240,270	61
Waipara River Region	190,440	43	291,980	66	482,420	109	-101,540	-21
Total	7,591,360	153	6,770,720	136	14,362,080	289	820,640	17

Some interesting results are presented in Table 5.8. Net offshore exchange occurs in three (Bottle Lake, Brooklands Spit and Waipara River region) of the eight sectors and only one sector (Christchurch City) maintains a balance between the onshore and offshore exchange. The highest rates of exchange (3.77 x 10^6 m^3 onshore and 3.45 x 10^6 m^3 offshore) occurred in the mid Pegasus Bay sector although the net exchange per length of region is not high ($25m^3.m^{-1}$). The three northern Pegasus Bay sectors (Leithfield region, Amberley region and Waipara River region) had the least gross exchange per length of sector ($183m^3.m^{-1}$, $133m^3.m^{-1}$ and $109m^3.m^{-1}$ respectively) but maintained reasonably high rates per length of sector ($43m^3.m^{-1}$, $61m^3.m^{-1}$ and $21m^3.m^{-1}$) of net exchange. The South Brighton Spit has the highest net exchange per length of sector, $77m^3.m^{-1}$ and the second highest gross exchange per length of sector, $360m^3.m^{-1}$ indicative of the changeable nature of this region.

Overall 14.36 million m^3 of sediment is involved in offshore/onshore transport each year for the entire bay. Of this 7.59 million m^3 is onshore and 6.77 million m^3 is offshore resulting in a net annual average onshore movement of $820{,}640m^3$ of sediment.

5.5 Concluding Remarks

This chapter presented the sediment characteristics of the beaches of Pegasus Bay. The RSA values are statistical measures of the sediment samples taken from the beaches. These measures reflect the past transport mechanisms and indicate that less selective processes operate in the north than the south. Furthermore the sediments in the north are much coarser and need higher current velocities to be transported than currents in the south.

Mean grain size and the sorting coefficient of each sample were used to infer the longshore sediment transport direction using the Sunamura and Horikawa (1972) model. The predominant transport is to the south although strong contrary flows are apparent to the north of the Waimakariri and Ashley Rivers and in the north of Pegasus Bay. There is also a contrary drift to the north along the Christchurch City beaches. This may be related to the high human usage of the area.

Potential longshore transport has been calculated from the wave records of three sites in Pegasus Bay. The Amberley and Waikuku direction of transport corresponds to those predicted in Sunamura and Horikawa model. However the New Brighton potential net longshore transport is to the south whereas the model indicates it is to the north. These contrasting directions highlight the need for in depth research into each component of the sediment budget.

The onshore/offshore component of the sediment budget is examined and presented. 14.36 million m^3 of sediment cycles in the nearshore zone of Pegasus Bay each year. The net movement of 821,000m^3 is onshore.

This chapter signifies the final component of the sediment budget. The sources, sinks and transfers of sediment have all been described, analysed and where possible quantified leading to the penultimate chapter - the sediment budget of Pegasus Bay.

Chapter Six
The Sediment Budget Model for Pegasus Bay

6.1 Introduction

This chapter brings the previous chapters together to establish a specific sediment budget model for Pegasus Bay. Sources, sinks and transfers of sediment identified in the previous chapters are quantified and placed into the context of the sediment environment of the bay as a whole.

6.2 Pegasus Bay- The Boundaries

The study area has been introduced in Chapters One and Two. In presenting the sediment budget model for Pegasus Bay, the boundaries of the area are revisited here. Pegasus Bay stretches for 50kms from Shag Rock in the south up to Double Corner in the north. Banks Peninsula forms the southern boundary and the cliffs of Double Corner form the northern boundary. The seaward boundary lies about the 15m isobath where mud and silt begins to be deposited offshore. The landward boundary is the dune toe or gravel ridge base where the backshore meets the dune or gravel ridge.

Sources, sinks and transfers of sediment for Pegasus Bay are listed in Table 6.1. As can be seen there are several overlaps with many features being sources and sinks or even a source, sink and transfer of sediment. The identification process of these features is based on the schematic sediment budget model outlined in Chapter One (Figure 1.3) and has been adapted to reflect Pegasus Bay as presented in Figure 6.1. Instead of the general components of the schematic sediment budget model this model identifies the specific sources, sinks and transfers unique to Pegasus Bay.

Table 6.1 *Sources, sinks and transfers of sediment within Pegasus Bay*

Sources	**Sinks**	**Transfers**
Avon River	Avon-Heathcote Estuary	Longshore
Heathcote River	Brooklands Lagoon	Onshore/Offshore
Waimakariri River	Dune Systems	
Ashley River	Beach Systems	
Kowai River	Offshore Zone	
Waipara River		
Avon-Heathcote Estuary		
Brooklands Lagoon		
Dune Systems		
Beach Systems		
Offshore Zone		

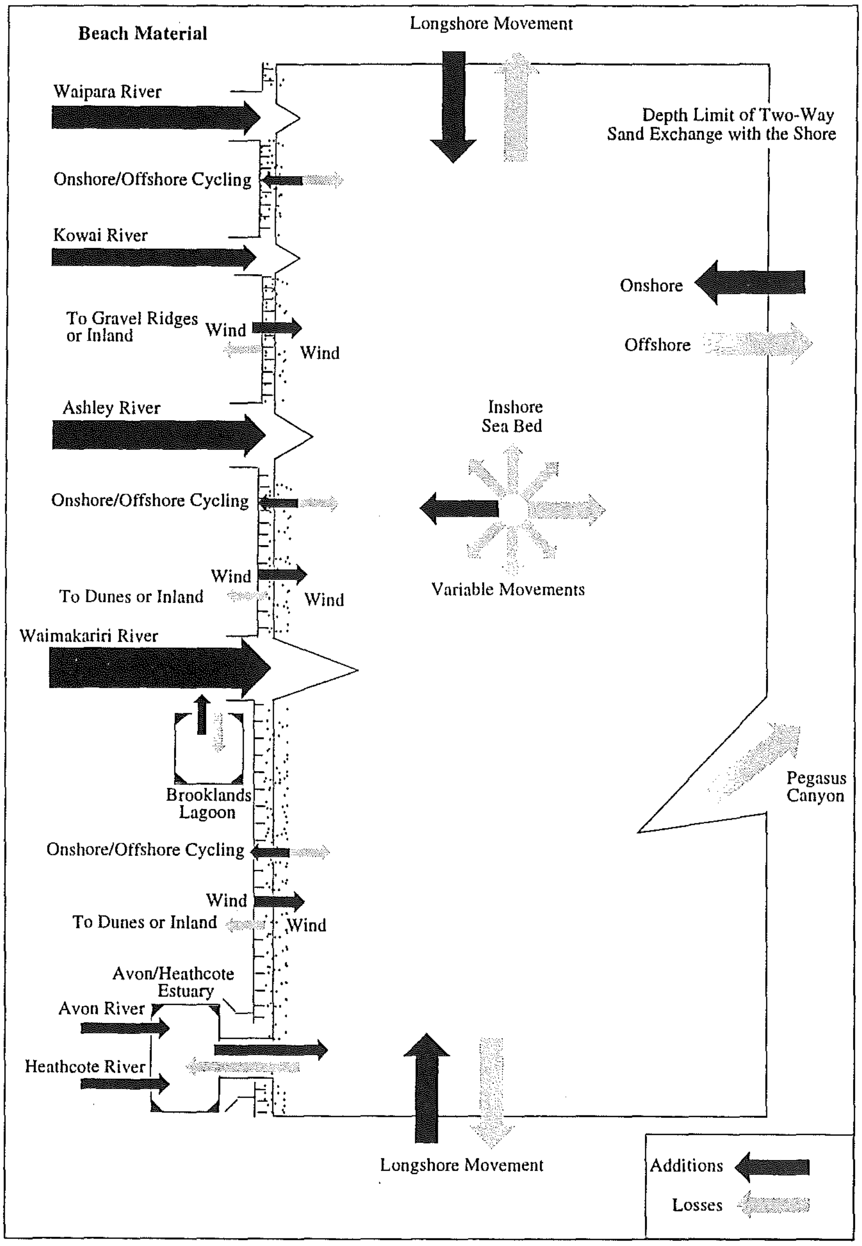

Figure 6.1 *Schematic sediment budget model of Pegasus Bay*

The six rivers of the region (Table 6.1) are the most dominant sources of sediment and have been displayed as such. The Avon-Heathcote Estuary and Brooklands Lagoon have been located and their ambiguous "source/sink" nature is demonstrated with both loss and addition arrows. The dune and gravel ridges are also presented in the same manner although in this case the transporting mechanism is air, not water. The onshore/offshore contribution or loss is also displayed. The final component of the budget is the longshore transport of sediment within or through the system. Although located at either end of the Pegasus Bay coastal cell, the transport in and out of the bay is taken as negligible and the transfers within the cell are more significant. Thus there are no cross-boundary flows at the ends of the system to account for.

Other cross-boundary flows are more difficult to assess. There is a lack of modern sediment on the outer continental shelf (>30m deep) as outlined in Chapter Three. It has therefore been assumed that little sediment moves in either direction about the 30m isobath and so although the 30m isobath is not the seaward limit of the budget, it is considered that there is little cross boundary flow at the seaward limit of the system. Wind blown transport to the dunes across the landward boundary is perhaps the most complex of all to quantify and has not been done for Pegasus Bay. Further complications exist in that the availability of sand for aeolian transport decreases in the north of Pegasus Bay due to the mixed sand and gravel nature of these beaches. The study of aeolian sand movements is a complete study on its own and so has not been considered here.

6.2.1 Spatial Delineation

Pegasus Bay does not exhibit uniform characteristics throughout the whole bay and so it is convenient to treat it as a system of component units. Therefore the bay has been divided into the eight sectors shown in Figure 6.2. These sectors are consistent with those used in Chapters Four and Five and the following is a brief description of each sector.

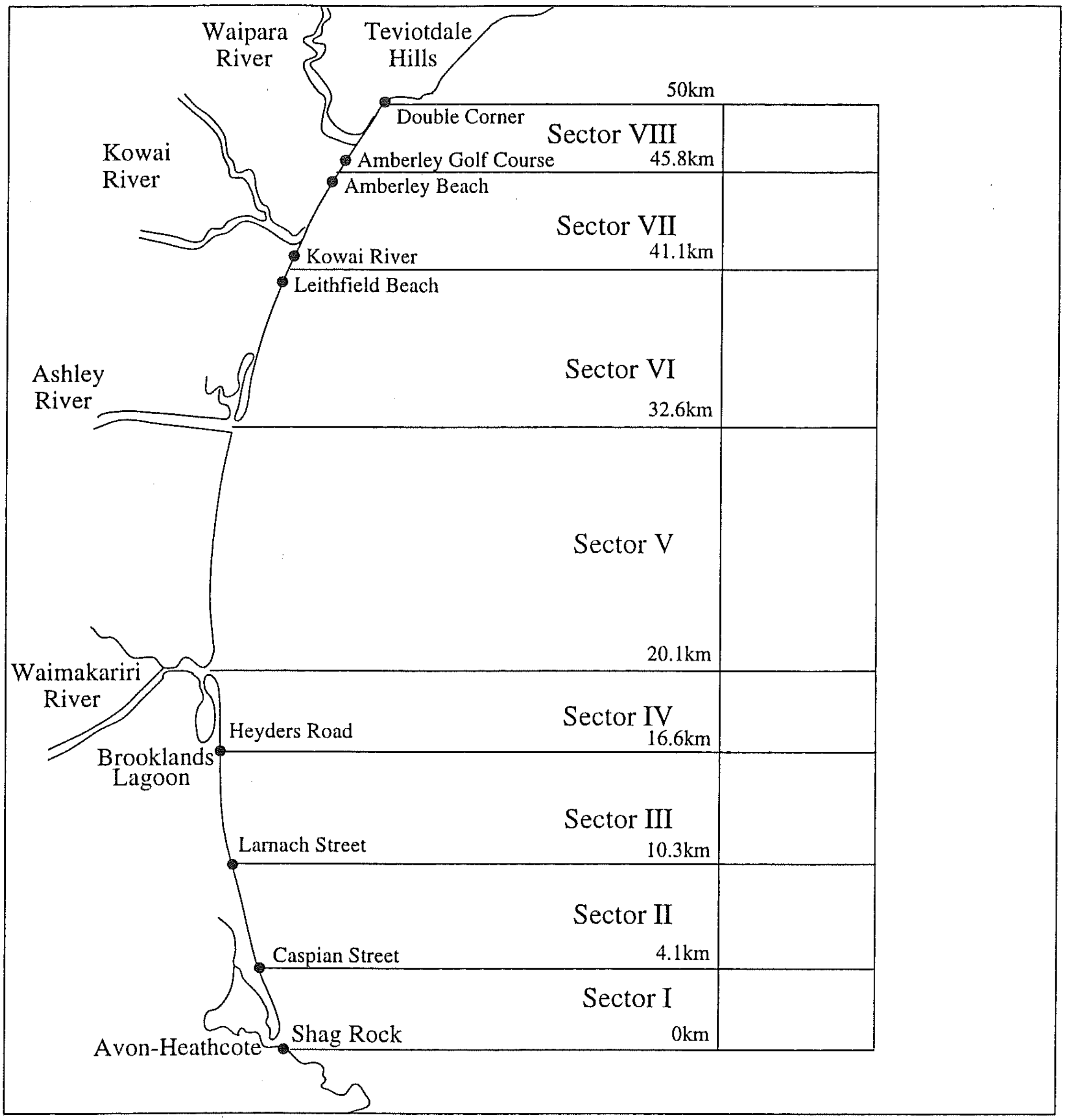

Figure 6.2 *Sediment budget boundaries for this study of Pegasus Bay*

Sector I South Brighton Spit

The South Brighton Spit region has been extended slightly from that first presented in Chapter Four to encompass the Avon-Heathcote Estuary inlet. The sector therefore covers the area from Shag Rock to Caspian Street (Figure 6.2). Sector I is 4.1kms long. The wave environment is dominated by north-easterly and easterly seas and is protected from the high energy southerly swells by the Banks Peninsula promontory. The Avon-Heathcote Estuary inlet area in particular is greatly affected by tidal processes as the tides ebb and flood through the restricted area. The beaches are composed of fine well sorted sands indicative of the process regime. The longshore component, as shown by the Sunamura and Horikawa (1972) model for Pegasus Bay (Figure 5.2), is in a net southern direction towards the Avon-Heathcote Estuary. The onshore/offshore exchange for this region is also high ($77m^3.yr^{-1}.m^{-1}$ as opposed to the average of the bay which is $17m^3.yr^{-1}.m^{-1}$).

