SUBAERIAL BEACH PROFILE BEHAVIOUR

William Hall

"Thesis submitted in fulfilment of the requirements for the degree of Master of Science, University of Sydney, 1988"
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Abstract

Long time series of beach profiles from Moruya and Narrabeen beaches, New South Wales were analysed to determine both the shapes which profiles will adopt under varying circumstances and when such changes will occur. Time series analysis determined that beneath secular trends and short term fluctuations there exists a regionally distinct low frequency beach response. Attempts to relate this response to wave data generally proved unsuccessful because of problems identified in the data design. Results indicated that the natural subaerial beach shape can be classified based upon long term profile behaviour. Secondary convex morphologies were identified as distinct from the observed primary concave profile. The two datasets represent a total of 1852 surveyed profiles. This study represents the necessary first step towards the quantitative evaluation of the several processes contributing to beach change.
I would like to sincerely thank Professor Bruce Thom for his guidance throughout this study particularly for his comments in the final drafting and for the use of the Moruya dataset.

Many thanks to my companions in the department Michael Hughes and David Hanslow without whom motivation would have been lost. Thanks also to Dr. Andy Short for the use of the Narrabeen dataset.

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List of Notation

ACF  Autocorrelation function
ADP  Accretion Dominated Period
AHD  Australian Height Datum
ANOVA Analysis of Variance
AR   Autoregressive
ARMA Mixed Autoregressive Moving Average
ARIMA Autoregressive Integrated Moving Average
CSA  Cross Spectral Analysis
C_w Deep water wave group phase speed m/s
C_o Deep water phase speed m/s = gT_o/2π
EDP  Erosion Dominated Period
FFT  Fast Fourier Transform
g  9.80665 m/s² gravity
H_o Deep water wave height
ISLW Indian Spring Low Water
MA   Moving Average model
N   Number of observations in a series
N(μ,σ²) A normally distributed random variable, mean μ, variance σ
PACF Partial Autocorrelation Function
P_o Deep water wave power (watts/cm x 10⁴)
p  1.027 g/cm³ density of sea water
π  3.1412 constant
r   Correlation coefficient
SDF  Spectral Density Function
T_o Deep water wave period
TSA  Time series analysis
X_e Set of discrete variables
Z_e Purely random process
V   Difference operator such that VX_e=X_e-X_e-1
1. Introduction

1.1 Beach Profile Behaviour

Proper management of coastal resources demands a detailed understanding of beach behaviour particularly in view of reports of widespread coastal erosion (Bryant, 1983; Vellinga, 1986; Douglas and Weggel, 1987). The beach is merely the active and visible part of the shoreface; consequently the processes which determine beach behaviour are not confined to the immediate vicinity of the subaerial beach which in most cases represents only the upper part of a much larger and more extensive system (Short and Wright, 1981). Regardless of this, the most immediate threat to coastal protection is manifest as subaerial beach cut.

Although the literature often use the term beach to refer to a much wider zone of context, this study is concerned with the subaerial beach, which is herein defined as the zone of unconsolidated sediment that extends from the uppermost limit of wave action to the low-tide mark. At the landward limit there is commonly an abrupt change in gradient and/or composition and the presence of permanent vegetation which may be in the form of established vegetated dunes, bedrock or man-made structures. Beyond the subaerial beach in a seaward direction is the inshore zone which normally extends across the bar and trough topography and is characterised as the zone of wave breaking and rapid energy dissipation. Although these zones are intimately related they are separated in the context of this study because of the markedly different processes to which each is subjected (figure 1.1).

Beaches have been the focus of immense scientific interest because of their immediate accessibility, observed variability, and intrinsic connection to much wider dynamic coastal environments. The beachface is the location of the final energy dissipation of waves. The beach gradient and configuration both influence and is influenced by the amount of energy imparted on the beach;
Figure 1.1  Definition diagram for beach morphology
processes and responses in the swash zone are directly linked with topography (Wright and Thom, 1977).

The natural beach may exhibit short-term dynamic equilibrium while long-term erosion or accretion may be occurring. Changes can occur at many different time scales. The changes to which beaches are subjected may be seasonal or longer in duration, they may be as short as a single tidal cycle or even occur from one breaking wave to the next. The beach profile is significant as an effective natural mechanism which responds to and causes wave instability, breaking and energy dissipation. The beach serves as an ever changing buffer protecting the coastal zone.

If over a given time period there results an excess of sediment removal over supply within a specified beach segment the beach will become increasingly less capable of serving as a buffer and coastal erosion will become increasingly more probable. Thom (1974) has suggested that coastal erosion in eastern Australia is a basic geological process associated with changes in sea-level, sediment supply and wave-climate. A general lack of sediment availability for beach and foredune construction and superimposed human activities have accentuated coastal erosion in many localities over the past 3000 or so years (Bird, 1976). Shoreline fluctuations on the central and south coast of New South Wales have been attributed to a long-term net loss of sediment from the active zone of the coastal system (Thom, 1974; Davies, 1974; Gordon et al., 1978; Jones et al., 1979) and to infrequent storm wave activity (Stockwell, 1969; Thom et al., 1973; McLean and Thom., 1975; Wright, 1976; Short, 1978, 1980).

Beach changes can involve changes in beach volume and/or beach configuration. In studies of beach and surfzone equilibria and responsiveness, Wright et al., 1984 observed that rates and directions of beach response were governed not only by the short-term history of wave and beach sediment characteristics but also by antecedent beach state. However in the long-term (> 1
the cycling of sediment between the inner shelf, in particular the shoreface zone (figure 1.1), and the surfzone added a further complexity to attempts to gain short-term predictability. Beach changes have been observed at many different frequencies both in Australia and elsewhere and can involve changes in beach volume, beach state or both (Komar, 1976).

Recent studies of the beach and nearshore have emphasised the relationship between wave energy levels and accompanying surfzone dynamics and the observed resultant beach and surfzone morphology (Homma and Sonu, 1962; Guza and Inman, 1975; Sasaki and Horikawa, 1975, 1979; Short, 1978, 1979, 1980; Wright et al., 1979; Wright, 1981).

Work in Australia, particularly by Wright and others (Wright et al., 1979; Wright, 1982; Short and Hesp, 1982) have successfully developed and applied process-response mechanisms in the beach and nearshore zone. This work has involved a classification of beach types as dissipative and reflective with several morphologic varieties in a sequence from one to the other. Associated with each beach type are characteristic levels of beach and backshore mobility, beach form and zones of sediment storage.

Wright and Short (1984) have determined that the morphology of a beach at any particular time is a function of its sediment characteristics, immediate and antecedent wave, tide and wind conditions and the antecedent beach state. Temporal and spatial differences in beach volume and configuration can be dramatic. They vary in time with changing wave conditions; both the average (modal) and range of temporal variations vary spatially with environmental conditions. This is illustrated by their examination of long-term records of surveys of different beaches with contrasting local environmental conditions. These data sets provide for empirical-statistical assessment of beach mobility, direction of change and response to environmental conditions. Such studies have been reported by Eliot et
Eliot et al.,(1982) and Eliot and Clarke(1982a) have noted that long-term trends and short-term fluctuations, related to sediment losses and storm activity respectively, are superimposed on periodic shoreline fluctuations. These occur in response to regular shifts in mean sea level (Radok,1976; Thom and Roy,1988) and wave climate (Davies,1957; McKenzie,1958; Foster et al.,1963; Read,1964; Short,1980).

Examination of beach survey data provides information on the magnitude, frequency and nature of beach changes. Survey data can therefore serve as a baseline or framework from which the relative severity and impact of any storm can be assessed.

1.2 Objectives of thesis

A monitoring programme has been in operation on the Moruya Heads-Broulee beach since January, 1972 (Thom et al., 1973) and on the Narrabeen-Collaroy beach since April, 1976 (Short,1980). During this period considerable changes have occurred on most NSW open ocean beaches (Thom and Roy,1988). The continuous beach survey records form a time-series which characterise the dimensions, frequencies and nature of beach profile changes observed. This information serves as a basis for the assessment of impact which different types of processes have on the subaerial beach.

A comprehensive analysis of all profile data has not previously been undertaken. While considerable advances have been made in the study of theoretical and empirical relations between beach processes and responses, little information is available concerning the long-term temporal behaviour of the subaerial beach. Still less information is available to define subaerial beach geometry beyond the purely descriptive.
This study aims primarily to undertake the following:

(i) To determine temporal components and patterns of beach profile oscillation which is indexed by the volume of sediment stored in the subaerial beach.

(ii) To classify profile shape for the subaerial beach using volume and beach width relationships and volume disposition indices.

(iii) To attempt to relate profile shape and wave power indices.

(iv) To use the findings in the development of an understanding of beach change patterns over time scales in excess of one year.

The study aims can be grouped into the provision of a detailed account of beach change including an examination of the sediment budget of the subaerial beach as well as the development of an understanding of sediment movements both normal and parallel to the shoreline.

It is not the purpose of this study to examine the mechanics of individual processes or their interaction in determining beach profile configurations.

1.3 Literature Review

Beach profile changes involve sediment exchanges between the subaerial and inshore zones. The literature on beach profiles is voluminous. Early work in Australia includes the first scientific discussion of beaches by Andrews (1912,1916) and contributions by McKenzie (1958), Foster et al., (1963), and Thom et al.,1973. Areas of concern include beach morphology, hydrodynamics and sediment transport. These aspects of beach profiles have been further examined by studies of causality and by descriptive and predictive modelling.

Beach profiles have long been observed to change both in terms of volume and configuration. The literature
on causes of changes in beach profiles tends to be divided upon the criteria of underlying frequencies of oscillation of subaerial beach sediment volume and form. Some of the first detailed analyses of beach cycles were performed by Shepard (1950).

Beach fluctuations in the long-term have been attributed to a long-term net loss of sediment from the active zone of the coastal system (Thom, 1974; Davies, 1974; Gordon et al., 1978; Jones et al., 1979). In the short time frame fluctuations are due to infrequent storm wave activity (Stockwell, 1969; Thom et al., 1973; McLean and Thom, 1975; Wright, 1976; Short, 1978, 1980), edge waves (Guza and Inman, 1975) and to the migration of rip current and cusp dominant features along the shore. Ziegler et al., (1959) working in the U.S found that storms caused rapid changes in beach volume and topography. Ziegler concluded that post storm profiles were either planar or concave upward while during quiescent periods they were convex upward. Later, Fox and Davis (1976) and Dolan and Hayden (1981) found similar responses in coastal systems to atmospheric (storm) processes. The concept of edge waves as morphologic agents has been investigated by many researchers (Dalrymple, 1975; Bowen and Inman, 1971; Guza and Inman, 1975; Dolan et al., 1979). Edge waves are normal trapped modes of longshore periodic wave motions and are a proposed cause of rhythmic topography. Guza and Inman (1975) found that edge wave resonances theoretically predicted and observed were not visible on the beachface during plunging incident wave conditions.