Sector II Christchurch City

The Christchurch City sector extends for 6.2kms from Caspian Street to Larnach Street at Waimariri Beach (Figure 6.2). The wave environment and sediment composition of this region is very similar to that of the South Brighton Spit. The sector is however more stable than the fluctuating spit area. A reverse trend of longshore transport was identified from the Sunamura and Horikawa model for Pegasus Bay (Figure 5.2). The onshore/offshore exchanges are almost in equilibrium (Table 5.8) resulting in a small net exchange of $5m^3.yr^{-1}.m^{-1}$ onshore).

Sector III Bottle Lake

The southern limit of the Bottle Lake sector is Larnach Street and it extends 6.3kms north to Spencerville and Heyders Road (Figure 6.2). There is little variation in the wave environment and beach composition from the previous two sectors. However this region is closer to the Waimakariri River, the major source of sediment for the bay and therefore receives more sediment. The net alongshore sediment transport direction is to the south and the region exhibits a net offshore movement of sediment of $20m^3.yr^{-1}.m^{-1}$.

Sector IV Brooklands Spit

Sector IV encompasses the whole of Brooklands Spit and the Waimakariri River mouth a total length of 3.5kms (Figure 6.2). The beaches are again composed of fine well sorted sands. This landform is a new feature in the Pegasus Bay landscape and is less than sixty years old. The fluctuations in sediment volumes are greater than in other regions of the bay for example the net onshore/offshore exchange for the region was $-64\ m^3.yr^{-1}.m^{-1}$ (Table 5.8)

Sector V Mid Pegasus Bay

The mid Pegasus Bay sector extends from the Waimakariri River in the south to the Ashley River in the north covering the largest area of the bay, 12.5km (Figure 6.2). The beaches in this region are comprised of fine sands derived from the Waimakariri and Ashley Rivers. Longshore transport in this region exhibits two transport directions both being away from the river sources. A great deal of sand cycles in the nearshore zone in Sector V but the net exchange is only $8m^3.yr^{-1}.m^{-1}$ above the average for the bay ($7m^3.yr^{-1}.m^{-1}$).

Sector VI Leithfield Region

The Leithfield region stretches for 8.5kms from the Ashley River to north of Leithfield Beach in the north (Figure 6.2). Within this sector is the demarcation from sand to mixed sand and gravel beaches. These northern beaches are not sheltered from southerly swells by Banks Peninsula and a higher energy wave environment results. The influence of the Ashley River is apparent on the sandy beaches and the predominant longshore transport direction is to the south The gravel beaches are either indicative of the past hydraulic regime of the Ashley River when it regularly supplied gravels to the coast or alternatively are influenced by the Kowai and Waipara Rivers further north which still supply gravels to the coast.

Sector VII Amberley Region

The southern limit of the Amberley region is between Leithfield Beach and the Kowai River and extends 4.7kms to north of Amberley Beach. The beaches within the region are all mixed sand and gravel and are influenced by both the Kowai and the Waipara Rivers. This northern Pegasus Bay sector experiences the high energy environment described in Chapter Two. Net longshore transport occurs to the south and the north of the Kowai and the gross onshore/offshore exchange ($133m^3.yr^{-1}.m^{-1}$) is the second lowest for the entire bay (Table 5.8).

Sector VIII Waipara River Region

The Waipara River region is the northernmost sector of Pegasus Bay. It extends 4.2kms from south of the Amberley Golf Club to the cliffs at Double Corner, the northern limit of the bay. The beaches in this zone are also mixed sand and gravel but the sand composition increases with distance from the Waipara River. Sector VIII is a high energy environment with strong winds and high southerly swells. Net longshore transport in this region is to the north and the net onshore/ offshore exchange per unit length of beach is $21m^3.yr^{-1}.m^{-1}$.

6.2.2 Temporal Scale

The temporal scale is perhaps the hardest to define for the budget. A sediment budget can cover many time scales. A short term sediment budget covers a time frame of less than one year. This type of budget in particular looks at seasonal variations or changes from month to month. Sediment budgets are usually calculated for a period of at least one year. Any short term fluctuations are cancelled out due to averaging of sedimentation rates and processes. This latter temporal scale has been used for this model.

The model presented here considers several coastal features and many geomorphological events such as storms and floods. However some events are not included due to their time frame being to long or short in comparison to the budget time frame. For example, extreme storms (with return periods grater than fifty years and major shifts in river positions fall out of the time scale of the model). The model has been derived based on a number of different sources of information and consequently the time frame varies for each. The following is a synopsis of the components of the sediment budget as to what the temporal scale of each encompasses, assumes or excludes.

River sediment outputs are average annual yields and were calculated from predicted mean rainfall for a year. Extreme high and low sediment yields are therefore not included due to averaging in producing a mean annual rainfall value. Drought in a river catchment could lead to a possible deficit in the coastal budget as the sediment yield for the river decreases. Conversely a one hundred year return flood in the catchment would lead to great volumes of sediment entering the coastal compartment. This data although excluding extreme events is thought to be representative of annual variations.

The volume calculations for the beach and dune/gravel ridge systems were based on data for a four to five year period and are thus averages for these periods. While the data is representative for the budget temporal frame it cannot be extrapolated to include future extreme events. The sediment removed by a one hundred year return coastal storm and/or the rate of recovery from that storm are not accounted for by a budget of this time frame. Instead this budget allows for an average of three to four storms per year and except for low frequency extreme events this average generally holds true.

Deposition rates for the Avon-Heathcote Estuary and Brooklands Lagoon have been calculated over long periods (decades) and then averaged to represent a yearly value. This assumes a constant depositional rate uniform over the entire feature and therefore disregards any possible mass erosion or accretion from a specific area. While this is important on a site specific scale, this small scale localised erosion/accretion is not important on the sediment budget scale.

Two of the potential longshore transport values have been calculated from less than one year of wave data. However the coverage of both winter and summer months to allow for any seasonal variations apparent in the wave environment allows for the assumption that the data is representative of an entire year. Furthermore it is assumed that these data are representative of consecutive years despite the absence of any low frequency events such as the one hundred year return coastal storms which can only be covered in budgets of longer temporal scales.

No matter which time frame is covered not all of the coastal phenomena and changes can be accounted for. One hundred year return floods or coastal storms, tsunami and inland drought are not included in this budget nor are any predictions of sea level rise. This model provides an average annual sediment budget based on data collected over both short and long terms which has then been extrapolated or averaged to represent an annual average value.

6.3 The Quantitative Model

In order to calculate a sediment budget there must be a known or accepted variable against which the other variables can be calibrated. The best known variable for this study is the state of the beach. According to eq. 1.1 the inputs, outputs and throughputs of the study must sum the beach depositional, erosional or equilibrium state. The known states for the eight beach sectors (Chapter Four) have been worked out as follows and are shown in Table 6.2.

Table 6.2 *Deposition and erosion rates for the various sectors of Pegasus Bay*

REGION		Deposition/ Erosion Rate (m^3)	Rates per length of coast ($m^3.m^{-1}$)
Sector I	South Brighton Spit	0	0
Sector II	Christchurch City	0	0
Sector III	Bottle Lake Region	0	0
Sector IV	Brooklands Spit	9,550	2.4
Sector V	Mid Pegasus Bay	55,018	4.2
Sector VI	Leithfield Region	4,700	0.47
Sector VII	Amberley Region	-489	-0.14
Sector VIII	Waipara Region	-673	-0.14
TOTAL		68,056	1.36

The South Brighton Spit, Christchurch City and Bottle Lake beaches are determined to be in a state of equilibrium. Historical cadastral maps and aerial photographs (C.R.C.) show that there have been no significant shoreline changes within the past fifty years and so it is assumed that these beaches are not eroding or accreting. The inputs and outputs for these regions should therefore sum to zero (Table 6.2).

The deposition rate for Brooklands Spit has been established using the volume data obtained from profile surveys (Chapter Four). The beach and dune volumes for this region equal 1,194,000m^3. Furthermore it is assumed that this material has been deposited since 1940, amounting to an average deposition rate 21,709$m^3.yr^{-1}$. It is understood that most of this sediment would have been deposited in the first 15 to 25 years after the Waimakariri River mouth shifted and so the above averaged rate is not indicative of recent deposition rates. If however 80% of the sediment was deposited in the first 30 years after the river mouth migration then a deposition rate for the past 25 years of 9,550$m^3.yr^{-1}$ would result. The inputs and outputs for this region should therefore sum to 9,550$m^3.yr^{-1}$ (Table 6.2).

The deposition/erosion rates for the remaining regions of Pegasus Bay have been established through measured changes of shoreline position. Todd and Little (in press) have established average rates of change at Pines, Woodend, Waikuku, Leithfield and Amberley Beaches. The most recent rates of change (1980 to 1993) have been utilised for this study. These rates have been expressed in

$m.yr^{-1}$ which equate to a horizontal change in position of mean low water level. For the purpose of this study a 1m horizontal change can be shown to correspond to a $1m^3$ volumetric change. The rate of change measured at each site has then been taken as representative of half the distance alongshore to the next site. This method gives deposition rates of $55{,}018m^3.yr^{-1}$ for Mid Pegasus Bay, $4{,}700m^3.yr^{-1}$ for the Leithfield region and erosion rates of $-489m^3.yr^{-1}$ for the Amberley region and $-673m^3.yr^{-1}$ for the Waipara region (Table 6.2).

The sediment budget for Pegasus Bay is illustrated in Figure 6.3. The longshore transport covers three broader sections of the bay than the 8 sectors shown in Figure 6.2. The longshore transport sections are based on the wave observation sites and the probable region to which the calculated sediment transport applies. The net budget for each of the 8 sectors is shown in Table 6.3. The longshore component for the three larger sections has been divided equally between the corresponding sectors relative to the length of the sector. Furthermore the northward component (Q_{nth}) of the longshore transport has been expressed as a negative value and the southward (Q_{sth}) component as positive. This figure is represented by Q_n in the budget of Pegasus Bay. The net onshore/offshore exchange has been established for the individual eight sectors and is represented by B_n in the budget of Pegasus Bay. The onshore component (B_{on}) is an addition to the budget and the offshore component (B_{off}) is a loss from the budget. The gross budget values are defined by the g subscript.

The river input to the bay (R) has been divided into the sectors based on the longshore transport for each section of the bay. Cell I therefore receives 100% of the input from the Avon and Heathcote Rivers and 10% of the input from the Waimakariri River. Cell II receives a higher proportion of the Waimakariri's input (15%). The length of Cell III is greater and the proportion of sediment from the Waimakariri reaching this section increases to 30%. The largest proportion of sediment yield from the Waimakariri River is deposited in Cell IV (40%). Only 5% of the sediment yield from the Waimakariri moves north into Cell V but this is additional to 50% of the yield from the Ashley River. Cell VI also receives 50% of the yield from the Ashley River. 100% of the Kowai River's yield enters Cell VII and similarly 100% of the Waipara River's yield enters Cell VIII.

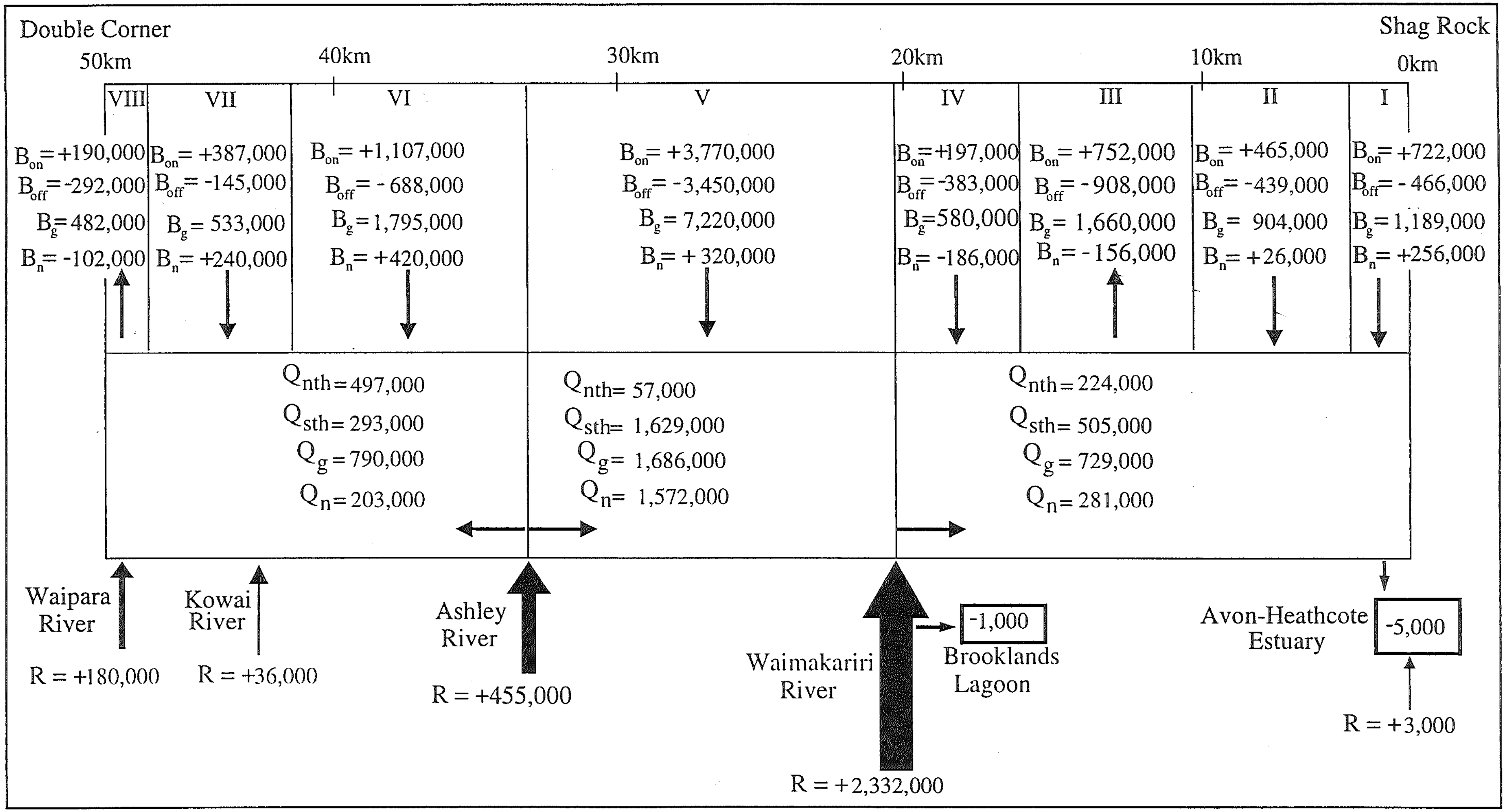

Figure 6.3 *A sediment budget model for Pegasus Bay incorporating potential longshore transport (Q), onshore/offshore exchange (B) and river inputs (R). All units are ($m^3 . yr^{-1}$)*

Table 6.3 *Net budget for the cells defined in Figure 6.2 and Pegasus Bay including net potential longshore transport (Q_n), onshore/offshore exchange (B_n) and river input (R).*

		Longshore (Q_n) ($m^3.yr^{-1}$)	Onshore (B_n) ($m^3.yr^{-1}$)	River (R) ($m^3.yr^{-1}$)	Total ($m^3.yr^{-1}$)
South Brighton Spit	Cell I	57,000	+256,000	236,000	549,000
Christchurch City	Cell II	87,000	+26,000	350,000	463,000
Bottle Lake Region	Cell III	88,000	-156,000	699,000	613,000
Brooklands Spit	Cell IV	49,000	-186,000	933,000	796,000
Mid Pegasus Bay	Cell V	1,572,000	+320,000	344,000	2,236,000
Leithfield Region	Cell VI	-99,000	+420,000	228,000	747,000
Amberley Region	Cell VII	-55,000	+240,000	36,000	331,000
Waipara Region	Cell VIII	-49,000	-102,000	180,000	127,000
	Total	1,650,000	+821,000	3,003,000	5,562,000

6.3.1 The Total Budget

A number of interesting features can be seen by examining the total sediment budget for Pegasus Bay (Figure 6.3). The gross budget for Pegasus Bay, ($\Sigma^8_{i=1}B_g + \Sigma^3_{j=1}Q_g + \Sigma^5_{k=1}R$), is 20,571,000 $m^3.yr^{-1}$ which represents all the transfers within the 50kms of the beach. The beach above the mean low water level has a total volume of 18,704,000m^3 so that the gross budget affects all of the beach volume in a given year. However if the dune/beach ridge volumes are considered then there is a total volume of 37,098,000m^3 so that the gross budget affects 55% of this volume in a given year. The total net budget amounting to gains of 5,562,000 $m^3.yr^{-1}$ represents 27% of the gross exchanges. The net changes for a sediment budget are commonly significantly less than the sum of the total transfers. The net value also shows that overall, Pegasus Bay beaches are in a surplus budget condition.

6.3.2 Longshore Transport

There is significant variation in the longshore drift potentials at each of the three locations. South of the Waimakariri River the net direction of transport is south. However there is the existence of a northward counterdrift. The predominant drift south exhibited in mid Pegasus Bay indicates that less than 5% of the sediment supply from the Waimakariri nourishes the beaches to the north. The dominant southward trend in the mid Pegasus Bay region also indicates that 95% of the sediment supply from the Ashley River supplies these beaches. Only 5% of the Ashley River sediments move north but this is also coupled with sediment from the Kowai and Waipara Rivers moving north nourishing this region of the bay. Gross longshore sediment transport along an open coast is typically of the order of 10^5 to 10^6 $m^3.yr^{-1}$. As can be seen here the net transport is 1.65 x 10^6 $m^3.yr^{-1}$ and the gross transport is 3.205 x 10^6 $m^3.yr^{-1}$. The net potential longshore transport accounts for 30% of the net budget. A change in the longshore component is more likely to impact on the local scale rather than the entire bay.

The overall trend of longshore transport is illustrated in Figure 6.4. The differing longshore directions are a product of the wave environment at each location. The predominant southern transport direction in southern Pegasus Bay can be attributed to a higher percentage of waves approaching the shoreline from the north-east. This effect is intensified in mid Pegasus Bay where due to the shore orientation waves approaching from the north-east form a more oblique angle with the shoreline. The drift north in northern Pegasus Bay is a response to the high percentage of southerly swells that are characteristic of this area.

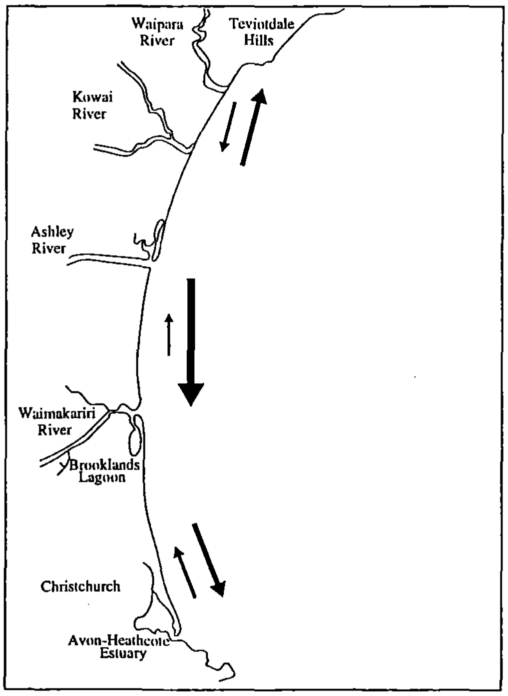

Figure 6.4 *The longshore transport direction and magnitude for Pegasus Bay*

6.3.3 Onshore/Offshore Exchange

There is a significant amount of sediment cycling in the nearshore zone. The onshore/offshore exchange accounts for 70% of the gross budget. This highlights the dynamic nature of the Pegasus Bay coastline as 14.363 x 10^6 $m^3.yr^{-1}$ cycles in the nearshore zone. The high proportion of the budget can be seen in the changes in beach form, particularly from swell profiles to storm profiles and back again. The gross onshore/offshore exchange affects 77% of the beach volume. The net onshore/offshore exchange amounts to 15% of the net budget indicating that perhaps there is internal movement from the sea bed.

6.3.4 River Contribution

The river inputs for Pegasus Bay are the only source of fresh material to the budget and collectively these sources represent 15% of the total gross budget. However more importantly the sediment yield from the rivers constitutes 55% of the net budget. This shows the importance of the rivers to the region. The Waimakariri River is the single largest contributor and alone represents 40% of the net budget. A change to the river would have dramatic affects on the coastal budget particularly in Pegasus Bay. Post 1935 when the Waimakariri River mouth shifted only 70% of its yield reached the coast. In this time (based on today's figures) the Waimakariri yield would have represented 32% of the net budget. The reduced yield equates to a 12.5% drop in the net budget. Thus, the growth of Brooklands Spit represented a significant diversion of sand from the coastal system for 25 to 35 years.

While the other rivers do not have inputs of the same order of magnitude, any reduction in sediment yield would be important locally. This is probably the reason for erosion occurring in the north of Pegasus Bay. The coastal environment is unlikely to have changed dramatically and so it is more likely that the river contribution cannot supply enough sediment to maintain a stable beach state.

6.3.5 Discussion

Examination of the net budget for each cell in conjunction with the beach state shows some interesting trends. Table 6.4 shows the total budget and the beach state for each cell and the per metre length of the cell. The beach state does not reflect the net budget for each cell although there is a strong positive correlation between the surplus and the state of the beach. The two lowest net budget values for the eight sectors ($70m^3.yr^{-1}.m^{-1}$ and $30m^3.yr^{-1}.m^{-1}$) belong to the Waipara and Amberley Regions both of which are erosionary. The highest two net budget values ($227m^3.yr^{-1}.m^{-1}$ and $179m^3.yr^{-1}.m^{-1}$) correspond to the most progradational areas of the bay, Brooklands Spit and mid Pegasus Bay.

Figure 6.5 shows the net budget versus the observed beach state. The line of best fit approximates the point at which the beach state transforms from an erosive to accretionary profile. This line can be used as an indicator of possible beach states based on a change in one or more of the sediment budget components.

Table 6.4 *Deposition and erosion rates and the net budget for the cells defined in Figure 6.2, per region ($m^3.yr^{-1}$) and per length of region ($m^3.yr^{-1}.m^{-1}$)*

REGION		Deposition/Erosion Rate		Net Budget	
		($m^3.yr^{-1}$)	($m^3.yr^{-1}.m^{-1}$)	($m^3.yr^{-1}$)	($m^3.yr^{-1}.m^{-1}$)
Cell I	South Brighton Spit	0	0	544,000	133
Cell II	Christchurch City	0	0	463,00	75
Cell III	Bottle Lake Region	0	0	613,000	97
Cell IV	Brooklands Spit	9,550	2.4	796,000	227
Cell V	Mid Pegasus Bay	55,018	4.2	2,236,000	179
Cell VI	Leithfield Region	4,700	0.47	747,000	88
Cell VII	Amberley Region	-489	-0.14	331,000	70
Cell VIII	Waipara Region	-673	-0.14	127,000	30
TOTAL		68,056	1.36	5,857,000	117

The correlation between the beach surplus and the state of the beach has been dampened by the differing phenomena in each specific sector such as beach composition, estuary dynamics and submarine canyons. A contributing factor to the beach state not precisely equalling the net budget could be that the sediment is not being stored in the beach above the mean low water level and instead is deposited on the nearshore profile. As the nearshore has also not been profiled no verification of this possible sink of sediment can be made. Another sink in the region that has not been quantified is the Pegasus Canyon. As of yet no estimates of the sediment lost offshore via this feature have been calculated. The amount of sediment lost from the system through abrasion has not been calculated. The more time a sediment particle spends in the coastal zone the smaller it becomes through abrasion. Once particles are smaller than 4ϕ they are generally lost from the system by wind inland or suspension offshore.

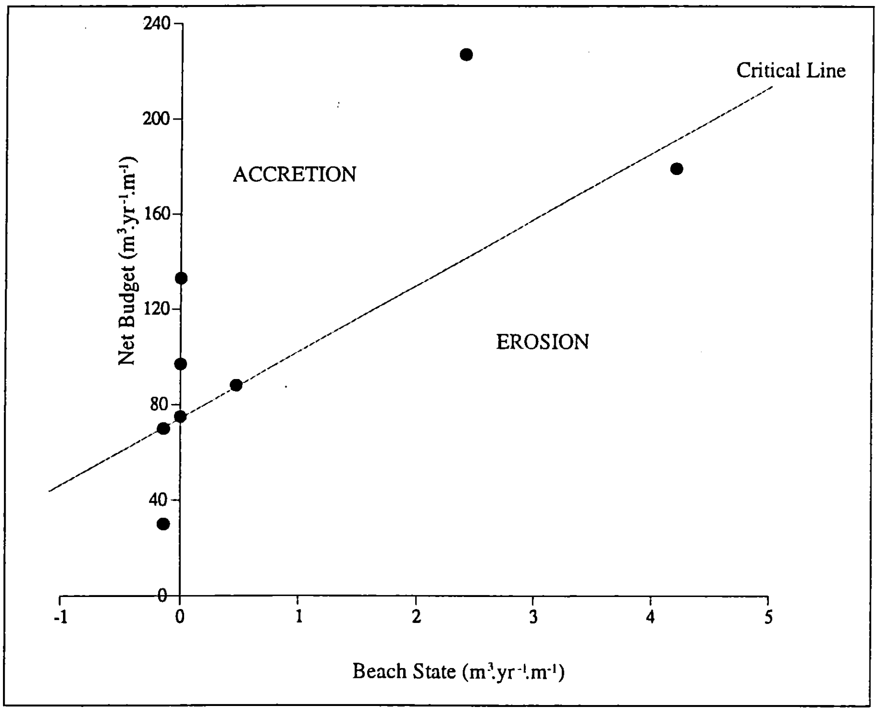

Figure 6.5 *Critical Line showing the transition between erosional and accretional beach states based on the net budget*

The beach is eroding in the Amberley Region despite the net budget indicating that the area has a surplus of sediment. Examination of Figure 6.5 shows that the values for the Amberley and Waipara River regions fall below the critical slope indicating that erosion is likely in this zone. The surplus that does exist is not sufficient to maintain a stable beach state in the long term. Instead material lost through abrasion, to the offshore or stored in the nearshore zone outweighs the surplus defined in the budget. Alternatively the suspended sediment yield calculated in 1985 by Griffiths and Glasby may not be indicative of the sediment being supplied to the coast today. This would mean that the erosive state of the beach is either a recent or short term phenomena. The last hypothesis is the most likely as the coastal environment is the least likely to change so dramatically. The means by which the sediment is being lost to the system has probably always existed but in recent times has come to outweigh the declining inputs into the coastal system.

6.4 Concluding Remarks

The schematic sediment budget presented in Chapter One has been modified to represent Pegasus Bay and has been displayed here. The model shows the relative importance of each of the inputs, outputs and transfers. This adaptation of the schematic model marks the first step in calculating a sediment budget for Pegasus Bay.

The boundaries of the budget were defined. Both the spatial and temporal scales have been examined. The cell boundaries for the budget were defined according to beach type, process environment and river input. However, the spatial boundary was harder to define. This sediment budget for Pegasus bay is based on average annual values gathered from data representing periods longer and shorter than one year. Averaging of data and extrapolation have been necessary.

The state of the beaches for each sector is presented. Three sectors (South Brighton Spit, Christchurch City, and south Bottle Lake) are in an equilibrium state, three (Brooklands Spit, mid Pegasus Bay and Leithfield) are progradational and the remaining two (Amberley and Waipara River)are in an erosional state. However, from the budget calculations overall, the coast of Pegasus Bay is in surplus. It can be seen that the amount of surplus is proportional to the state of the beach. Generally the erosional beaches have the lowest surplus of sediment and the progradational beaches the greatest amount of surplus although the relationship is not strictly linear and depends on individual site characteristics.

Both the gross and net budgets affect a considerable percentage of the beach volume. The net budget for Pegasus Bay represents 27% of the gross exchanges within Pegasus Bay. The longshore transport in each of the regions affects the distribution of the sediment yield from the rivers. The predominant drift in the

Bay is to the south although it is to the north in northern Pegasus Bay.