Eliot et al., (1982) and Eliot and Clarke (1982a) have noted that such long-term trends and short-term fluctuations are superimposed on periodic shoreline fluctuations. These occur in response to regular shifts in mean sea level (Radok, 1976) and wave climate (Davies, 1957; McKenzie, 1958; Foster et al., 1963; Read, 1964; Short, 1980).

Aubrey et al., (1980) developed a linear statistical estimation model based on empirical orthogonal function
(EOF) analysis to predict seasonal changes in beach profiles along the Californian coast of the U.S. using variations in incident wave energy. Aubrey et al., concluded that weekly mean wave energy was the best predictor of beach changes. Short (1979) also related changes in observed beach morphology to the cumulative wave power.

Sonu and Van Beek (1971) were among the first to postulate that beach profile changes are a function of pre-existing morphology. They developed a model, derived from the analysis of beach profile data, that predicted beach profile shape based on pre-existing sediment storage, beach width and surface configuration. The concept that morphological changes are a function of pre-existing morphology implies an ordered sequence of change.

The most intensive treatment of the process-response mechanisms in the beach and inshore (nearshore) zones have been conducted by Wright and Short and others in Australia (Wright et al., 1979; Wright, 1982; Short and Hesp, 1982; Wright et al., 1985; Short and Wright, 1983). The morphodynamic model developed proposes that open coast beaches are characterised by three distinctive beach types: dissipative, reflective and intermediate comprising six beach states (Short and Wright, 1985). The first type has been labelled dissipative because wave energy is largely expended shorewards across a surfzone. The second has been labelled reflective because a significant portion of wave energy is reflected from the beachface. The intermediate type contains elements of both reflective and dissipative types. Each beach type has a characteristic plan and profile configuration, surfzone circulation and modes of wave energy dissipation.

The modern classification developed by Short and Wright is an outgrowth of the impetus given to beach studies by Homma and Sonu (1962) who first drew attention to intermediate (rhythmic) beach types. In the last decade models of systematic beach changes and types have
been presented by Sonu (1973), Sonu and Young (1970), Sonu and Van Beek (1971), Sonu and James (1973), Fox and Davis (1976), Davis and Fox (1971, 1972), Hayes (1972), Winant et al., (1975), Hino (1975), Guza and Inman (1975) (who first defined reflective and dissipative beach extremes which are now used to describe low and high energy beaches), Huntley and Bowen (1975), Aubrey et al., (1976), Abele (1977), Wright and Thom (1977), Owens (1977), Wright et al., (1979) (who conducted experiments aimed at characterising the surfzone circulation and dynamics associated with the various beach types), Short (1979) (who produced a three-dimensional sequential model of beach change linking dissipative, intermediate and reflective types under rising and falling wave conditions), Wright (1981), Bryant (1983), Short and Wright (1983), Wright and Short (1983), Short and Hesp (1982), Wright et al., (1985). Each of these studies have attempted to put some order in the observed range of beach morphologies and or dynamics.

Recent studies of beach instability and associated problems of beach erosion versus accretion have focused either on sediment budget imbalances related to littoral drift (Chapman, 1982), or on onshore-offshore sediment migration and associated 'cyclic' or seasonal changes in beach and inshore profiles. Prominent examples of the latter include studies of the critical conditions responsible for the shift in beach profile from the accreted swell (or summer) profile to the erosional storm (or winter) profile (Komar, 1976; Davis and Fox, 1972; Sonu and James, 1973; Winant et al., 1975). Others have predicted the likelihood of sediment moving offshore versus onshore over simple beach topographies in terms of critical wave steepness, sediment fall velocity and beach slope (Dean, 1973; Hattori and Kawamatu, 1980; Sawaragi and Deguchi, 1980). Thom and Bowman (1980) have suggested that it is impractical to address the problem simply in terms of shifts between extreme swell and storm profiles since either extreme or intermediate topographies may be arrested by environmental conditions for extended periods.
and since the cyclic alternation between extremes often requires several years to complete.

Several studies of patterns of sediment volume change have been recently reported by Clarke and Eliot (1982,1983a) and Eliot and Clarke (1982a,1982b). A primary objective of these studies of beach change has been to develop analytic procedures that quantitatively describe and predict shore normal and shore parallel movement of sediment so as to provide a detailed account of three dimensional systematic variations in beach morphology. These changes occur in time domains which have been described by the secular trends of least squares analyses (Clarke and Eliot,1982,1983a; Eliot and Clarke,1982a, 1982b), the results of spectral analyses (Fisher et al.,1984), or as time series associated with empirical orthogonal function modes (Winant et al.,1975; Dolan et al.,1977; Aubrey,1979; Aubrey et al.,1980; Aranuvachapan and Johnson,1979; Bowman,1981). Aubrey and Ross (1985) also using EOF developed a quantitative method to describe sequential changes in profile morphology. Clarke and Eliot have suggested that the results of such studies yield a context for process studies that are necessarily tied to explanation of topographically controlled regional and local beach responses.

1.4 Regional Setting
(a) Moruya

The Moruya Heads-Broulee beach is a crescent-shaped beach, 5.5 km long, between Broulee and the Moruya River breakwater, 250 km south of Sydney (Figure 1.2). The beach is aligned slightly south of east and is exposed to waves emanating from easterly directions between north-east and south (Thom et al.,1973). Headlands at the extremities of the beach cause refraction of ocean swell from the north and south and act as barriers to littoral drift from adjacent beaches (Hall,1981).
Figure 1.2 Location and regional morphology for
(A) Narrabeen and (B) Moruya field sites
Tides are semi-diurnal with a maximum spring range of 2 metres and a minimum neap range of 1 metre. The active beach is backed by a series of dune ridges which have accumulated since the postglacial transgression. Sediments are predominately well sorted, fine to medium grained ($M_d = 0.15 - 0.35$ mm), clean quartz sands, the proportion of shell being less than 10% on the subaerial portion of the beach.

(b) Narrabeen

The Narrabeen-Collaroy beach at 3.6 km is the longest beach in the Sydney region (Figure 1.2). The Narrabeen-Collaroy compartment extends from North Narrabeen to Long Reef. Headlands and the significant reef structure cause refraction of swell particularly from the south (Short, 1980).

The beach experiences a semi-diurnal, microtidal tide regime, the average spring tide range is 1.6 metres and average neap tide range is 1.2 metres. The active beach is extensively backed by urban residential development, although some sections have been reclaimed and dune and vegetation reconstruction undertaken. The beach and inshore zone are composed of medium sized quartz and carbonate sand with mean settling velocities ($W_m$) ranging from 0.045 m/s in the surfzone to 0.066 m/s off the beachface.

(c) Wave climate

Both study sites are situated in a moderate to high energy east coast swell environment (Davies, 1973). Moderate energy and relatively long period (8-14 second) southerly and southeasterly swell prevail year round. Superimposed on this swell regime is a highly variable wind wave climate influenced by mid-latitude cyclones in the Tasman Sea, summer northeasterly sea breezes and occasionally tropical cyclones to the north of the region (Lawson and Abernathy, 1975; Short and Wright, 1981).

As exposed, open coast beaches they are subjected to a range of swell and wave inputs from the north through east, southeast and south. Individually the embayments differ little in degree of orientation and exposure to
the wave and swell inputs. The large temporal variation in beach conditions is largely a consequence of the highly variable deep water wave climate and corresponding surf climate (Short and Wright, 1981; Trenaman, 1985; Trenaman and Short, 1988).

The primary data source for the deep water wave climate comes from surface measuring instruments (waverider buoys) operated by the Maritime Services Board of New South Wales. These instruments are called waverider buoys. They are accelerometers sensitive to vertical accelerations and are capable of transmitting their readings to shore for recording. The wave database is a compilation of 17 years of records. The waverider buoy is located 3 km east of Botany Bay, at the 70 metre depth contour. Daily data from the waverider provided statistics on significant wave height and period. No attempt has been made to replace missing data from the waverider records by extrapolation, hindcasting or from other sources.

1.5 Methodology

Beach profile changes essentially involve onshore-offshore and alongshore shifts of sand associated with changes in the incident wave regime. The strategies for examining these complex changes are varied in the literature.

This study applies various analytical procedures to determine information pertaining to the temporal and spatial modes of variation in the sediment volume of the subaerial beach.

1.5.1 Data types, sources and acquisition techniques

A monitoring programme has been in operation on the Moruya Heads-Broulee beach since January, 1972 and on the Narrabeen-Collaroy beach since April, 1976. During this
period considerable changes have occurred on most New South Wales open ocean beaches. The time-series of beach survey data therefore provides evidence of the characteristics of this change and forms the primary database for the analyses presented here.

Profile observations and database

(i) Moruya, 1972-1986

At Moruya four profiles located in the middle of the embayment (Figure 1.3) have been regularly surveyed (Thom et al., 1973). Profiles are surveyed with conventional dumpy level and surveying staff from pegs established in the vegetated foredunes to a distance beyond Indian Spring Low Water (ISLW) dictated by inshore conditions at the time of survey. The surveys extend from the backshore across the beach zone, levelling at 5 metre increments, to below ISLW from bench marks tied to the Australian Height Datum (AHD). Initially surveys were carried out at fortnightly intervals but since early 1976 only monthly surveys have been made.

(ii) Narrabeen, 1976-1987

At Narrabeen six profiles have been regularly surveyed to date (figure 1.4). The surveys are carried out monthly using the Emery method (Emery, 1961) and extend from points related to fixed benchmarks at the approximate position of the natural incipient foredune, across the beachzone, levelling at 10 metre intervals, and extend into the inshore to include bar-trough topography (Short, 1980).

The times of both surveys have been chosen to coincide with spring low tides to facilitate ease of surveying and permit maximum detail to be obtained extending into the inshore. At Moruya this is to allow at least ISLW to be reached for profile closure. Strong winds and high waves often reduced the precision of the offshore segment of the survey.
In this study the subaerial beach is taken to include the backshore zone and upper foreshore zone down to ISLW. The subaerial sand store of the beach is the volume of sediment seaward of a backshore datum point and above ISLW (Figure 1.1). Other terminology used accords with definitions by CERC (1975).

A detailed illustrated log of sea, weather, nearshore and beach conditions at the time of the survey has been maintained. At Moruya a photographic record has also been undertaken.

From personal observations, modal wave heights at the breaker zone may be slightly higher on Moruya than on Narrabeen beach. This may possibly be due to the more open ocean aspect of Moruya.