A great deal of sediment is transported in the nearshore as shown by the onshore/ offshore exchange. This illustrates the dynamic nature of the Pegasus Bay coastline. The onshore movement from the sea bed accounts for 15% of the budget surplus and 30% can be attributed to internal transfers.

The river contribution, especially that of the Waimakariri River, is extremely important to the net budget, (55%). Changes in the amount of river sediment supplied to the coast can play an important role in the state of the beaches. The Waimakariri River only supplied 32% of the net budget while its load was being stored in Brooklands Spit and Lagoon as opposed to 40% at present. For Cell I this would have meant a drop in surplus from 133 $m^3.yr^{-1}.m^{-1}$ to 116 $m^3.yr^{-1}.m^{-1}$. This would have lead to an unstable beach state as compared to the present state. It can therefore be said that the changes in spit dynamics during this time (as described in Chapter Four) can in part be attributed to the decreased yield of the Waimakariri River. Any further decreases in yield could result in further migrations of the spit such that a hazard to people and property occurs.

It appears that a decline in the river input from the Kowai and Waipara rivers in recent years has led to an erosive beach state in the north of Pegasus Bay. This theory is based on the premise that the coastal regime is unlikely to have been modified to such an extent as to have caused erosion at this location.

A change in state of the budget can lead to a change in state of the beaches in Pegasus Bay. The correlation between the observed beach state and the surplus of the budget is strong enough to determine a critical line at which point a beach will change its state. This critical line does not allow for equilibrium states and is only an approximation to when the beach will change its state. Bearing this in mind the critical line serves as a useful predictor of possible shoreline behaviour based on a change to one of the sediment budget components. It may even be that this critical value is different for each section of the beach. A change in beach state caused by a decrease in sediment supply, through dune recontouring or river yields, can be approximated according to the correlation between the beach state and the net budget. Furthermore this critical value can be used as a basis for other studies of this nature.

The following chapter presents the major findings and conclusions of this study. Also mentioned is possible future research which could enhance the sediment budget presented here.

Chapter Seven
Conclusions

The derivation of a sediment budget for Pegasus Bay is an important step in improving the state of coastal knowledge of the region. This thesis has brought together a wide variety of information, new and old, into one cohesive unit to be used for future consultation. The aims of the research were as follows:

1. establish the boundaries of the sediment budget within Pegasus Bay;
2. calculate the annual contribution of coarse sediment to the coast from the Avon, Heathcote, Waimakariri, Ashley, Kowai and Waipara Rivers;
3. establish any additions or losses from the beach sediment budget;
4. establish any contributions or losses from the system through longshore transport, onshore and offshore transport, or through human activity;
5. establish the state of balance or imbalance in the sediment budget and relate it to trends in coastal behaviour.

It was stated in Chapter One that the beaches and sediment movements of Pegasus Bay were not uniform nor discrete and therefore should not be treated as such. Thus it was necessary to establish the internal and external boundaries of sedimentary processes. The establishment of cell boundaries divided the bay up into manageable unique sectors. This was initially accomplished by examination of the process environment. The process environment of Pegasus Bay can be split into three distinct sections. These are southern Pegasus Bay, south of the Waimakariri River; mid Pegasus Bay, from the Waimakariri River to the contemporary demarcation zone between sand and mixed sand and gravel beach composition; and northern Pegasus Bay, north of the demarcation zone. The northern sector of Pegasus Bay has a much higher energy environment than that of southern and mid Pegasus Bay and so these regions can not be regarded as uniform. The bay was divided into further sectors based on beach composition and the nature of the beach system itself. Eight distinct sectors with consistent features throughout each were identified.

There are six rivers feeding the coast of Pegasus Bay. In order to fulfil Aim Two the river input for the region needed to be assessed and quantified. The Avon and Heathcote Rivers discharge into the estuary and so the sediment does not directly reach the coast. Their contribution is minimal on a regional scale, only 3,000 $m^3.yr^{-1}$.

In stark contrast to this is the Waimakariri River which is the largest contributor of sediment to the coast, supplying 2,332,000 $m^3.yr^{-1}$. The Waimakariri River has changed considerably since 1935 when the river mouth shifted north. The contribution to the coast has varied as Brooklands Lagoon has infilled and the spit has formed such that 30% of the sediment yield of the Waimakariri River was not reaching the open coast between 1935 and 1980. Since this time the rate of infill and deposition on the spit has decreased so that less than 1% of the annual sediment yield is now being trapped by Brooklands Lagoon.

The contemporary Ashley River rarely transports gravel to the coast. However, the annual contribution to the coast of this river is 455,000 $m^3.yr^{-1}$ and it is the second largest source in the bay. Sediment from the Ashley River is transported along the shore in both directions away from its migratory mouth.

The Kowai River is only periodically open to the sea and so does not transport great volumes of sediment to the open coast. Instead sediment is transported during periods of high intensity flows so that a total of 36,000m^3 is supplied to the adjacent shoreline each year. Like the Kowai River the Waipara River mouth is often closed by a gravel barrier. Only during high precipitation events and spring snow melt does the Waipara River have open access to the sea. This is a more regular occurrence than the Kowai River. In conjunction with the larger catchment than the Kowai, more sediment (180,000$m^3.yr^{-1}$) is supplied to the coast.

The rivers of Pegasus Bay constitute the greatest sediment source to the coastal system. A total of $3,005,000m^3.yr^{-1}$ is supplied to the open coast. Any changes in the ability of the rivers to supply sediment would have a dramatic impact on the coast. The offshore zone ($821,000m^3.yr^{-1}$) and longshore transport ($1,650,000m^3.yr^{-1}$) are the other two important sources of the bay.

The additions and losses of sediment to the coastal system have been examined and identified in accomplishing the third Aim. Many landform features are both sources and sinks of sediment. The Avon-Heathcote Estuary has been identified as a sink of sediment trapping $5,000m^3.yr^{-1}$. Brooklands Lagoon is also a sink of sediment except in this case it traps the sediment before it reaches the coastal environment. The "source/sink" nature of the dunes/gravel ridges could not be determined due to the short term basis of the data. The other sources and sinks are discussed in conjunction with the other aims.

Longshore transport for southern, mid and northern Pegasus Bay was established in order to achieve Aim Four. It was found that a net amount of 281,000 $m^3.yr^{-1}$ is transported south in southern Pegasus Bay. The predominant direction in mid Pegasus Bay is also to the south although here the magnitude increases to 1,629,000 $m^3.yr^{-1}$ as there are more oblique waves approaching the shore at this site. Net longshore transport in northern Pegasus Bay is to the north as this region is dominated by high energy southerly swells.

Aim Four also addresses the onshore/offshore exchange for the region. Each of the eight sectors were examined in order to establish the onshore/offshore exchange. Three of the eight sectors exhibited a net offshore movement of sediment while the other sectors experienced onshore movement of sediment. The overall result for all of Pegasus Bay was a net onshore movement of sediment of the order of $831,000m^3$ each year. The onshore/offshore transport accounts for 70% of the gross sediment budget. This signifies a very active part of the coastal system.

The calculated budget of Pegasus Bay reflects the state of the coastal system and in doing so fulfils Aim Five. It was found that all regions of Pegasus Bay were in sediment surplus with a net surplus for the bay of $5,843,000m^3.yr^{-1}$. However this does not coincide with recorded rates of shoreline movement such as accretion or erosion. Therefore material must be lost or stored elsewhere, not identified by this present analysis. The southern three sectors were determined to be in an equilibrium state. The Brooklands Spit, mid Pegasus Bay and Leithfield sectors are all in a depositional state while the two northern sectors are erosional. Although these findings do not match the net budget figures there is a strong correlation between the state of the beach and the net budget. A critical line has been drawn as a flip point about which a shore changes from erosionary to accretionary based on the status of the net budget. This line shows that the net budget can exhibit a sediment surplus and at the same time have an erosionary beach state. The amount of surplus in the particular cell determines the state of the shore. The net budget indicates that all beaches have a surplus of sediment that should therefore be reflected in an accretionary beach state. This is not the case for northern Pegasus Bay which has been found to be erosional. The surplus identified by the net budget is not sufficient to maintain a stable beach state. Any further decrease to the inputs will result in further erosion of the coastline. Only an increased supply of sediment will restore the pre-erosionary beach state.

The sediment budget model highlights the importance of the river input to the Pegasus Bay coastal system. River inputs constitute 55% of the net budget. A change in the input, particularly that of the Waimakariri which supplies 40% of the net budget, would have significant ramifications on the budget. The South Brighton Spit fluctuations since the river mouth shifted can in part be attributed to the decreased sediment supply to the open coast.

This sediment budget analysis was conducted in part as an attempt to create new knowledge about the Pegasus Bay region as a whole. It can be seen from the above that what has been presented here as a sediment budget for Pegasus Bay is a platform from which further research can be undertaken. With this platform a more precise sediment budget for Pegasus Bay can be calculated. The final results of this work have shown that despite the addition of information gained through this study of Pegasus Bay there is still a void in the knowledge of the sedimentary processes. The accuracy of this sediment budget has been hampered by a number of factors and the following summarises the necessary steps to derive greater accuracy.

The major anomaly of the sediment budget is the surplus sediment of the budget which is not reflected in the beach state. Profiling of the nearshore zone would give an indication of what is going on under the sea surface. It is quite possible that much of the surplus sediment of the budget is being stored offshore or lost from the system to deeper water. This type of profiling is normally difficult and subject to errors and so is not often carried out. Changes in the bottom surface would need to be carried out on a regular basis (monthly) to establish any rates of deposition or erosion within this zone.

The values that have been calculated for this budget could have been enhanced by more accurate and plentiful data. Foremost is the longshore component of the sediment budget. The accuracy of this component is limited by the wave observations that it is based on. The problem however is not just confined to the wave data that has been collected but also to a lack of more comprehensive records. Daily records of wave observations at several sites along the Pegasus Bay coastline (particularly at the transition between cells) could then be used to obtain the longshore component for each of the cells in this budget. Some uniformity between the records at each site is also of importance.

The river inputs into the Pegasus Bay coastal system are based on 1985 data. This is the most recent data source for the region and yet several changes in the hydrological regime may have occurred since then. This is particularly true for the northern section of the bay and may account for the erosion despite it being in apparent sediment surplus.

Abrasion of sediment has not been widely researched and even less so in the Pegasus Bay region. Particles that spend a long time in the coastal system are worn such that their size diminishes to less than 4ϕ. These particles are then lost from the system via wind inland or suspension offshore. The quantity of sediment lost from the system each year through these mechanisms is not known. Such an investigation would be an appropriate input to the model.

A combination of the above mentioned research problems and the data that is presented here would lead to a comprehensive sediment budget of Pegasus Bay. This study has provided the basis from which other studies can develop.

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Appendix One

Wave and Wind Observation Recording Sheet Instructions

TIME

(a) Record time to the nearest quarter-hour at which the obserbation is make.

(b) Use the 24-hour clock system to avoid confusion between a.m. and p.m. (e.g. 2.00a.m. is 0200, 1.00p.m. is 1300, and 3.15p.m. is 1515).

(c) Use NZST, hence during daylight saving 1-hour must be subtracted from actual time to get NZST.

NEAREST TIDE

(a) Record whether the nearest tide is high (H) or low (L).

(b) Record time to nearest tide to the nearest half-hour (e.g. 2.5hr).

(c) Record whether tide is rising or falling.

WAVE HEIGHT

This observation of based solely on the judgement of the observer.

(a) Mean: Estimate the average breaking wave height to the nearest 0.25 metre.

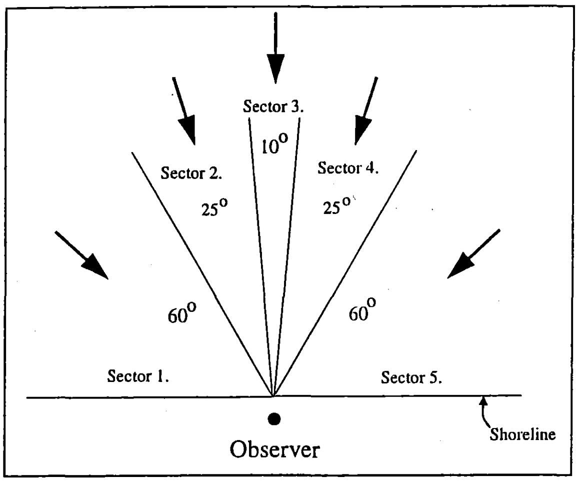
(b) Max: Estimate the highest breaking wave height to the nearest 0.25 metre.

WAVE PERIOD

This is the average time period between waves arriving at the shore. Record both the number of waves arriving during a time interval of greater than 1 minute, and the total time period in seconds, (e.g. 8 waves in 65 seconds). Note that must start and stop timing on a wave, with the initial one being wave zero.

WAVE ANGLE

Record whether the wave is ARRIVING from 1, 2, 3, 4 or 5 as shown in diagram below.



BREAKER TYPE

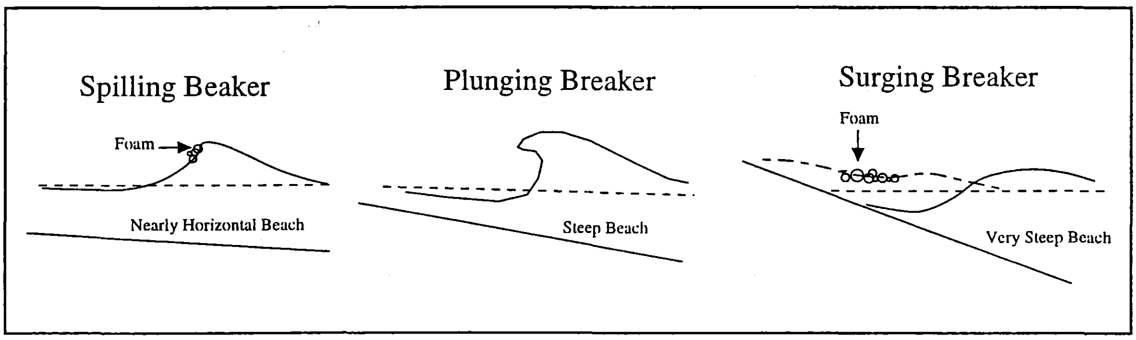
Circle one of the following 4 types of breakers (see diagram for help)

(a) Spilling (Sp): occurs when the wave crest becomes unstable and flows down the front face of the wave, producing an irregular foamy water surface. Often happens in large seas and with strong winds blowing off the sea. These waves are sometimes referred to as "rollers".