(iii) Database

The continuous survey data of distance from datum and elevation above datum generate matrices of two-dimensional height/location data. However because of variable array lengths the survey data is reduced to two forms of volumetric information. Firstly to a time-series of total profile volumes, the volume of sediment of the subaerial beach at each profile station was calculated as the amount of sediment above the ISLW and seaward of a fixed benchmark for a 1 metre wide profile. Secondly, to volumetric information for horizontal segments of beach related to AHD. These segments correspond with swash profile zones identified by Duncan (1964), Schiffman (1965), and Pollock and Hummon (1971) and will assist in the understanding of three dimensional changes in subaerial beach sediment budgets.

1.5.2 Computer Programming and Analyses

Software was developed specifically for this thesis to perform analyses of data for purposes of understanding temporal and shape changes to beaches. Programs developed performed data editing and reformatting, mathematical computations and graphics output. Examples of programs given in appendix C are:
Program DATASORT performs data matrix manipulations.
Figure 1.3 The Moruya beach compartment with profile locations shown (after Thom and Bowman, 1980).
Figure 1.4  The Narrabeen beach compartment with profile locations shown (after Short, 1979).
Program MORVOL creates volumetric time series from Moruya master datafile.
Program NARVOL creates volumetric time series from Narrabeen master datafile.
Program INTER creates interpolated time series.
Program NORMAL creates normalised data matrix.
Program SEASON creates annually filtered time series.
Program SMOOTH creates variably filtered time series.
Program ACFPLOT produces ACF graphics.
Program POWER calculates daily wave power.
Program WEIGHT applies weighted filter to wave data.

All data storage, manipulation and analysis was achieved using the CDC Cyber 825/830 mainframe with peripheral Calcomp plotter maintained by the University Computing Centre, Sydney University.

Fortran V computer language was used throughout on the NOS operating system.

1.5.3 Application of methods

Detailed methodology precedes results in chapter 2 and chapter 3. The study is two-faceted with time series analysis of profile behaviour contained in chapter 2 and profile shape behaviour contained in chapter 3.
Time Series Analysis of Beach Profile data

2.1 Introduction / aims

This chapter aims to determine the temporal components of beach profile oscillation which is indexed by the volume of sediment stored in the subaerial beach. Analyses of beach dynamics have largely focused on volumetric changes (erosion and accretion) as expressed by profile variability with particular emphasis on seasonal variability (Winant et al., 1975; Aubrey et al., 1980).

Time-series analysis (TSA) will be applied with the following specific aims:

(i) To specify the main features of the series
(ii) To decompose the series so as to uncover and assess
     (a) trends (long term change in the mean)
     (b) regular cycles (periodic cyclic changes)
     (c) irregular fluctuations (residuals or random elements within the series)
(iii) To predict future values of the series
(iv) To suggest hypotheses which might explain changes over time
(v) To examine two or more time-series to suggest cause and effect relationships

These aims will be assessed here with the exception of four and five which will be detailed in chapter 3.

The concept of time domain analysis is well represented in the scientific literature (e.g. Jenkins and Watts, 1968; Box and Jenkins, 1976). A time-series may be defined as a collection of observations made sequentially in time. The data forming the series may be a continuous trace or observations at discrete intervals of time. This chapter will detail an examination of time-series showing variation in the volume of sediment stored in the subaerial zones of sandy beaches. Of most interest in time-series analyses has been to determine low-frequency, cyclic changes in the volume of sediment
stored in the subaerial sector of the beach and further to speculate as to the causes for sediment exchange at varying frequencies. The emphasis therefore centres on temporal variability of beach form and sediment volume.

The methods of TSA constitute an important area of statistics. While most statistical theory is concerned with random samples of independent observations, the special feature of TSA is the fact that successive observations are usually not independent and that the analysis must take into account the time order of the observations. When successive observations are dependent, future values may be predicted from past observations. If a time-series can be predicted exactly, it is termed deterministic. However, most time-series are stochastic in that future values are only partly determined by past values. Cox and Miller (1965) have defined stochastic processes as simply 'the mathematical analysis of systems that change in accordance with probabilistic laws'. For stochastic series exact predictions are impossible and must be replaced by the idea that future values have a probability distribution which is conditioned by a knowledge of past values (Chatfield, 1984).

Traditional methods of TSA decompose series into a trend, a seasonal fluctuation and other irregular fluctuations. The trend may be defined as long-term change in the mean. In TSA difficulty may be encountered in defining what is meant by long-term. Where variables oscillate over long time periods a short-term time-series would display such an oscillation as a trend. Granger (1966) defines trend in mean as comprising all frequency components whose wavelength exceeds the length of the observed time-series. In the context of this study this definition is accepted. The short-term herein refers to periods of approximately < 3 months and intermediate-term being the observable seasonal oscillations between 3 months and 1 year. Periods longer are generally considered long-term.

Many time-series exhibit a variation at a fixed period. Examples would include 4, 8 or 12 month cycles.
This can be measured and/or removed from the series to produce de-seasonalised data. In addition, oscillations may occur which do not have fixed periods but which are predictable to some extent.

After trend and cyclic variations have been removed from a series, a residual series remains. This may be random. However, this apparently irregular variation may still contain cyclic variation and this may be explained in terms of probability models which will be discussed later.

2.2 Time series analysis and beaches: a review

Traditional time-series analysis has been previously applied to all branches of science. Background references to established techniques would include Box and Jenkins (1976), Kendall (1976), Bloomfield (1976), Gottman (1981), Chatfield (1984) and others.

Analyses of beach dynamics have largely focused on volumetric change (erosion and accretion) as expressed by profile variability with particular emphasis on seasonal variability (e.g. Winant et al., 1975; Aubrey et al., 1980; Eliot and Clarke, 1982a). Such studies in the time domain are aimed at predicting intermediate term (seasonal) advances and retreats of the shore.

In Australia, Clarke and Eliot have applied time-series analysis to data for the subaerial beach at Warilla, NSW (Clarke and Eliot, 1982, 1983a; Eliot and Clarke, 1982a, 1982b). They have determined secular trends, annual and biennial cycles of sediment exchange and aperiodic variation for the volume of sediment comprising the subaerial beach.

At Stanwell Park near Sydney, Bryant (1983) has sought to establish correlations between the Southern oscillation index and measurements of beach width made between 1933 and 1983 which form a time series.

Wright et al. (1984) performed analyses on a 6.5 year time-series of daily wave data, daily beach state
and monthly beach and surfzone profile data for Narrabeen beach, Sydney. Empirical orthogonal function analyses were performed on the profile data. In areas where short-term (daily or weekly) fluctuations in incident wave energy equal or exceed the seasonal fluctuations, concern lies with predicting the concomitant short-term beach change, or alternatively, beach stability (Wright et al., 1985).

2.3 Methods

The data forming a time-series may be a continuous trace or observations at discrete intervals of time. The beach monitoring programme at Moruya and Narrabeen produces a time-series of discrete monthly values of subaerial beach volume.

2.3.1 Overview and the concept of Stationarity

A time-series is termed stationary if there is no systematic change in the mean, if there is no systematic change in the variance and if strictly periodic variations have been removed. In qualitative terms, the stationarity assumption implies that the law that generates the data is constant over time (Granger, 1966).

The probability theory of time-series is essentially concerned with stationary time-series and for this reason TSA requires a non-stationary series to be transformed into a stationary series prior to any analysis. The general procedure to do this is to remove the trend and seasonal variation from a dataset and then try to model the variation in the residuals by means of a stationary stochastic process.

Three fundamental concepts underlie TSA. Firstly, the technique of autocorrelation may be used to demonstrate dependency between observations in a series at different lags. Secondly, any observed series is a realisation of a particular stochastic model. Thirdly, each stochastic model has a characteristic autocorrelation pattern, making it possible to identify
the type of generating stochastic process from the calculated correlogram.

The approach to TSA adopted in the following sections will be:
(i) Simple descriptive techniques - plotting the data, looking for trends, seasonality and other qualitative features (Section 2.4.1).
(ii) Transform the data to meet stationarity requirements via least squares methods (Section 2.4.2).
(iii) Condition data via filters to separate low and high-frequency fluctuation as required (Section 2.4.3).
(iv) Introduce the major diagnostic tool called the autocorrelation function to aid description of process evolution through time (Section 2.4.3). Inference based on this function is called analysis in the time domain.
(v) Determine types of probability models for time-series (Section 2.4.4).
(vi) Determine forecast functions via procedures of Box and Jenkins (1976) (Section 2.4.5).
(vii) Introduce the spectral density function which describes how variation in a time-series may be accounted for cyclic components at different frequencies. Inference based on this function is called analysis in the frequency domain (Section 2.4.6).

2.3.2 Data Preparation

Prior to any time-series analysis (TSA) we must have discrete observations spaced at equal time intervals. Kendall (1976) described and assessed calendar problems. The methods used to clean up the series vary according to circumstance and opportunity. The raw data is initially transformed to volumetric information. As $dt = 1$ month a linear interpolation is applied to the raw volumetric data to correct for calendar irregularities (Program INTER, see appendix C-4).

This technique gives satisfactory results because the number of equally spaced points is approximately
equal to the number of original points. Hence the detail of the original data is not ignored.

2.3.3 Least Squares Methods

Many series are non-stationary in that they exhibit trends in mean and or variance. Least squares methods can be applied to determine the general tendency of a data series and so detrend the data. This is a method of representing the relationship implicit in the observed series. The methods produce a line which expresses the relation between the observation and time throughout the range of both variables. A line of best fit is obtained such that the deviation between the observations and the line are minimised.

If the values of this line are subtracted at the appropriate points from the corresponding observations, a detrended series results which has mean zero. The variable being examined is the dependent variable $Y_1$, the other variable (time) is the independent variable $X_1$, the fitted line has slope $b$, and crosses the y axis at a point $a$. The equation of the line is:

$$ Y_\star = a + b X_\star $$  \hspace{1cm} (2.1)

$Y_\star$ is the estimated value of $Y_1$ at specified values of $X_1$.

A complete discussion of least squares methods can be found in Draper(1981) and will not be discussed in this text.

2.3.4 Filtering

The analysis of time-series which exhibit cyclic variations can be approached using the techniques of data filtering or data smoothing.

A sequence of data usually consists of two parts; an underlying signal or meaningful pattern of variation, and a superimposed noise or random variation. Filtering refers to the application of techniques developed for enhancing a signal with respect to noise. Noise is generally short-term and fluctuates rapidly while signals in contrast tend to be long-term. Serial values of the signal tend to be autocorrelated whereas noise is
completely independent in behaviour. Hence an averaging process of adjacent serial points will tend to converge on the signal alone. The sequence of estimated values forms a smoother curve than the original series and consequently the techniques are often called data smoothing.

The application of filters permits:
(i) measurement of cyclic components in the series and/or
(ii) elimination of cyclic components to produce a deseasonalised series

A linear filter procedure converts one time-series \( X_t \), into another \( Y_t \), by the linear operation;

\[
Y_t = \sum_{r=-q}^{+s} a_r X_{t+r}
\]

where \((a_r)\) are a set of weights.

In order to smooth out local fluctuations the weights are selected such that \( \sum a_r = 1 \). The operation is often referred to as a moving average.

Moving averages are often symmetric with \( s = q \) and \( a_s = a_{-s} \). The simplest example of a symmetric smoothing filter has;

\[
a_r = \frac{1}{(2q+1)} \quad \text{for } r = -q, \ldots, +q
\]

and \( S_m(X_t) = \) smoothed value of \( X_t \)

\[
S_m(X_t) = \frac{1}{(2q+1)} \sum_{r=-q}^{+q} X_{t+r}
\]

Having estimated the smoothed series we can look at the local fluctuations by examining:

Residual from smoothed series

\[
\text{Res}(X_t) = X_t - S_m(X_t)
\]

\[
\text{Res}(X_t) = \sum_{r=-q}^{+s} b_r X_{t+r}
\]

Filters are designed to produce an output with emphasis on variation at particular frequencies. To produce a smoothed series \( S_m(X_t) \), the local
fluctuations which constitute the high-frequency variation must be removed. For this a low-pass filter is used. To produce a residual series Res(Xₜ), the low-frequency variations must be removed. For this a high-pass filter is used.

For these purposes a program was developed to filter the series data at variable frequencies (Program SMOOTH, appendix C-7). Program SEASON was also developed to apply a seasonal (12 month) filter (appendix C-6).

2.3.5 Autocorrelation Function

An important guide to the properties of a time-series is provided by the autocorrelation function, defined as the linear correlation between a time-series and the same series at a later interval of time. The function often provides insight into the probability model which generated the data. The autocorrelation coefficient is analogous to the ordinary correlation coefficient which measures association between two series of variables. The autocorrelation coefficient measures correlation between successive observations in a discrete time series.

The correlation between observations in a series at a distance or lag k, apart is given by;

\[
\rho_k = \frac{\sum_{t=1}^{N-k} (x_t - \bar{x})(x_{t+k} - \bar{x})}{\sqrt{\sum_{t=1}^{N} (x_t - \bar{x})^2}}
\]

(2.7)

\(\rho_k\) is called the autocorrelation coefficient at lag k. Statistically there is little point in calculating \(\rho_k\) for values of k greater than about \(N/4\), where N is the number of observations in a series. A useful aid in interpreting a set of autocorrelation coefficients is a graph called a correlogram in which \(\rho_k\) is plotted against the lag k. Autocorrelation function plots display the
autocorrelations up to 60 lags and two standard error limits. Standard errors are calculated using the method devised by Ling and Roberts (1980) and are computed on the assumption that the series is random. Standard errors are used in significance testing. Examination of the correlogram will disclose intervals of time at which the time-series has a repetitive nature (Chatfield, 1984).

2.3.6 Probability Models

The modelling of time-series can be divided into deterministic and probabilistic models. In time series analysis successive observations are usually not independent and the analysis must take into account the time order of the observations. When successive observations are dependent, future values may be predicted from past observations. If a time-series can be predicted exactly, it is termed deterministic. However, most time-series are stochastic in that future values are only partly determined by past values (reference). For stochastic series exact predictions are impossible and must be replaced by the idea that future values have a probability distribution which is conditioned by a knowledge of past values (Richards, 1979).

A stochastic model describes how a series fluctuates in time, the oscillations being a reflection of autocorrelation between values in the series. A series must be stationary before a stochastic process can be identified. The observed time-series may be considered as the output from a linear system, as described by the stochastic process equation, and which transforms random input shocks into the observed output. The stochastic process represents a simple statement of the linear function which forms a black-box model of the transformation process.

The observed series is a realisation of a stochastic model of which there are five main types:
(i) Purely random models

The simplest process is one with no memory. The observations are mutually uncorrelated, independent values. This type of series is referred to as white noise. This is defined as:

\[ x_t = \varepsilon_t \]  

(2.8)

(ii) Autoregressive models

The autoregressive linear function states that the value of the series at a given time, \( t \), is dependent on a prior observed value(s) times a constant(s), \( \varnothing \), plus the present random shock or error term \( \varepsilon_t \). The meaning of autoregression is evident, since this relationship is a lagged regression of the series on itself. The simplest AR model is:

\[ x_t = \varnothing_1 x_{t-1} + \varepsilon_t \]  

(2.9)

This is a 1st order autoregression, written \( \text{AR}(1) \). Higher order models involve autoregression on successively more remote preceding values.

(iii) Moving average models

The moving average linear function states that the value of the series at a given time, \( t \), is a linear weighted sum of present and past random values. The simplest MA model is:

\[ x_t = \varepsilon_t + \Theta_1 \varepsilon_{t-1} \]  

(2.10)

This is a 1st order moving average, written \( \text{MA}(1) \). MA and AR models are the two main types of stochastic function. In both types of model, the random component is important because it enables a specific model to generate an infinite number of realisations. The most obvious difference between AR and MA process output is that AR process produces a smoother output with a higher degree of sequential correlation between successive values of the \( x_t \) series.

(iv) Mixed AR - MA models

A mixture of AR and MA components may sometimes provide a more parsimonious model, since a finite MA
model is equivalent to an infinite AR model. A mixed (ARMA) model of order p,q is represented as:

\[ x_t = \theta_0 x_{t-1} + \theta_1 x_{t-2} + \ldots + \theta_p x_{t-p} + \epsilon_t + \Theta_1 \epsilon_{t-1} + \Theta_2 \epsilon_{t-2} + \ldots + \Theta_q \epsilon_{t-q} \]

The ARMA(1,1) model is most common:

\[ x_t = \theta_0 x_{t-1} + \epsilon_t + \Theta_1 \epsilon_{t-1} \]

(2.11)

which is stationary if \(-1 < \theta_0 < 1\) and invertible if \(-1 < \Theta_1 < 1\).

(v) Autoregressive integrated moving average models

If an observed series is non-stationary in the mean then the series can be differenced. If a series \( X_t \) is replaced by \( V^d X_t \) this creates an integrated model capable of describing certain types of nonstationary series. This type of model is termed an intergrated model because the stationary model which is fitted to the differenced data has to be summed or integrated to provide a model for the non-stationary series.

If \( W_t = V^d X_t \)

the general autoregressive integrated moving average (ARIMA) process is of the form:

\[ W_t = \alpha_1 W_{t-1} + \ldots + \alpha_p W_{t-p} + Z_t + \ldots + \beta_q Z_{t-q} \]

(2.12)

This ARIMA process which describes the dth differences of the data is of order \((p,d,q)\).

An AR, MA or mixed model may therefore be determined for a differenced series and the resulting model for the undifferenced series is called an integrated (ARIMA) model.

Although a given model may generate an infinite number of series, it is still possible to identify the model generating a particular series because each model type generates series with a characteristic pattern of autocorrelation.

Thus, given a stationary series of \( N > 50 \) observations, equation 2.7 (for \( r_k \)) can be used to calculate autocorrelations for lags up to \( k = N / 4 \) and the plot of \( r_k \) against \( k \) (the correlogram) may be examined in order to suggest the nature of the underlying generating stochastic model.
Box and Jenkins (1976) emphasise a strategy for stochastic model building which is followed in this study, and requires the following approach:

(i) Observation and Description (section 2.4.1)
(ii) Identification, estimation and diagnostic checking (section 2.4.3)

The partial autocorrelation function is simply a plot of the values of $\phi_p$ against the order of the process $p$. It is the set of last coefficients in AR processes of ascending order. $\phi_p$ signifies the $j$th coefficient in a $p$ order AR process. Partial autocorrelations provide a measure of excess correlation between observations not accounted for by coefficients in lower order AR processes. The PACF is an aid to identification because if the process is AR($p$), the value of $\phi_{k+p+1}$ will be zero because there is no residual excess correlation to be accounted for by the next higher order process.

The determination of theoretical ACF and PACF for various stochastic processes is discussed by Box and Jenkins (1976); Chatfield (1984) and others and will not be further elaborated in this text.

Purely random processes by definition have no correlation between successive terms. Sample autocorrelations, $r_k$, may not be zero but are expected to reside within the 95% confidence limits.

ACF for AR processes decay slowly to zero as damped oscillations and/or exponentials. This is expected because the generating process implies dependency on prior values of the observed series $X_t$. The PACF for AR($p$) processes cut off with only $\phi_p$ non-zero.

ACF for MA processes have no dependency on prior series values $X_t$ but only on a finite sequence of prior random shocks $e_t$. The ACF of a MA process therefore cuts off after the lag which equals the process order. PACF for MA($q$) processes decay.

The analysis of ACF and PACF plots for stationary series are therefore diagnostic in model identification.
Having identified the stochastic process from the diagnostic plots the parameters of the model can be estimated. The $\theta$ parameters of an AR model and/or the $\theta$ parameters of a MA model are expressed in terms of the population autocorrelations $\rho_{w}$. By substituting the sample autocorrelation estimates $r_k$ in these expressions, estimates are obtained for the model parameters. The methodology is fully explained by Box-Jenkins(1976) and is not further discussed in this text.

Estimates were obtained using standard statistical subroutines in the Box-Jenkins procedures of SPSS-X (Anon,1986). The estimated models are checked for adequacy of fit to the data before further use including forecasting is attempted (section 2.3.8). Model checking involves consideration of the nature of residuals from the model. The residual series ACF is diagnostic and should be random for all lags. No serial correlation should remain.

These methods were applied to develop an understanding of the temporal component of profile behaviour.

2.3.7 Spectral Analysis

Spectral analysis is a procedure which estimates the spectral density function which describes how the variation in a time-series may be accounted for by cyclic components at different frequencies. The spectral density function is a plot of the contribution made to the total variance of a series by oscillatory components (cosine functions) in different frequency bands over a range of frequencies. The simplest derivation of the spectral density function is by a discrete fourier transform of the autocovariance function (Jenkins and Watts,1968; Chatfield,1984).

The overall effect of the Fourier transform of the data is to partition the variation of the series into components at frequencies $\frac{2\pi}{N}, \frac{4\pi}{N}, \ldots, \pi$. The $p$th harmonic ($\omega_p$) is therefore the component at frequency $\frac{2\pi p}{N}$. A time-series should be stationary prior to
spectral analysis. Points to observe in examining the spectrum are peaks, whether the spectrum is large at low-frequency (implies non-stationarity in the mean), and the general shape of the spectrum (Cooley, 1967).