(b) Plunging (Pl): occurs when the wave crest curls over the front face of the wave and falls into the base of the wave, producing a high splash and much foam. This wave is sometimes referred to as a "Dumper".

(c) Plunging/Spilling (Ps): occurs when there is a combination of spilling and plunging waves.

(d) Surging (Su): occurs when the wave crest remains unbroken while the base of the front of the wave advances up the beach.



NUMBER OF BREAKERS

Record the number of rows of breakers e.g. in normal conditions there would be one, in storms there may be several.

RUN - UP WIDTH

This observation is based on the judgement of the observer.

(a) Estimate the distance, to the nearest metre, from the most landward row of breakers to the position where waves stop running up the beach.

(b) Record whether the run-up position is to the; lower foreshore (LF), mid foreshore (MF), upper foreshore (UF), dune toe (DT).

WIND

(a) Speed: estimate from accompanying chart.

(b) Direction: estimate from direction of beach orientation.

WIND FORCE (Beaufort Scale)

No.	Wind	Effect on Land	km/hr
0	Calm	Smoke rises vertically	<1
1	Light air	Direction shown by smoke but not by wind vanes	1-5
2	Light Breeze	Wind felt on face; leaves rustle; wind vanes move	6-11
3	Gentle Breeze	Leaves and twigs in motion; wind extends light flags	12-19
4	Moderate Breeze	Raises dust, loose paper and small branches	20-28
5	Fresh Breeze	Small trees in leaf begin to sway	29-38
6	Strong Breeze	Large branches in motion; whistling in telegraph wires; difficulty with umbrellas	39-49
7	Near Gale	Whole trees in motion; difficult to walk against wind	50-61
8	Gale	Twigs break off trees; progress impeded	62-47
9	Strong Gale	Slight structural damage occurs; chimney pots and slates blown off	75-88
10	Storm	Trees uprooted and considerable structural damage	89-102
11	Violent Storm	Widespread damage	103-117
12	Hurricane	Winds of this force only encountered in tropical revolving storms	above 117

Appendix Two
Site Descriptions

Each profile is measured as a distance from Sumner Head and are to the north of this locale. This number is displayed adjacent to the profile name.

South of Pukeko Street 3.00km
This profile is situated at the end of Rocking Horse on the South Brighton Spit to the south of Pukeko Street. The benchmark is a terrier located on the curb approximately 150m from the dune edge. A house is sited to the north of the profile but to the south of the profile is uninhabited.

Plover Street 3.96km
The benchmark for the Plover Street profile is located at the intersection of Rocking Horse Road and Plover Street. The profile extends through a playground behind the dune system.

Caspian Street 5.13km
This profile is at the distal end of the South Brighton Spit at the junction of Marine Parade and Caspian Street. The benchmark is located in the middle of Caspian Street some 75m from the dune fences which the profile encompasses.

Beatty Street 6.50km
The benchmark for the Beatty Street profile is located on the northern footpath of Beatty Street. The profile extends through the dune system where a series of fences is apparent.

North of Rodney Street 8.15km
This profile is located outside house no.264 of Marine Parade. The benchmark is located on the footpath in front of a fire hydrant marker. The dunes of this profile are backed by Marine Parade.

Rawiti Street 9.52km

The Rawiti Street profile benchmark is situated at the intersection of Marine Parade and Rawiti Street. The dunes are backed by Marine Parade

Larnach Street 11.30km

Larnach Street profile is located north of the Waimariri Beach surf club. The dune system is more extensive and the benchmark is a tanalized post adjacent to a car parking area.

South of Bottle Lake 14.00km

This profile is located at the south end of the Bottle Lake Forest Park. The profile benchmark is located in the dune system and is a tanalized post over a pipe.

Heyders Road 17.55km

The Heyders Road profile is located to the north of Heyders Road. The benchmark is an iron tube located in the dune system and crosses across a fence at the base of the dune.

Brooklands C1891 18.91km

This profile is located on Brooklands Spit. The benchmark is and iron tube behind the dune system. A tanalized post is located 50m from this in the dune system.

Brooklands C1972 19.72km

An iron pipe marks the benchmark behind the dunes at this profile site on Brooklands Spit. A tanalized post 37m from the benchmark is located in the dunes and is clearly visible from the beach.

Brooklands C2070 20.70km

This is the last profile section on Brooklands Spit. It is adjacent to a dune blowout. The benchmark is a pipe behind the dune system 91m from the tanalized post in the dunes.

Pines Beach 23.00km

The Pines Beach Profile is to the north of the Waimakariri River. The benchmark is the floor level of the Pines Beach surf club house. There is a carpark behind the surf club.

Woodend Beach 27.55km

A camping ground exists behind the dunes of this profile. The benchmark is a waratah between the camping ground and the sand dunes. An access track crosses the profile at the landward dune edge. A surf life saving lookout is located on the beach.

Waikuku Beach 33.40km

The benchmark for the Waikuku Beach profile is the floor level of the Waikuku Beach surf life saving club house. There is a parking area behind the club house.

Ashworths 39.80km

The benchmark for this profile is a railway iron 13m from the dunes and just seaward of a four wheel drive track. The profile is south of the main access track.

South Leithfield 41.19km

This profile is marked by pink fluorescent stakes to the south of the Leithfield Beach settlement. A four wheel drive track behind the dunes crosses the profile cross section.

Leithfield Beach 42.00km

The Leithfield Beach profile is backed by the settlement's camping ground. A corrugated iron fence is the benchmark and the profile extends out to the beach to the north of a water tank.

Kowai River 44.22km

Adjacent to the true right bank of the Kowai River is the Kowai River profile. The benchmark is the corner post of a fence and the site is north of a four wheel drive track that leads to Leithfield Beach settlement.

Newcombes Road 44.50km

The Newcombes Road profile is situated through the farming property at the end of Newcombes Road. This site is marked by two fluorescent stakes in the gravel ridge.

Amberley Beach 46.82km

South of the Amberley Beach Carpark lies the Amberley Beach profile. The benchmark is a red and white post which stretches across the artificial gravel ridge to the second red and white post.

Amberley Golf Club 48.59km

This profile site is seaward of the Amberley Golf Course Club House. The corner post of the Golf Club's fence is the benchmark of the profile. It extends to a red and white post located behind the gravel ridge.

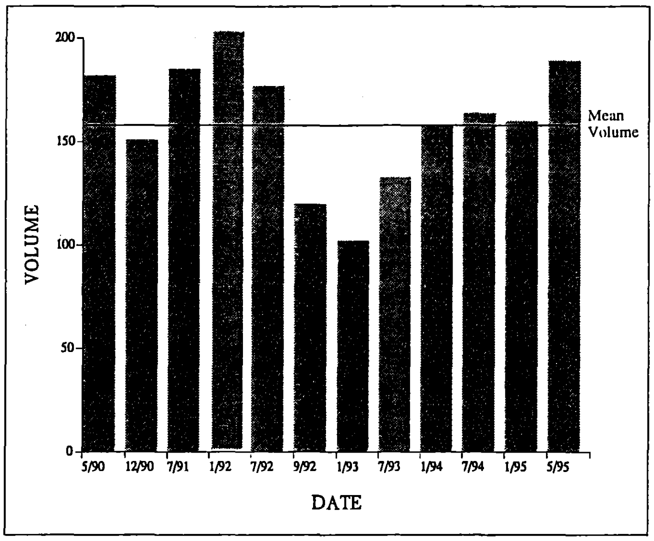
Teviotdale 51.25km

North of the Waipara River is the Teviotdale profile. A red and white post is situated seaward of the concrete benchmark located behind the gravel ridge.

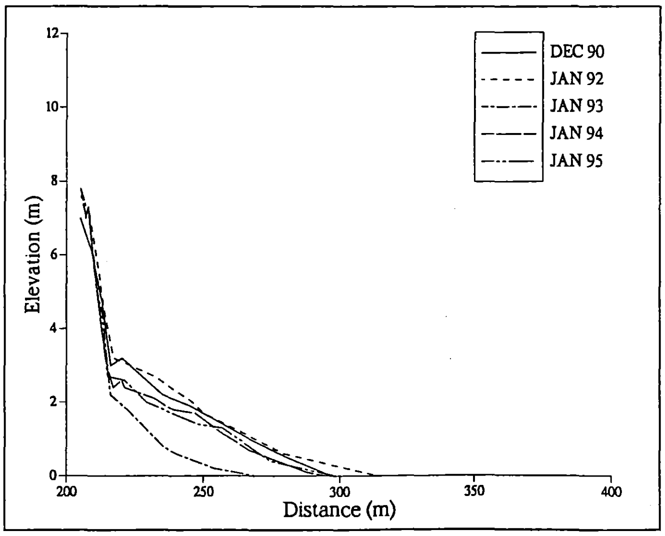
Double Corner 52.50km

The most northern profile is located to the south of the cliffs of Double Corner. Two fluorescent stakes define the profile which runs to the north of the four wheel drive track which extends from the Waipara River to the end of the bay.

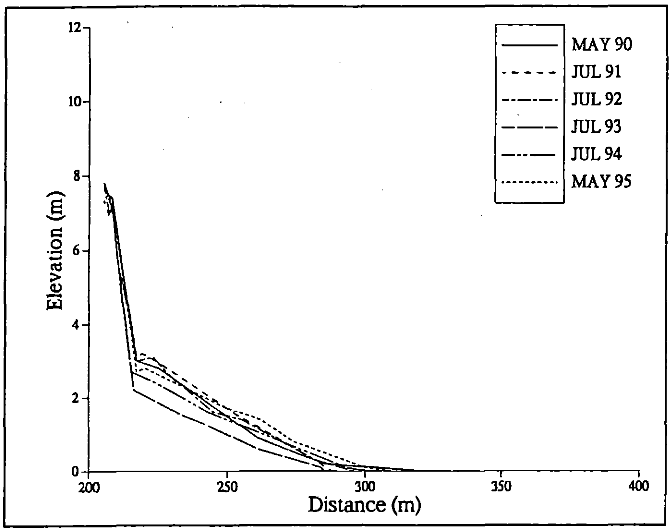
Appendix Three
Beach Profiles and Volumes