Spectral analysis is used to approximate non-periodic functions by simpler periodic ones (applying a cosinusoidal window). The spectral density function provides the same information as the correlogram, in that each stochastic process has a characteristic theoretical spectrum and is therefore simply an alternative visual representation of the data (Quimpo, 1968). Theoretical spectra are derived in much the same way as theoretical correlograms; a random process has a flat spectrum since no frequency dominates. An AR(1) process with $\theta_1$ coefficient has an exponentially declining spectrum and if $\theta_1$ is negative the spectrum increases exponentially to a maximum value at a high frequency. An AR(2) process would display a broad peak centred on the frequency $w = 2\pi/\gamma$ where $\gamma$ is the wavelength of the pseudo-cyclic oscillation. Examples of theoretical spectra for different processes are shown by Box and Jenkins (1976).

Cross spectral analysis examines the relationship between pairs of components in two time-series. These relationships are analysed by the square of the correlation of the amplitudes of each frequency, and this measure is called the coherence $c(w)$. The coherence measures the linear correlation between the two components of the bivariate process at frequency $w$. The closer $c(w)$ is to one the more closely related are the two processes at frequency $w$. The SDF plot illustrates spectrum estimates plotted on a log (base 10) scale versus frequency measured in cycles per unit time ($f$). This is so that asymptotic variance is independent of the level of the spectrum and also for spectra showing large variations in power the log scale allows more detail to be shown over a wider range.
2.3.8 Box-Jenkins Forecasting

The classic application of model building techniques is in forecasting, which involves making estimates of point and interval values at successive lead times.

Forecasts were made using the SPSS-X Box-Jenkins subroutines using estimated models (Anon, 1986). Appendix D lists an example of the specification files used in model forecasts.

The problem is to estimate $X_n^q$ where $q$ = lead time. The longer the lead time, the more likely is the underlying model to change and the more unreliable the forecast will become. The results of Box-Jenkins forecasts produce an interval forecast with upper and lower confidence limits which indicate the uncertainty associated with estimation of future values. The Box-Jenkins procedure is based on the fitting of ARIMA models to a given set of data. This represents the final product of modelling. The data is differenced until stationary, nonseasonally by $V^dX_t$ and seasonally by the operator $V^{12}$. $W_t$ denotes the differenced series. Models are fitted to $W_t$ by selection of values for $P$, $SP$, $Q$ and $SQ$, based upon examination of the correlogram of the differenced series.

The adequacy of a fitted model is checked by examining the residual series from the fitted model for randomness. For a series $X_t$ the forecast of $X_{n+q}$ is given by $X(N,q)$ which indicates the prediction of $X_{n+q}$ made at time $N$ of the series value $q$ steps ahead.

Before proceeding to a discussion of results two fundamental points should be made. Firstly, the data contained in a time-series are only a finite record of a much longer and possibly infinite series of values. Secondly, the assumption of stationarity implies that the statistical properties of the series are independent of absolute time. Consequently the series under observation represents one particular realisation of an infinite number of possible realisations. What this implies is that we are dealing with a sample. Clearly, no amount of
analysis can provide information about fluctuations in the series over intervals less than the length of the sampling interval.

2.4 Results for Moruya and Narrabeen

2.4.1 Descriptive Time-Series Analysis

Profile change occurs at many varied time scales. Change may be seasonal or longer or as short as to occur from one breaking wave to the next. A profile may exhibit short term equilibrium while long term accretion or erosion may be occurring. This analysis cannot provide information about fluctuations in the series over intervals less than the one month sampling interval.

The regular survey data set provides information on the frequency characteristics of profile behaviour. Eliot et al. (1982) and Eliot and Clarke (1982a) have observed that long term trends and short term fluctuations related to sediment losses and storm activity respectively are superimposed on periodic shoreline fluctuations.

The initial approach to time series analysis (TSA) is to apply simple descriptive techniques prior to any data transformations. By plotting the data the form of trend lines can be assessed and the visualisation of the series may indicate if it is desirable to transform the series. Series plots therefore visualise trends, seasonality and other qualitative features.

The series of original data for beach volume and width were plotted for all Moruya and Narrabeen profiles (appendix A). The spatially limited Moruya profiles demonstrate high correlation (table 2.1). The time series is dominated by major erosional events and subsequent beach recovery. A qualitative assessment of the Moruya time series reveals a number of erosive episodes of varying magnitude. From the initial survey of January, 1972 – mid 1973 the beach accreted. From mid 1973 – mid 1974 the beach eroded culminating in substantial beach
## Table 2.1  Cross correlation matrix for profile volume and width

<table>
<thead>
<tr>
<th>Profile</th>
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<table>
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<td>-0.041</td>
<td>0.139</td>
<td>0.728</td>
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<table>
<thead>
<tr>
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<th>Narrabeen profile width</th>
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</tr>
</thead>
<tbody>
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<td>2</td>
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<tr>
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</table>
volume reduction. From mid 1974 - mid 1978 the behaviour was of oscillations between progressive accretion and sudden rapid erosive events. Following mid 1978 the beach accreted progressively to above mid 1973 levels. The beach reached a quasi-stable volume by 1981 about which it has oscillated till the present.

At Narrabeen beach the series appear inconsistent between profiles. Only profiles 6, 7 and 8 display patterns partially consistent with those observed at Moruya. The correlation matrix (table 2.1) emphasises inter profile variability. The Narrabeen series do not display consistent trends alongshore in time. The Narrabeen series demonstrate alongshore transitional behaviour. Profiles may be qualitatively grouped as: profiles 1 and 2, profiles 3, 4 and 5, and profiles 6, 7 and 8. The trend for profiles 1 and 2 is essentially linear and decreasing. For profiles 3, 4 and 5 (3 and 5 discontinuous) the trend line is logistic in that an increasing rate of growth is followed by a decreasing rate of growth. Narrabeen profiles 1-5 exhibit similar magnitude effects for the 1978 storm event. Profiles 6, 7 and 8 trend lines appear to exhibit two phases or levels, separated by a growth or recovery phase from 1978 - 1981 which exhibits similarities with Moruya trend lines.

These time series (appendix A) therefore help visualise obvious trends, events, seasonality and turning points (for example: Narrabeen profile 4 where an upward trend has suddenly changed to a downward trend). For some series the variation may be dominated by obvious features or a more complex model may be required. Plotting the data also indicates if series transformation is desirable. Transformations are undertaken to stabilise variance and means (section 2.3.2 and 2.3.3). Series visualisation also aids identification of model type needed to describe the series. The time series plots indicate trends in all data series which will be assessed in section 2.4.2.

Due to the discrete monthly interval sampling nature of the series many of the observed short term
fluctuations may obscure longer term behaviour. Such short term fluctuations superimposed on the longer term trends may be attributed to the development or destruction of beach cusps and rhythmic topography or to the movement of such features alongshore. However similar long term trends are recognisable in the illustrated profiles.

2.4.2 Secular Trends

To determine the general tendency of the profile data the series were initially decomposed by least squares methods to assess long term change in the mean. In TSA difficulty may be encountered in defining what is meant by long term. Where variables oscillate over long time periods a short term time series would display such an oscillation as a trend. Granger (1966) defines trend in mean as comprising all frequency components whose wavelength exceeds the length of the observed time series.

Narrabeen profiles 3, 5 and 7 should be discarded from overall discussion because these data sets are of less duration.

Prior to analysis the series were interpolated (Program INTER, appendix C-4) to produce discrete observations spaced at equal time intervals. As the sample interval equals one month the linear interpolation is applied to raw volumetric and width data to correct for calender and interval irregularities.

The time series were detrended by separating linear regression estimates and residuals prior to analyses. Figure 2.1 illustrates detrended series for Moruya profile 3 and Narrabeen profile 4. When a series is stationary it is usual to express the data in the form of a series of deviations from the mean, that is;

\[ x_t = X_t - \bar{x} \]  

(2.13)

The results of estimations of secular trend (tables 2.2 and 2.3) indicate overall accretion for all Moruya profiles. Rates of accretion of 7.5 m³/m/year for
Figure 2.1  Deterred time series for

(A) Moruya profile 3  (B) Narabbeen profile 4

B

Narabbeen Beach, N.S.W.

MONUVA BEACH, N.S.W.
### Original data

<table>
<thead>
<tr>
<th>Level</th>
<th>Profile 1</th>
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<th>4</th>
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</thead>
<tbody>
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<td>ISLW</td>
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<td>0.01390</td>
<td>0.02390</td>
<td>0.02390</td>
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<tr>
<td>0.5 m</td>
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<td>0.02120</td>
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<td>0.00589</td>
<td>0.01150</td>
<td>0.01210</td>
</tr>
<tr>
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### Normalised data

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</thead>
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<td>1.5 m</td>
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</table>

**Table 2.2** Regression coefficients for Moruya volume as a function of time. Results are given for both original and normalised data for ISLW and half metre incremented levels above ISLW.

### Original data

<table>
<thead>
<tr>
<th>Level</th>
<th>Profile 1</th>
<th>2</th>
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<th>6</th>
<th>8</th>
</tr>
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<tbody>
<tr>
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<td>0.01320</td>
<td>0.02860</td>
</tr>
<tr>
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<td>0.02480</td>
</tr>
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<td>0.00945</td>
<td>0.02100</td>
</tr>
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<td>0.00755</td>
<td>0.01720</td>
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### Normalised data

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<th>8</th>
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<tr>
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</tr>
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<td>-2.066</td>
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<td>17.281</td>
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</table>

**Table 2.3** Regression coefficients for Narrabeen volume as a function of time. Results are given for both original and normalised data for ISLW half metre incremented levels above ISLW.
volume above ISLW are representative. Results for Narrabeen indicate erosion for northern profiles (1,2,4) decreasing progressively southwards alongshore to a net accretion tendency for southern profiles (6,8). Rates of subaerial volume change range from losses of 3.9 m$^3$/m/year to gains of 11.7 m$^3$/m/year. Rates for normalised data were also assessed to permit comparison. Beach width results demonstrate equivalent trends (tables 2.4 and 2.5).

Shoreline fluctuations in the long term on the central and south coast of NSW have been attributed to a long term net loss of sediment from the active zone of the coastal system (Thorn,1974; Davies,1974; Gordon et al., 1978; Jones et al.,1979). These are distinct from short term fluctuations due to infrequent storm wave activity (Stockwell,1969; Thom et al.,1973; McLean and Thom,1975; Wright,1976; Short,1978,1980); to edge waves (Guza and Innan,1975); and to the migration of rip current and cusp dominant features along the shoreline. In the short term beach changes can involve changes in beach volume and/or beach configuration. Both volume and shape can be repeated. However in the long term while shape may be reattained (section 3.4.4) total subaerial volume may not recover. Over the specified study period when there results an excess of sediment removal over supply, as the profile 1,2,4 Narrabeen series indicate, coastal erosion will become increasingly more probable.