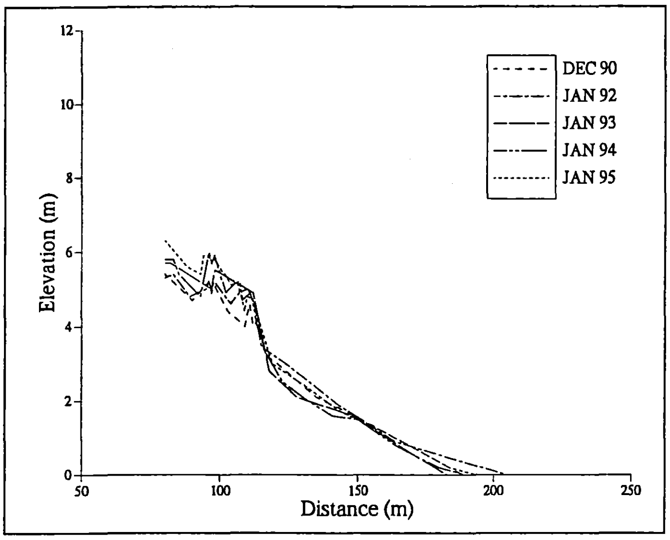
Beach volumes at Plover Street



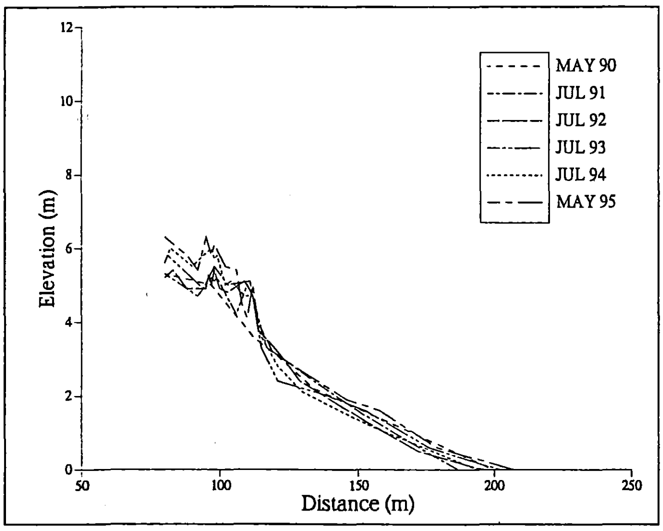
Summer beach profiles at Plover Street



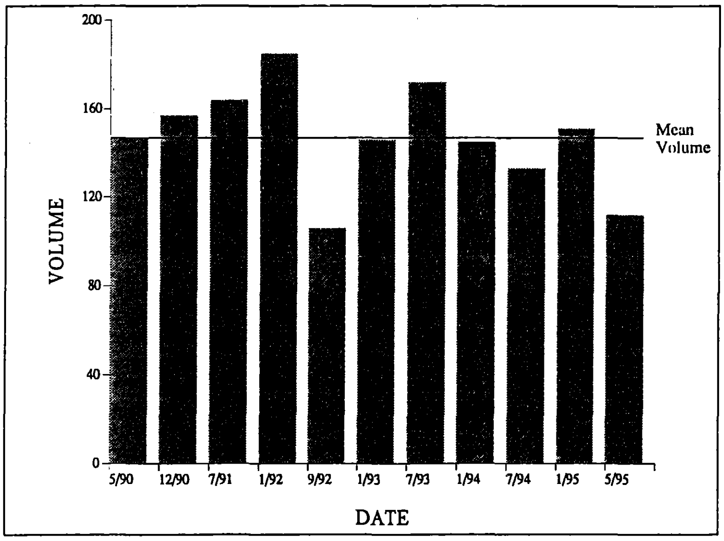
Winter Beach Profiles at Plover Street



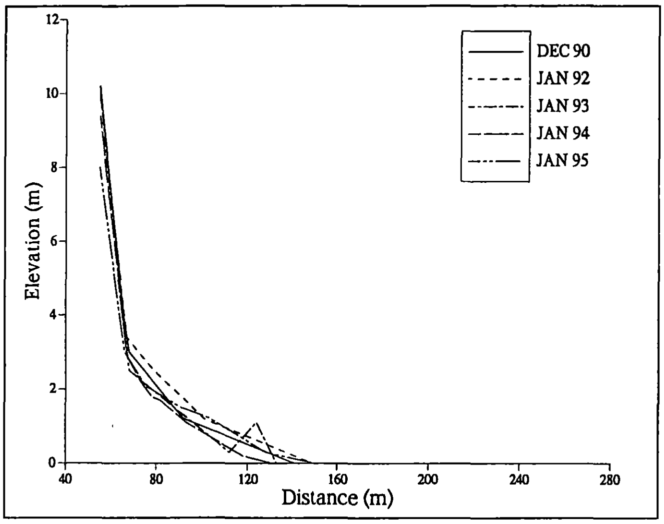
Summer Beach Profiles at Caspian Street



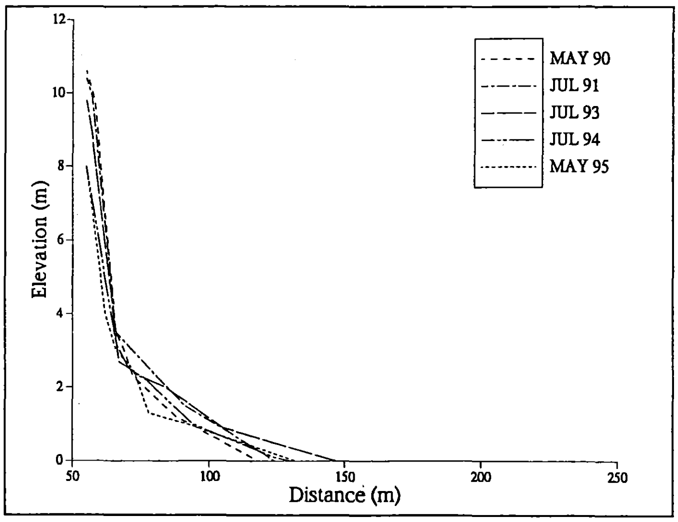
Winter Beach Profiles at Caspian Street



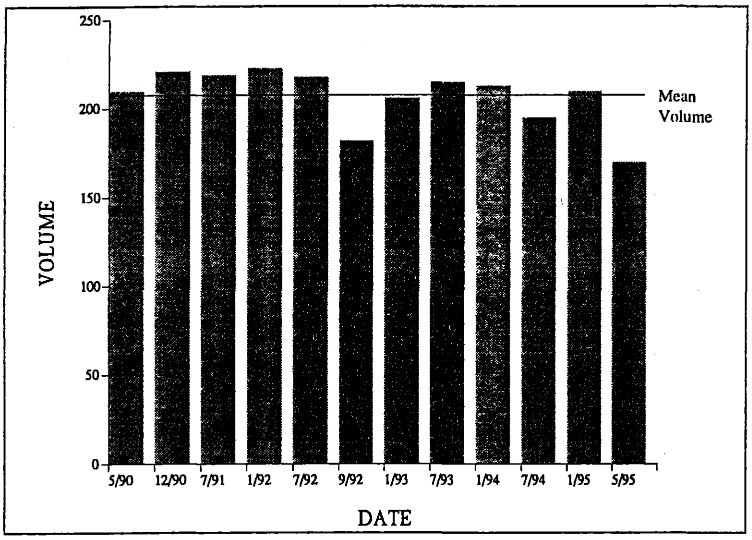
Beach Profile Volumes for North of Rodney Street



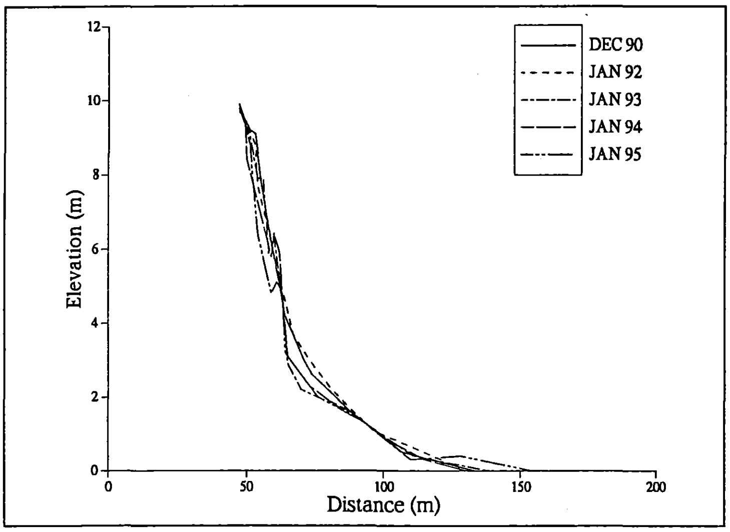
Summer Beach Profiles at North of Rodney Street



Winter Beach Profiles at North of Rodney Street



Beach Profile Volumes at Rawiti Street



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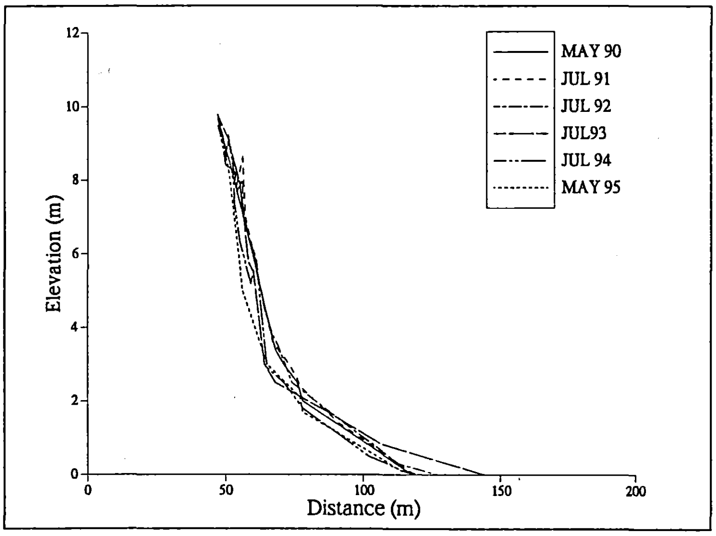
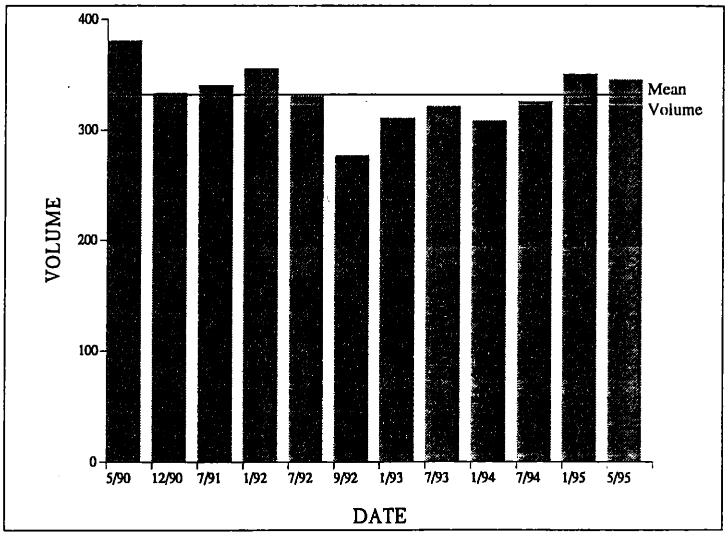
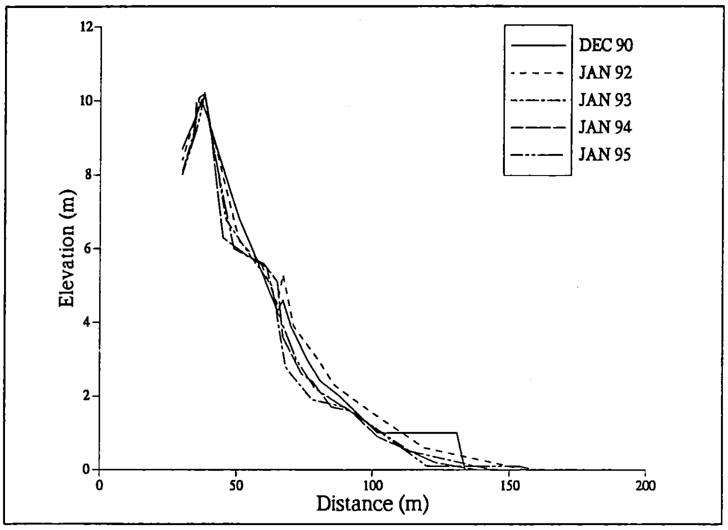


Winter Beach Profiles at Rawiti Street



Beach Profile Volumes for Larnach Street



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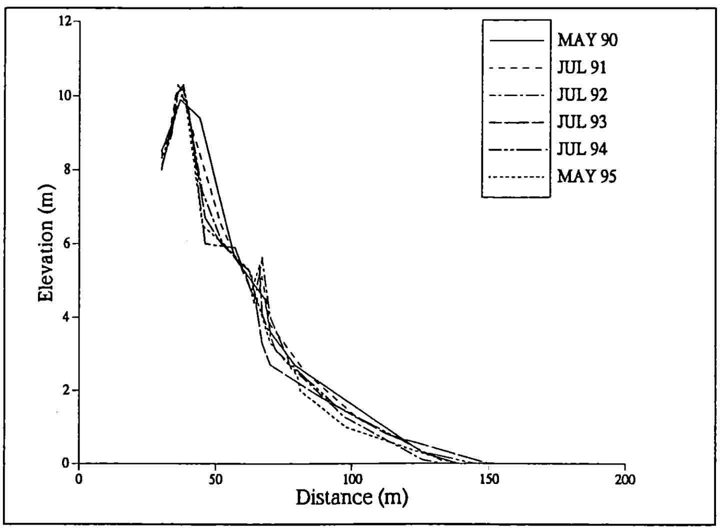
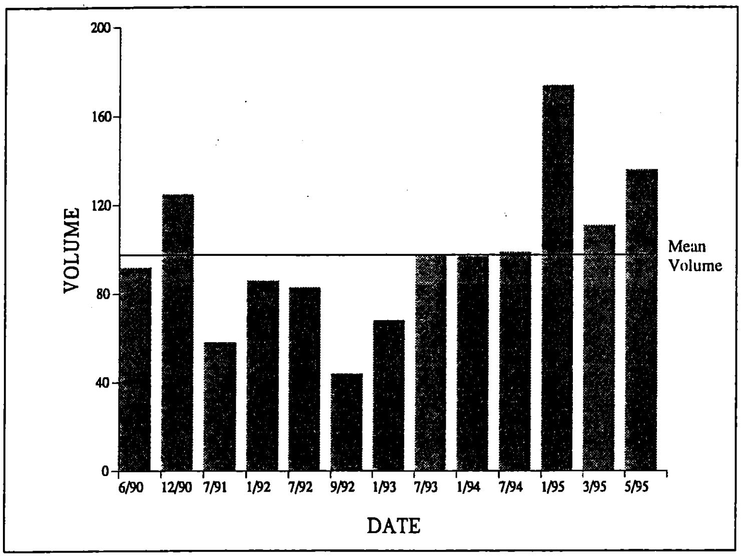
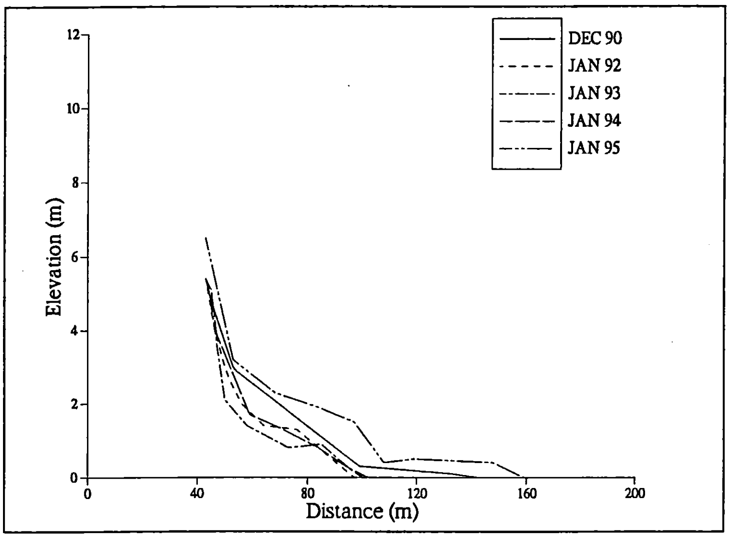