2.4.3 Beach Profile Oscillations

Traditional TSA methods decompose series into a trend (section 2.4.2), regular cycles (periodic changes) and other irregular fluctuations (residuals or random elements within the series). All data series were initially interpolated and detrended (section 2.4.2). The resulting series were assessed using TSA techniques to identify dominant temporal components and residual behaviour. The autocorrelation and partial autocorrelation functions were calculated for the
Table 2.4 Regression coefficients for Moruya width as a function of width. Results are given for both original and normalised data for ISLW and half metre incremented levels above ISLW.

<table>
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<tr>
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<th>4</th>
</tr>
</thead>
<tbody>
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</table>

Table 2.5 Regression coefficients for Narrabeen width as a function of time. Results are given for both original and normalised data for ISLW and half metre incremented levels above ISLW.

<table>
<thead>
<tr>
<th>Level</th>
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<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-4.5420</td>
<td>-4.0420</td>
<td>-2.4190</td>
<td>6.0456</td>
<td>7.3082</td>
</tr>
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<td>8.8288</td>
</tr>
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<td>8.4377</td>
<td>9.8817</td>
</tr>
<tr>
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<td>-4.4060</td>
<td>-3.1340</td>
<td>9.9230</td>
<td>11.3010</td>
</tr>
</tbody>
</table>
detrended series (figure 2.2) for lags $k = 1$ to 60. The autocorrelation function plotted against lag (correlogram) was used to demonstrate dependency between observations in a series at different lags.

The autocorrelation functions for Moruya profiles are not immediately conclusive. The slow exponential decay of positive correlations as lag increases generally indicates nonstationarity. However, as the series have been transformed the autocorrelations indicate that the series are being dominated by a large magnitude, low frequency oscillation. The time series plots for Moruya (appendix A) illustrate how the magnitude of the dominant 1974 erosion event is well in excess of higher frequency oscillations. The autocorrelation and partial autocorrelation indicate that the series would require further manipulation before a stochastic process could be estimated (section 2.4.4). The autocorrelations for beach width data reflect high variability.

The primary autocorrelations for Narrabeen are immediately more informative. Cyclic behaviour is evident in the autocorrelation functions of the detrended series. All profiles indicate a biennial cycle with profile 8 being the exception with an obviously dominate annual cycle. Profiles 3,5 and 7 should be viewed with restraint because they are derived from shorter time series. All autocorrelations indicate short term correlation of at least six months suggesting seasonality in profile behaviour as most profiles with above or below average parameters are followed by similarly biased successions.

The dominant significant peak however is a biennial cycle. All profiles have an annual cycle of varying magnitude and of less significance than the biennial.

The distinction in ACF decay rates between Narrabeen profiles 1,2 and Narrabeen profiles 4,6 indicates different temporal behaviour. Profile 4 features the slowest decay which indicates the longest memory. As a series autocorrelation becomes increasingly sinusoidal this indicates less short term disturbances and a more pronounced seasonal of otherwise periodic behaviour.
Figure 2.2(a) Autocorrelation as a function of lag (months) for detrended profile volume and width series
Figure 2.2(b) Autocorrelation as a function of lag (months) for detrended profile volume and width series
Figure 2.2(c) Autocorrelation as a function of lag (months) for detrended profile volume and width series.
Various stochastic models will be determined in section 2.4.4.

The correlograms for beach width time series for Narrabeen are not as immediately diagnostic in the identification of dominant temporal components. High crenulation reflects high variability although profile 8 is obviously annual.

The Narrabeen autocorrelations and partial autocorrelations reflect the alongshore variability not visible at Moruya where the profiles are spatially constrained.

Seasonality in wave climate (section 3.4.6) helps explain the behaviour of profile 8 Narrabeen. Trenaman(1985) evaluated directional wave data for the Sydney wave climate. There exists strong seasonality in direction with north-east waves becoming more prominent in summer (December-February) and south-east waves dominating in winter (July-September). Alongshore sediment transport to the south due to north-east waves causes profile 8 accretion and alternatively transport to the north due to south-east waves causes depletion. The profile is located in a boundary (headland) location. Without headland bypassing (no obvious signs) the sediment is essentially dammed in this locale each summer. Profile 8 beach width autocorrelation implies stationarity in width while the slow decay in the volume autocorrelation indicates a low frequency trend on a seasonal pattern which is interpreted as berm building till the present.

The autocorrelation for Narrabeen profile 6 suggests a possible trend departure towards the centre of the beach towards a triennial cycle. This suggests that the beach probably behaves differently alongshore in time, each segment oscillating at a different frequency. Possible explanation must reside in temporal studies of wave climate directional data, as clearly a bias towards any directional component will effect longshore transport of sediment on the beach.
Where a largely dominate underlying event resides in a time series interpretation can only improve with removal of that signal from the series. So to improve interpretation of the Moruya time series a shorter series was analysed, equivalent to the Narrabeen series in duration, from 4/76 to 3/87 and therefore excluding the dominant 6/73 to 6/74 event. Results (figure 2.3) indicate a weak biennial signal still however obscured by a longer period oscillation. Results for beach width time series provide a better representation indicating annual cycles partially obscured by shorter period cycles.

Further TSA of series which are identified to contain cyclic variations was approached using the techniques of data filtering or smoothing. Filter techniques were employed to separate the underlying (obscured) signal or meaningful pattern of variation from the superimposed random or noise variation. Via application of various filters, output was produced with emphasis on variation at particular frequencies which were identified from primary correlograms.

Many time series exhibit variation at fixed periods. Examples would include 4, 8 or 12 month cycles. These can be measured and or removed from the series to produce deseasonalised data. In addition oscillations may occur which do not have fixed periods but which are predictable to some extent.

Results (figure 2.4) indicate the function of annual or seasonal components. Series for Narrabeen (2,4,6,8) and Moruya (3) were separated into a smoothed low frequency oscillation and high frequency (< 12 months) oscillation and diagnostic autocorrelation and partial autocorrelation plots examined.

Narrabeen profile 2 residuals correlogram illustrates the significance of the annual cycle and the smoothed series correlogram confirms the dominant biennial cycle.

Narrabeen profile 4 residuals correlogram weakly confirms the annual, the plot indicating that higher frequency disturbances characterise this profile. The
Figure 2.3  Autocorrelation as a function of lag (months) for shortened Moruya volume and width series
Figure 2.4(a) Autocorrelation as a function of lag (months) for deseasonalised series for Moruya profile 1 for (A) smoothed (B) residual series.
Figure 2.4(b) Autocorrelation as a function of lag (months) for deseasonalised series for Narrabeen profile 2 for (A) smoothed (B) residual series
Figure 2.4(c) Autocorrelation as a function of lag (months) for deseasonalised series for Narrabeen profile 4

for (A) smoothed (B) residual series
Figure 2.4(d) Autocorrelation as a function of lag (months) for deseasonalised series for Narrabeen profile 6 for (A) smoothed (B) residual series
Figure 2.4(e) Autocorrelation as a function of lag (months) for deseasonalised series for Narrabeen profile 8 for (A) smoothed (B) residual series
smoothed series correlogram indicates that a lower than biennial frequency cycle is influencing the profile, the biennial recording only weak significance.

Narrabeen profile 6 residuals correlogram confirms the annual cycle which is also significant at 36 and 48 months. However the plot is obscured by higher frequency disturbances with noise especially between 12 and 36 months. The smoothed series correlogram reaffirms the lower frequency 36 month cycle for this profile as indicated by the cycle wavelength, peak and zero upcrossing.

Narrabeen profile 8 residuals correlogram clearly confirms the annual cycle which was already apparent in unfiltered correlograms for this profile. The smoothed series correlogram indicates low frequency dominance with an inflexion suggesting periods possibly of 84 months, however interpretation beyond n/4 lags is dubious, which in this case equals 30 months.

The Moruya residual correlogram is less conclusive being dominated by higher frequency oscillations. The correlogram for the smoothed series indicates dominance of the major signal previously discussed. The correlogram zero crossing and behaviour closely approximates that of Narrabeen profile 4. The filtered beach width time series demonstrate more definitive annual behaviour for the residuals although the correlograms for the smoothed series are inconclusive.

A shortened Moruya series was analysed, equivalent to the Narrabeen series time window, so as to exclude the dominant 6/73 - 6/74 event low frequency oscillation. Results (figure 2.5) indicate an improved interpretation. The correlograms and plots of smoothed series are remarkably similar to those for the equivalent Narrabeen filtered series with the exception that the 1980 event at Narrabeen (section 3.4.3) did not register effect at Moruya. A possible cyclonic induced north easterly wave source would explain this although this was not confirmed. The residual beach volume series correlograms have become further complicated by high frequency
Figure 2.5  Shortened and deseasonalised Moruya time series and autocorrelation as a function of lag(months) for (A) smoothed (B) residual series
disturbances and do not illustrate the annual cycles which beach width series correlogram indicate. Volumetric behaviour is therefore more aseasonal than probable beach width.

The comparability of the low frequency signal for Moruya and Narrabeen is further emphasised by examining the cross correlation coefficients for the filtered series (table 2.6). Profiles 1, 3 Moruya and 4, 8 Narrabeen record high coefficients while 2, 6 record lower but still significant values.

Cross spectral analysis was applied to relate Moruya profile 3 to Narrabeen profiles 2, 4, 6 and 8. Results (figure 2.6) indicate that the filtered series have similar spectral signatures. Narrabeen 2 and 4 have marginally higher variance in lower frequencies and lower variance in higher frequencies. For Narrabeen 6 and 8 the variance is marginally higher across the entire frequency band. Profiles 2 and 4 are predominantly in phase with Moruya profile 3 and profiles 6 and 8 are predominantly out of phase. The coherence is high in the important low frequency portion of the plot for all comparisons. Lower coherence in the low frequencies shifts towards lower frequencies in a transition alongshore from profile 8 to profile 2.

As high frequency disturbances obscure interpretation of possible temporal components Moruya profile 1 was transformed by a 4, 8 and 12 month linear filter sequence. The correlogram of 4 month filter residuals (figure 2.7) indicates no obvious cyclicity for periods less than 4 months. There is no short term correlation and the series is essentially random. The time series plot (figure 2.8) illustrates how short term fluctuations occur about the stabilised mean.

The 8 month filter alone does not smooth the low frequency signal (figure 2.9) appreciably more than is achieved by the 4 month filter. The initial 5 month cyclicity in the residuals correlogram is not explained.