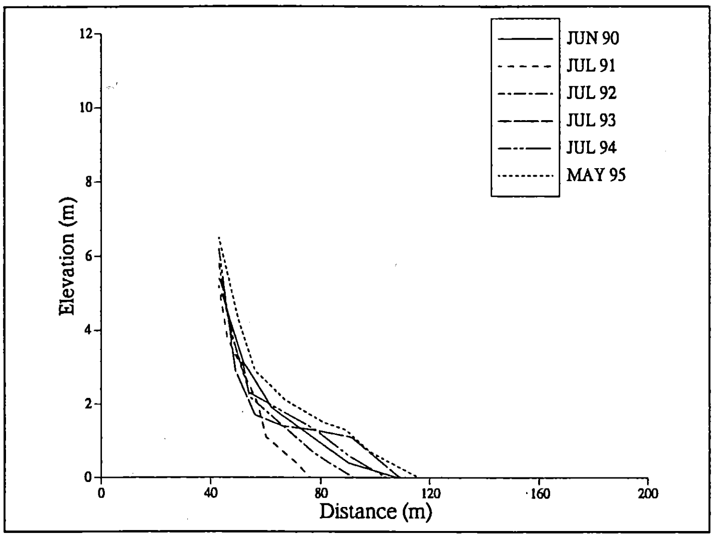
Winter Beach Profiles at Larnach Street



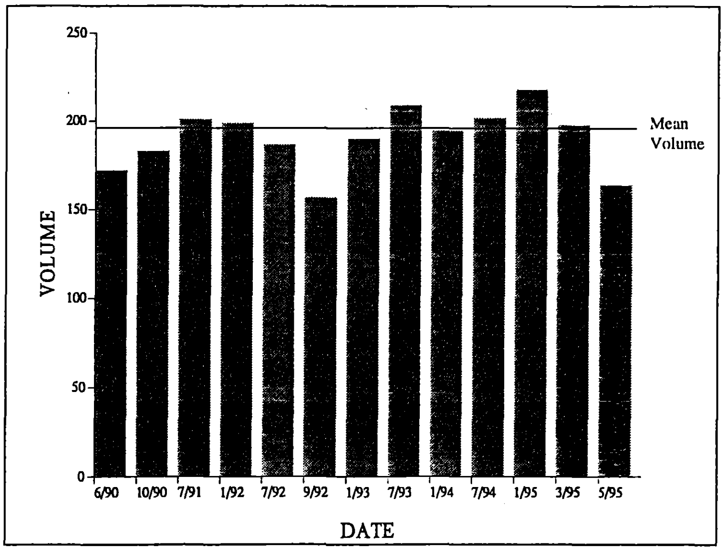
Beach Profile Volumes for C1972



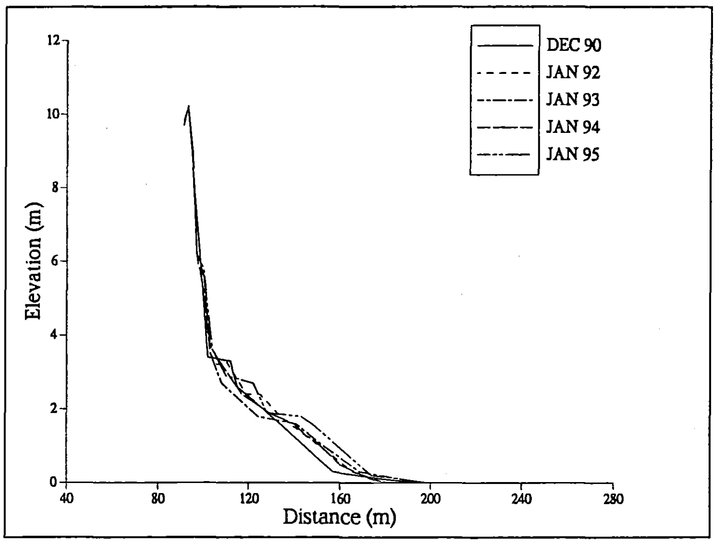
Summer Beach Profiles at C1972



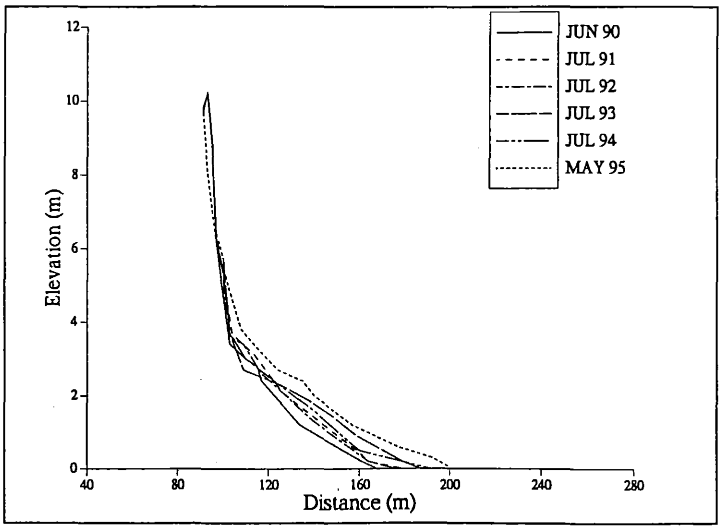
Winter Beach Profiles at C1972



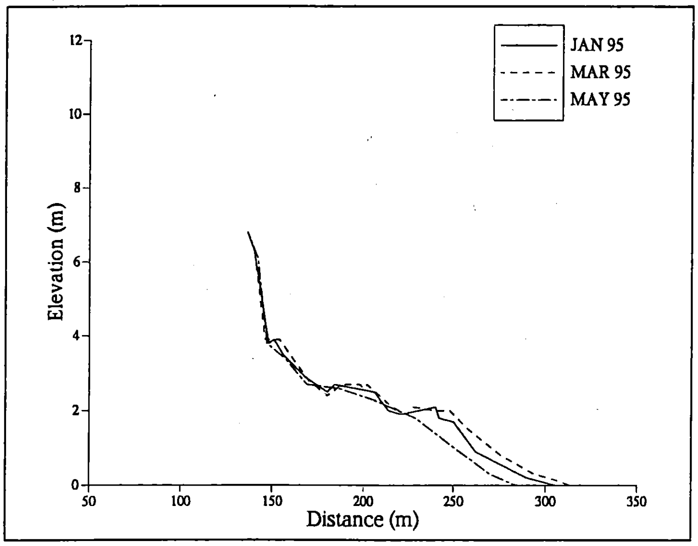
Beach Profile Volumes for C2070



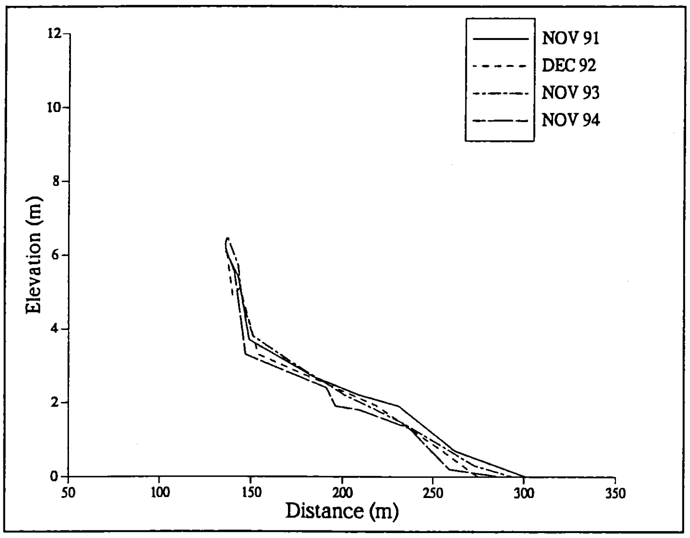
Summer Beach Profiles at C2070



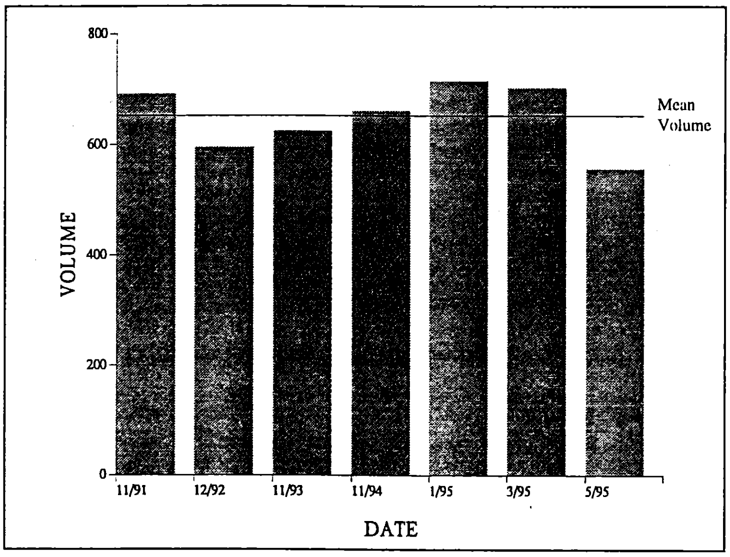
Winter Beach Profiles at C2070



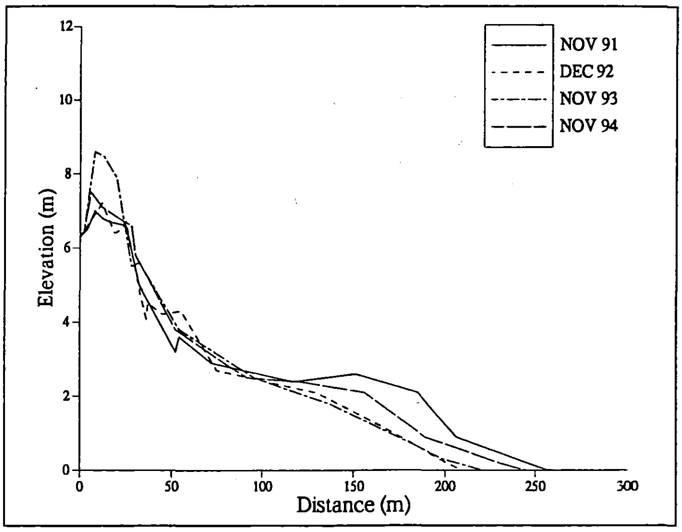
1995 Beach Profiles at Woodend Beach



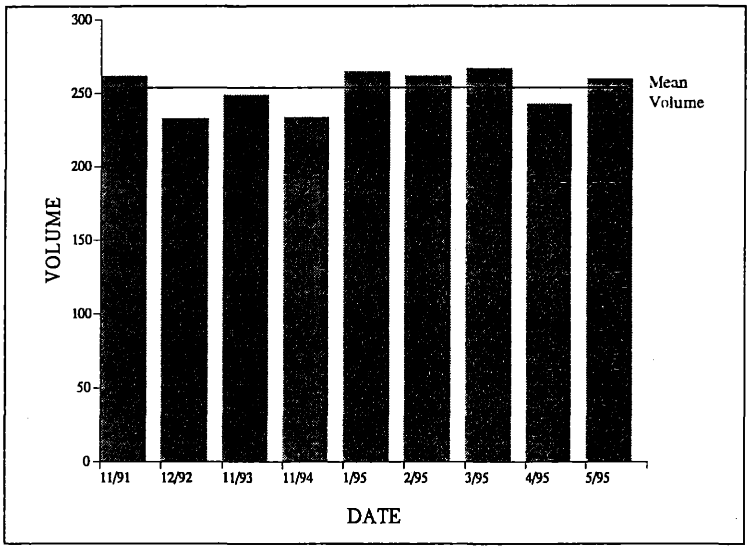
Past Beach Profiles at Woodend Beach



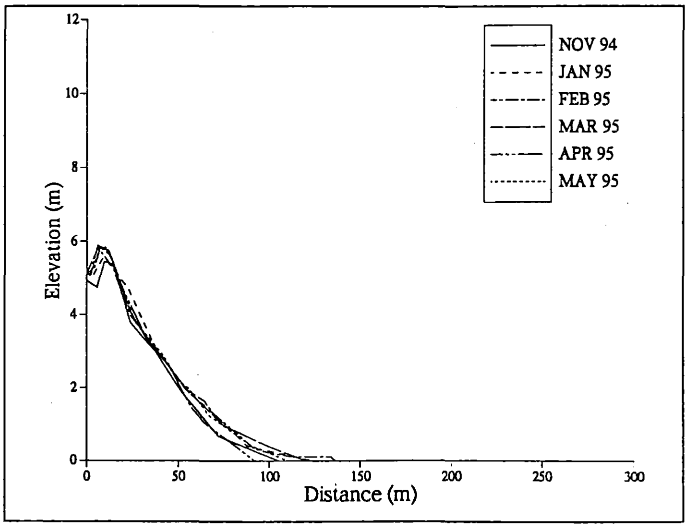
Beach Profile Volumes for Pines Beach



Past Beach Profiles at Pines Beach



Beach Profile Volumes for Waikuku Beach



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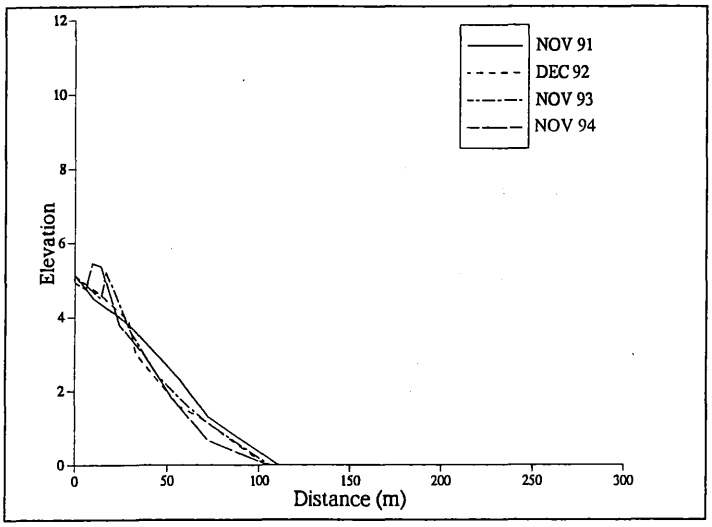
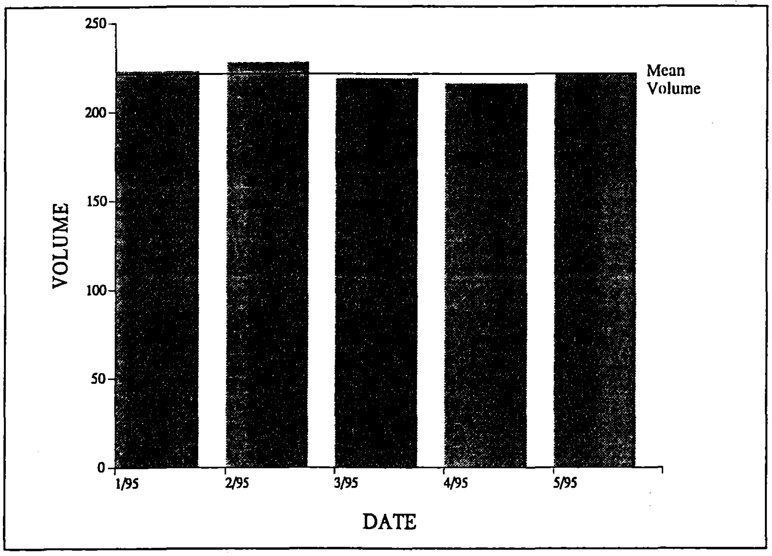
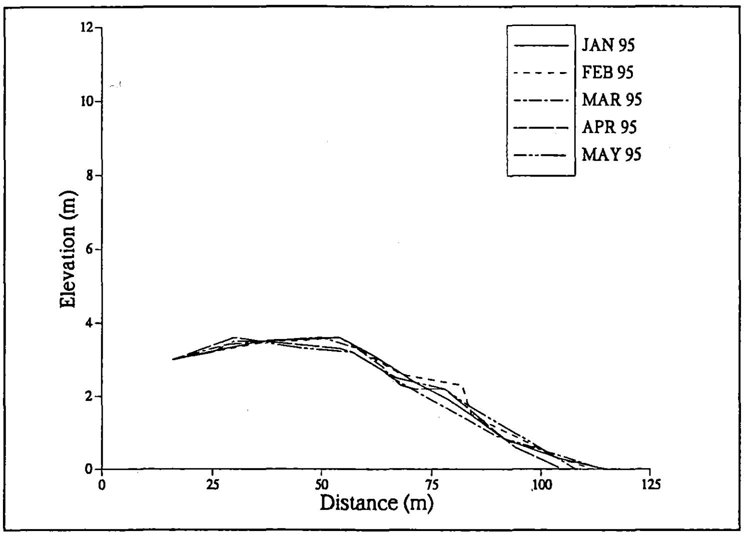