By the application of a sequence of 4, 8 and 12 month filters the temporal behaviour of short term
### Smoothed series

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### Residual series

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<td>0.160</td>
<td>0.114</td>
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<td>0.586</td>
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Table 2.6 Cross correlation matrix for Moruya and Narrabeen
Results are given for both the smoothed and residual series from the 12 month filter.
Profiles 1 and 3 are from Moruya.
Profiles 2, 4, 6 and 8 are from Narrabeen.
Figure 2.6  Cross spectral analyses for Moruya profile 3 against Narrabeen profiles 2, 4, 6 and 8 for deseasonalised volume time series. Spectral density illustrated as a function of frequency (1/time)
Figure 2.7 Correlogram for Moruya profile 1 volume residual series for (A) 4 month filter (B) 8 month filter
Figure 2.8  Residual volume time series for Moruya profile one for 4 month filter
Figure 2.9 Smoothed volume time series for Moruya profile one for (A) 4 month (B) 8 month filter
disturbances can be determined. Figure 2.10 shows autocorrelation and partial autocorrelation plots for this sequence. The residuals indicate that the annual is weak and that the biennial and a possible 48 month cycle are dominant at Moruya. Thus by deleting high frequency disturbances the intermediate term temporal components can be identified. Figure 2.11 shows the equivalent 12,8,4 month filter sequence correlogram for Narrabeen profiles 4 and 8. The annual cycles are obvious but the biennial appears more significant which is not what was original suspected for profile 8. The significance of the 48 month peak in the earlier correlogram for Moruya 12 month filter residuals is here confirmed.

2.4.4 Probability Models for Observed Time-Series

The Box-Jenkins approach was employed to identify, estimate and forecast (section 2.4.5) time series data by means of a general class of stochastic models (Box and Jenkins, 1976). The fundamental concept of the approach is that any observed series is a realisation of a particular stochastic model; a stochastic time series meaning that future values are only partially determined by past values.

The identification of the type of generating stochastic process is possible because each stochastic model has a characteristic autocorrelation and partial autocorrelation function plot.

Once a time-series is stationary, it is possible to consider the problem of identifying within that sequence of observations a stochastic process which expresses the relationships between successive values in the series.

An observed series at time t, denoted X_t, is modelled as a function of past values and/or current and past values of the random shocks, both at seasonal and nonseasonal lags. This section is concerned with model identification and parameter estimation via diagnostic
Figure 2.10 Autocorrelation and partial autocorrelation as a function of lag (months) for Moruya profile one residual volume series derived from 4, 8, 12 month linear filter sequence.
Figure 2.11  Autocorrelation and partial autocorrelation as a function of lag (months) for volume series for (A) Narrabeen profile 4 (B) Narrabeen profile 8 derived from 4,8,12 month linear filter sequence
statistics and plots. Section 2.4.5 evaluates forecast functions.

The applicable statistical models are based on autoregressive and moving average processes (section 2.3.6). Autocorrelation function plots display the autocorrelations up to 60 lags and two standard error limits. Standard errors are calculated using the method devised by Ling and Roberts (1980) and are computed on the assumption that the series is random.

The process of model building is evaluated in detail for Narrabeen profile 8 to exemplify the application of methods and procedures.

The interpolated time series of Narrabeen profile 8 exhibits two noteworthy attributes. There is an upward tendency in the series mean and the series exhibits a periodic component consisting of a regular seasonal pattern with peaks occurring in summer each year. Thus the series is nonstationary.

Models were identified for original and transformed data (both with and without a fitted constant, \( e^x \)) and results compared. To transform the data, the natural logarithm (base e) of the series was taken to remove possible varying amplitude in the series over time so that the residuals from the fitted series would have a constant variance. These series were alternatively nonseasonally and seasonally differenced so as to identify the best model applicable. Nonseasonal differencing was used to convert a nonstationary series to a stationary series with a constant mean and variance. Seasonal differencing was used to model the systematic 12 month period variation identified from ACF plots.

The SPSS-X Box-Jenkins specification file used in the model identification (appendix D) therefore implemented the 'variate difference' method (Anderson, 1976).

Results for the primary ACF plots (example figure 2.12) indicated that the series was nonstationary since early autocorrelations remain large rather than decaying rapidly. A periodicity of 12 was suggested by the
Figure 2.12 Autocorrelation as a function of lag(months) for Narrabeen profile 8 interpolated volume time series
autocorrelation of 0.636 which is larger than adjacent lags and is echoed at multiple periods (24, 36...months). The extreme similarity of ACF and PACF plots determined for both the original and transformed series indicated that the log transform was not necessary for the series implying that variance is stable throughout time.

Results indicated that the standard deviation of the differenced series was minimised for one degree of non seasonal differencing. This series was formed from the original series \((x_t)\) by differencing to remove trend by:

\[
W_t = V^d x_t
\]

where in this case \(d = 1\) and so

\[
W_t = V^d x_t = (x_t - x_{t-1})
\]

Figure 2.13 illustrates the ACF plot for this series. By comparison other combinations of differencing were not as effective. The ACF and PACF plots suggested fitting a model with one moving average parameter for the stationary series as theoretical plots for MA(1) processes are finite and cut off after \(p_1\).

The next stage involved parameter estimation. The SPSS-X Box-Jenkins specification file (appendix D) indicates the model estimated.

Results indicated that the residual series variance was minimised where a constant term was included in the estimation. Parameter estimates for the differenced series were:

- MA parameter lag 1 = 0.092188
- Constant = 0.462500
- Residual series variance = 406.11

The differenced series behaviour can be defined therefore as:

\[
W_t = VX_t = 0.46250 + 0.092188 Z_{t-1}
\]

where \(Z_{t-1}\) defines a random process at lag 1.

The goodness of fit of the parameter estimates was indicated by the ACF plot for the residual series (figure 2.14). This indicates that the residuals were not entirely random but contained cyclicity suggesting that a seasonal model should be applied with a period = 12 months.
Figure 2.13  Autocorrelation as a function of lag (months) for nonseasonally differenced Narrabeen profile 8 volume series

Figure 2.14  Autocorrelation as a function of lag (months) for residual series derived from Narrabeen profile 8 nonseasonal differencing
Therefore although not optimal in the minimisation of standard deviation for a differenced series a seasonal model was considered because of the presence of a strong periodic component in the series. A new series was formed from the original by;

\[ W_t = V^d V_{12}^D x_t \]

where in this case \( d = D = 1 \) and so;

\[ W_t = VV_{12} x_t = V_{12} x_t - V_{12} x_{t-1} \]
\[ W_t = ( x_t - x_{t-12} ) - ( x_{t-1} - x_{t-13} ) \]

Figure 2.15 illustrates the ACF plot for this series. This suggests fitting a model with one moving average parameter and one seasonal moving average parameter.

Parameter estimates for the series were;

- MA parameter lag 1 = 0.33538
- SMA parameter lag 12 = 0.84531
- Constant = -0.17188
- Residual Series Variance = 324.190

The ACF plot for the residual series was now random for all lags (figure 2.16) and residual variance decreased indicating an improved model application.

The series behaviour may be defined therefore as;

\[ W_t = VV_{12} x_t = 0.33538 z_{t-1} + 0.84531 z_{t-12} - 0.17188 \]

which is a moving average process. The MA process is indicated by the identification phase PACF which cuts off at lag \( q = 1 \).

Results for other selected profiles are given in table 2.7 for both beach volume and width time series model estimates. These indicated minimisation of \( W_t \) series standard deviation for one degree of nonseasonal differencing and corresponding lower residual series variances. Series with one degree of seasonal differencing in addition to one degree of nonseasonal differencing produced the next most efficient estimates. ACF plots for nonseasonally differenced series estimates selected seasonality in some series but values for the ACF did not exceed the standard error limits and were therefore statistically random.
Figure 2.15 Autocorrelation as a function of lag (months) for nonseasonally and seasonally differenced Narrabeen profile 8 volume series.

Figure 2.16 Autocorrelation as a function of lag (months) for residual series derived from Narrabeen profile 8 nonseasonal and seasonal differencing.
<table>
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<th>MA Constant</th>
<th>MA Estimate</th>
<th>SMA Estimate</th>
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<td>324.19</td>
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**Table 2.7** Parameter estimates for moving average models for selected profiles
MA denotes moving average
SMA denotes seasonal moving average.
Tests of second order MA process models produced minor residual variance reductions but MA(1) models remained more parsimonious in description of the \(W_e\) series. Tests of model identification using a biennial operator \(V^2\) failed to reduce the series standard deviation or produce more effective estimates.

2.4.5 Forecasting Beach Change

The unique feature of time series is that successive observations are usually not independent. When successive observations are dependent, future values of the series may be predicted with a probability distribution which is conditioned by a knowledge of past values (Box and Jenkins, 1976; Richards, 1979; Chatfield, 1984) using identified, estimated stochastic models (section 2.4.4).

Because of the inherent variability of coastal systems it is not surprising to find that profile time series are stochastic. Exact forecasting procedures are discussed in Box and Jenkins (1976). The forecasts in this section were determined using SPSS-X BOX-JENKINS subroutines. The SPSS-X specification file (appendix D) indicates the model used in forecasting the series.

If after identification and estimation steps (section 2.4.4) a model was deemed acceptable, it was used to compute forecast functions. Results indicate forecasts with upper and lower confidence limits.

Results for the estimated optimal model (section 2.4.4) for Narrabeen profile 8 volume time series (table 2.7) are graphically displayed (figure 2.17) with the established series followed by the forecast function and bounded by estimated 95% confidence limits. The inclusion of a constant term decreased residual series variance and improved the forecast function confidence limits. When original rather than log base data was used the forecast confidence limits were significantly narrowed indicating that prediction based on the original untransformed data was more reliable.
Figure 2.17  Forecast series for estimated stochastic model for (A) optimal Narrabeen profile 8 (B) optimal Moruya profile 3 (C) seasonal Moruya profile 3 series
Results for Moruya profile 3 volume time series are illustrated (figure 2.17) for both a one degree seasonal and nonseasonal differenced series and the optimal one degree nonseasonal differenced series for comparison. Although the latter model is statistically optimal and produces closer confidence intervals the forecasts are clearly unrealistic incorporating trend but not seasonality or other fluctuations. The former model forecasts appear qualitatively more acceptable yet the confidence intervals diverge rapidly from 1 to 12 leads. At lead time 12 the width of the 95% confidence interval almost equals the total predicted volume in magnitude.

Clearly where the variation of the systematic part of the time series (trend and seasonality) is dominant the model may not be effective. The application of the model techniques to the entire series is probably dubious in itself because of the previously identified major low frequency signals in the Moruya time series. The application of the technique to a shorter series since 1981 when the maximum defective beach profile volume was attained would generate closer confidence intervals but fail in predictability of larger magnitude, low frequency events.