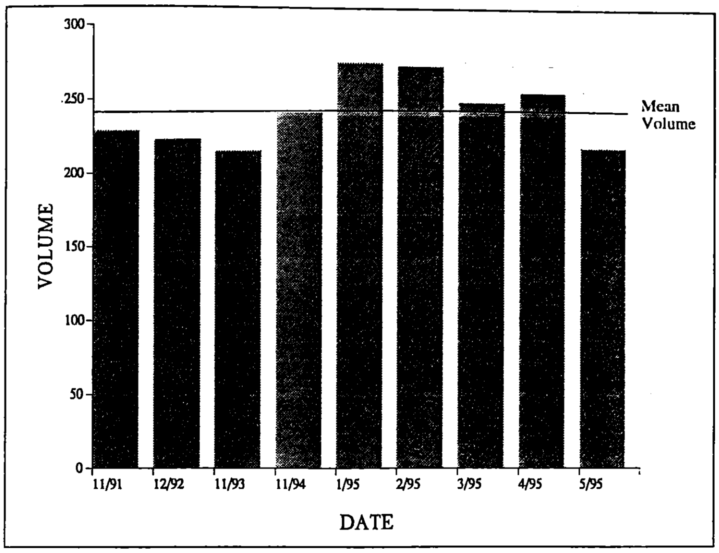
Past Beach Profiles at Waikuku Beach



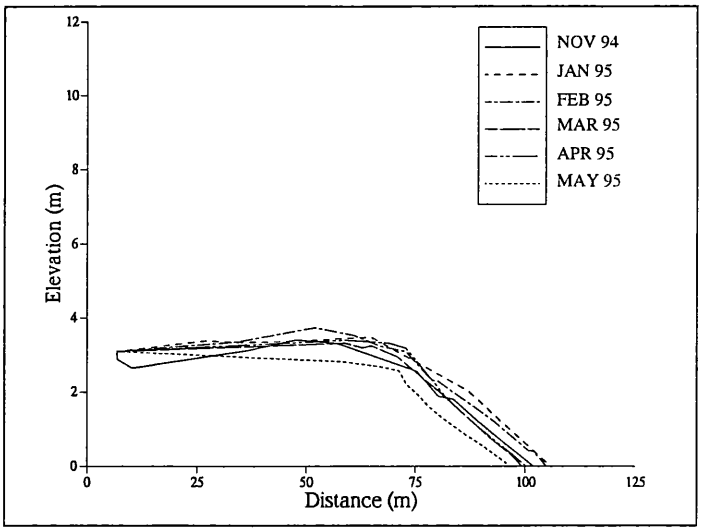
Beach Profile Volumes for South Leithfield



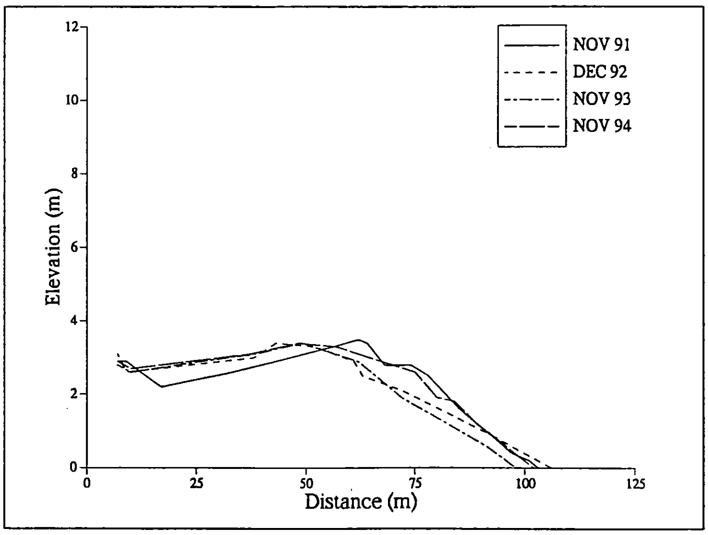
1995 Beach Profiles at South Leithfield



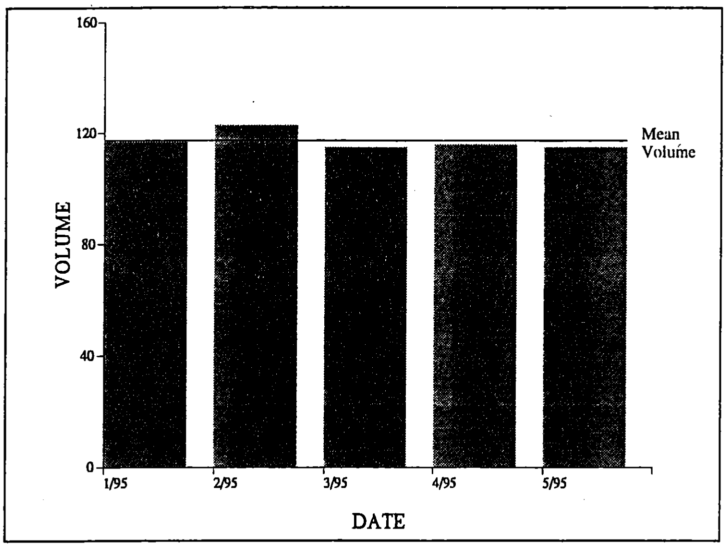
Beach Profile Volumes for Kowai River



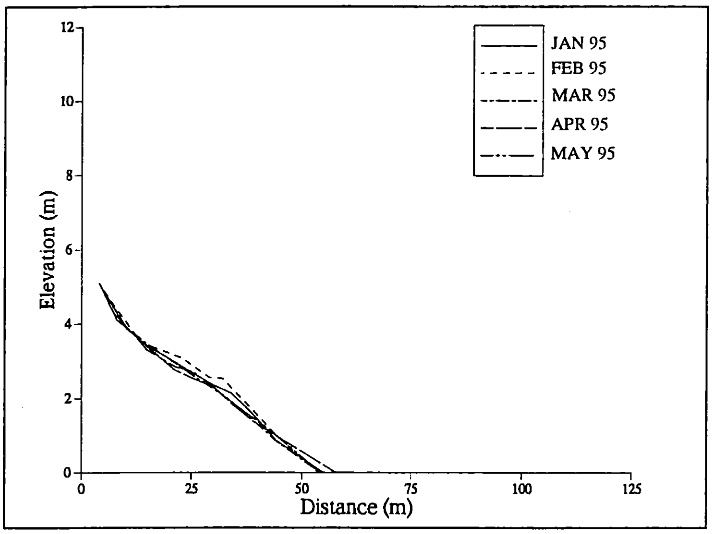
1995 Beach Profiles at Kowai River



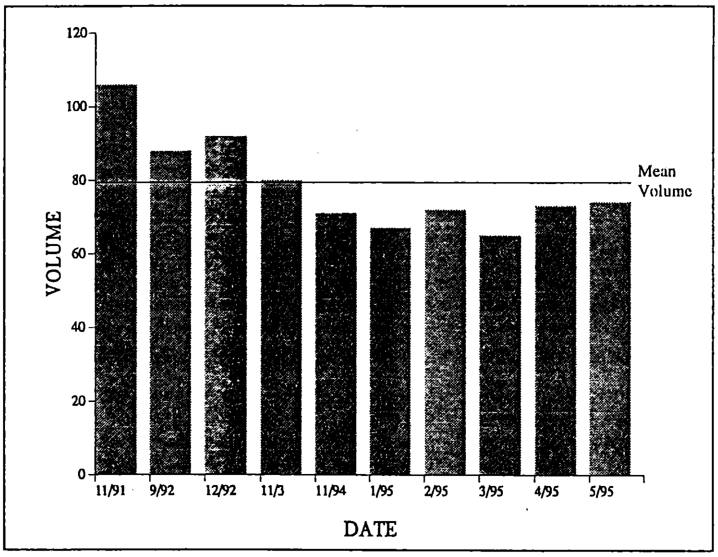
Past Beach Profiles at Kowai River



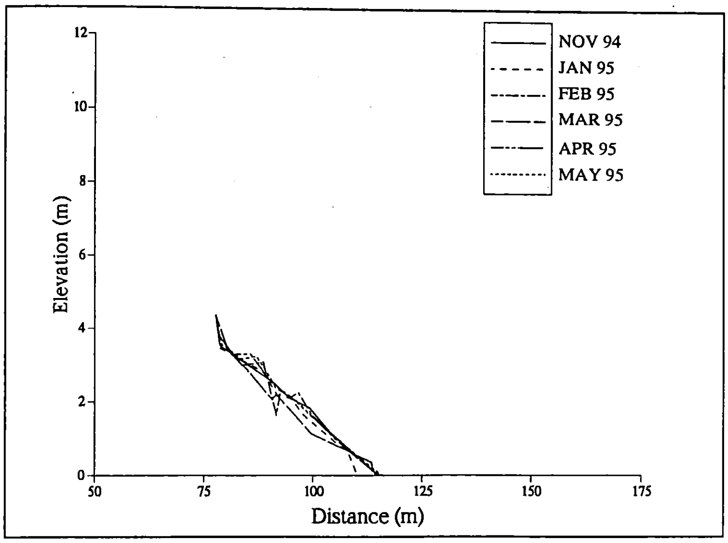
Beach Profile Volumes for Newcombes Road



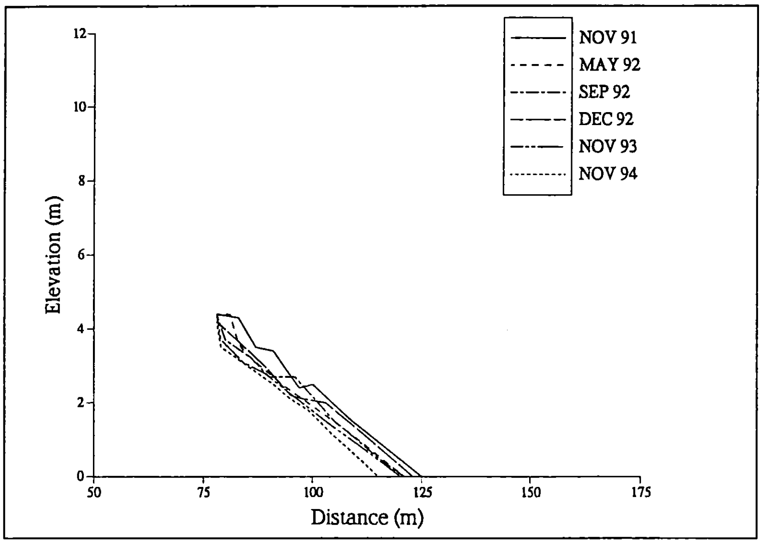
1995 Beach Profiles at Newcombes Road



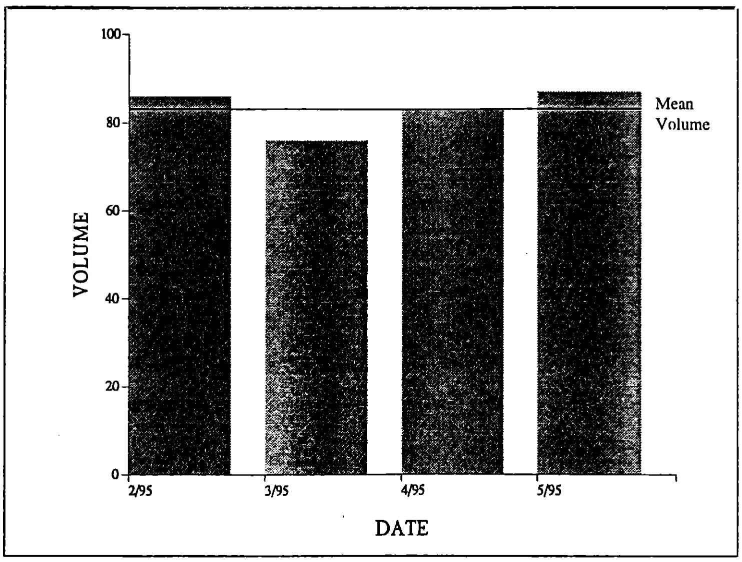
Beach Profile Volumes for Amberley Golf Club



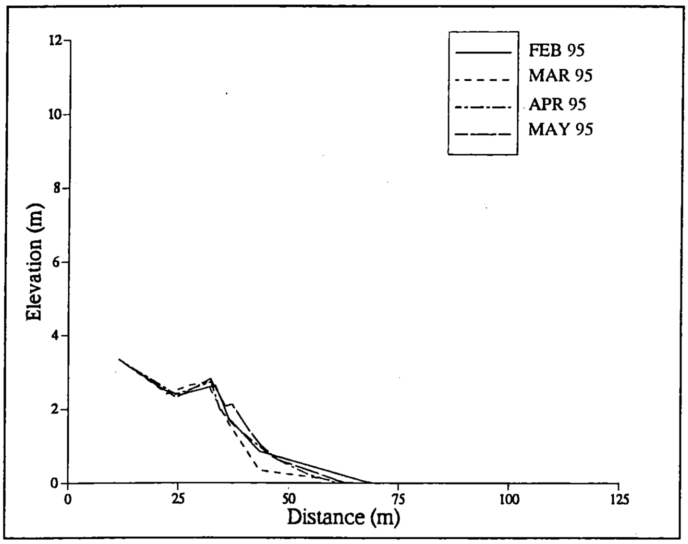
1995 Beach Profiles at Amberley Golf Club



Past Beach Profiles at Amberley Golf Club



Beach Profile Volumes for Double Corner



1995 Beach Profiles at Double Corner