To revert to simple methods may be perfectly adequate for profile time series with pronounced trend and/or seasonality. For example the series might be represented as a linear trend (statistically significant; section 2.4.2) together with seasonal and error terms in the form:

\[ X_\tau = a + bt + s_\tau + e_\tau \]  

(2.14)

where \(a\) and \(b\) are constants. Simplicity is the advantage of such a model. Regardless these models still fail to predict the aperiodic storm events where the error term \(e_\tau\) may then exceed \(s_\tau\) and \(a + b_\tau\) to totally dominate \(X_\tau\).

2.4.6 Periodic Components of Beach Change

Spectral analysis estimated the spectral density function for various time series: the SDF described how...
variance in the series was explained by cyclic or periodic components at different frequencies.

SDF plots against frequency \( f \) were widely used to confirm periodicity initially identified in correlograms (section 2.4.3). The advantage of the SDF is it allows determination of the exact magnitude of influence that a particular temporal component at frequency, \( f \), has in a series by its contribution to the percentage of total power. Obvious trend or seasonality should be removed from the series prior to carrying out a spectral analysis as other effects will be comparatively small and are unlikely to be visible in the spectrum of the raw data.

Figure 2.18 illustrates SDF versus frequency plots for Moruya profile 4 and Narrabeen profiles 4 and 8 for trend corrected and interpolated series of beach volume and width. The SDF plots generally typify the spectrum shape observed for all raw data series. The variance is biased towards low frequency which indicates short term correlation and/or nonstationarity in the series. Table 2.8 provides the percentage contribution of significantly recurring peaks generally observed for all series. These are a biennial, and annual with weaker peaks at 3 and sometimes 6 months. The SDF plots bias (figure 2.18) generally indicate dominance of low frequency signals and the broad flat band in higher frequencies (i.e. 12 months) is indicative of high variability and/or randomness of oscillation in the short term. The SDF plots for profile width generally differ from those for profile volume in being less acutely biased towards low frequencies. Width behaviour in the short term is therefore essentially random. The Moruya spectral signature differs from the typical Narrabeen signature in being more acutely biased towards low frequencies: Moruya profile 4 volume has 67.63% of total power in the lowest band where Narrabeen volume profiles typically have around 45%. This may reflects the inclusion of the 1974 event in the Moruya series which is not included in the Narrabeen series (section 3.4.3). SDF plots for a shortened Moruya series which exclude the low frequency 1974 event failed to
Figure 2.18 Spectral density as a function of frequency for (A) Moruya profile 4 (B) Narrabeen profile 4 (C) Narrabeen profile 8 for detrended volume and width series.
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Table 2.8 Percentage of total spectral density estimate contained in various bands for selected time series. F1** indicates band 1 which is the longest period determined.
significantly change the spectral signature and rejects this as the total source of low frequency dominance. Results for Narrabeen profile 8 emphasise the dominance of seasonal fluctuations with greater variance in the annual band. Cross spectral analysis of Narrabeen profile 8 volume and width series (figure 2.19) indicates high coherence for periods longer than 6 months with the annual cycles clearly related. The series are also in phase and statistically significant for these lower frequencies. Problems with spectral analysis develop when series are too short and the seasonal variation too large for spectral analysis to give useful results. The SDF plots are shown with a bandwidth of 2 to improve confidence interval but the lack of points particularly in the Narrabeen plots hinders interpretation.
Profile Shape Analysis

3.1 Introduction

This chapter has the following specific aims:

(i) to examine the nature and magnitude of changes in profile shape for the subaerial beach using volume and width relationships;

(ii) to classify profiles for eroded and accreted states;

(iii) to examine the nature and function of incipient foredune development;

(iv) to relate available wave data to profile shape as a means of explaining observed changes. A specific question will be addressed: to determine whether the beach eroded, accreted or simply reshaped given initial shape and subsequent wave input.

In addition to information on the temporal patterns of change, beach survey data provides information on the nature and magnitude of beach profile change. Change is documented therefore not only as a long time-series of subaerial beach volume but of profile shape or the volume disposition of sediment stored in the subaerial beach.

The shape or morphology of sandy beaches and adjacent surfzones is significant because the beachface is the location of the final energy dissipation of waves. The beach configuration and gradient determines the amount of energy imparted on the beach which influences the processes and responses in the swash zone located on the lower beachface. Davis (1985) suggests that the topographic configuration displayed by most beach and adjacent nearshore profiles can be simply generalised into three zones within the profile that are subjected to rather different conditions. Firstly, the backshore extends from the normal high-tide level to the landward margin of the beach. Secondly, the foreshore which is equated with the intertidal zone. Finally, the nearshore represents the rather wide zone between the low-tide level and the seaward limit of the bar-trough topography.

Changes in profile dimension and shape express in part the relatively rapid changes in beach state and in
part the much slower changes in gross sediment volume. Discrete changes in volume represent erosion and accretion of the subaerial beach. Changes in profile shape do not lead to the same implications. What this suggests therefore is that superimposed on a time-series of overall volumetric change is a more rapid sequence of volume disposition movement or change in profile shape.

3.2 Beach profiles: a review

Investigation of beach profiles was initiated by the problem of coastal erosion (Bruun, 1954). Beach erosion is evident as a persistent problem among many coastlines (Vellinga, 1986; Douglas and Weggel, 1987). In these studies the profile is seen as the key to understanding beach behaviour.

Profile behaviour is indicative of influencing factors such as waves, tides and the effects of material and hence the profile has been adopted as a basis for classification. King (1959) refers to two main types of resultant profiles: the storm profile with break point bars related to steep waves and the summer profile with swash bars related to flatter wave shapes. An understanding of profile behaviour enables the future erosion potential to be determined. Other applications include maximising the recreational utility of the coastline (Cowell and Kotvojs, 1987).

Bruun (1954) attempted to resolve the complexities of beach erosion problems through studying the shape of the equilibrium beach profile. The equilibrium profile was defined (equilibrium under waves of constant character) and can be considered a statistical average profile.

Numerous theoretical and empirical models have been proposed (Bruun, 1954; Rector, 1954; Eagleson et al., 1963; Dean, 1977, 1983; van der Graaf, 1977; Bowen, 1981; Vellinga, 1982, 1986; Leont'ev, 1985) to predict equilibrium profiles. Conclusively these all involve a power function
of distance from the shoreline which defines a concave upwards profile.

King (1959) observed the profile starts at the berm crest because the back slope of the berm has not been directly shaped by the waves. King observed vertical scarp occurrence under the destructive action of waves, stating that eroding or eroded beaches do not have a straight profile but one which approaches a parabola in form. Such concavity is predicted by Dean's profile equation (Dean, 1977),

\[ h = - A x^m \]  

where:

- \( h \) is elevation above water level
- \( x \) is distance seaward of the shoreline
- \( A \) is a scale factor (function of sand grain size)
- \( m \) is a shape factor (set at 2/3)

Similar relationships have been found by Vellinga (1982, 1986) but for a uniform erosion profile. Significantly, the work of Bruun, Dean and Vellinga on profile prediction is only definitive of the inshore zone. Still, the equations are widely employed. The application of Dean's equation landward of the submarine beach is neither theoretically nor practically correct. This was indicated by the inconclusive results obtained by Westrupp (1984).

Sonu and others developed models for systematic beach profile changes (Sonu and Van Beek, 1971; Sonu, 1973; Sonu and James, 1973). Sonu, however, is significant for his consideration of the subaerial portion of the beach and for the development of three-dimensional models of beach change. Sonu and Van Beek's beach transition model aimed to predict successive beach profiles in terms of beach width, sediment storage and surface configuration. Their model required knowledge of existing profile shape and wave antecent parameters.

Sonu observed profile shape to be typically concave under erosion but convex under accretion. As a result of the inclusion of the berm by Westrupp (1984) an overall convex profile was indicated, rather than a concave
profile as was qualitatively apparent and widely theorised. As Sonu concluded (Sonu and Van Beek, 1971), because of the difficulty of modelling the subaerial beach it is largely excluded from consideration in profile shape studies.

Existing beach profile relationships do not model the morphology of the subaerial beach. Beyond Sonu, recent work by Cowell (1986) and Cowell and Kotvojs (1987) has considered both relationships based upon theoretical submarine beach profiles together with separate relationships for the dry beach berm. It is intuitively correct to consider separate relationships because of the distinct processes operating within these zones. Cowell and Kotvojs (1987) have defined the complete beach by:

\[
h = \begin{cases} 
  bH + z_e - (x - x_b) \tan \beta, & x_b < x \leq x_e \\
  -A(x - x_e)^m, & x > x_e
\end{cases} 
\]  

(3.2)

where;

\begin{itemize}
  \item \( bH \) is elevation of berm
  \item \( \beta \) is beach face slope
  \item \( z_e \) is water level without waves
  \item \( x_e \) position of shoreline relative to absolute datum
  \item \( x_b \) berm width
  \item \( x \) distance from origin
  \item \( h \) elevation
  \item \( A \) scale factor
  \item \( m \) shape factor, set at 2/3
\end{itemize}

This model applies to low energy beaches. The general form of the profile in cross section is concave upwards which is indicative of adjustment to surfzone processes (Dean, 1983), and convex upwards in cross section for the berm inclusion relationship. The Cowell and Kotvojs model is essentially a beach face model incorporating the intertidal and flat berm zones.

Profiles also indicate the widely observed secondary morphologies of beaches. These functions include the wave built bar, low tide terrace and berm. Cowell and
Kotvojs (1987) suggest that each of these features is superimposed upon the underlying primary beach profile. Such features tend to be ephemeral to varying degrees. This is not a new concept. Earlier qualitative research had proposed this notion (King, 1959) which was later supported by work by Hayden et al., (1975), Eliot and Clarke (1988) and others. Using empirical orthogonal function analysis (EOF) techniques they have identified modes of profile variation and isolated secondary morphologies. Differences between theoretical and measured profiles occur where these secondary morphologies occur. Hayden et al., (1975) determined the component features of the profile as the mean profile, the bar/berm, and the low-tide terrace. EOF analyses have shown bars and low tide terraces to be orthogonal to the mean profile. This implies that the mean profile and secondary morphologies are independent.

Kotvojs (1987) further considered whether a model for the dry beach face could be joined to Dean's equation. Under the assumptions of the model the equilibrium profile is independent of the presence of bars, troughs and terraces and the offshore limit is the breakpoint. The presence of bars, should therefore not affect the underlying beach profile. They can be considered as being superimposed on the equilibrium profile. Kotvojs (1987) distinguishes shape classes as a function of sediment abundance, tidal range and wave energy. The equilibrium profile shape differed between beach types. The forces responsible for producing the profile determine the value of the shape factor, m. Kotvojs (1987) concluded 'the mean beach profile was found to have a different shape for different beach types. It is consequently not possible to model all beach types by the one general equation.'

Recent studies of the beach and nearshore have emphasised the relationship between wave energy levels and accompanying surfzone dynamics and the observed resultant beach and surfzone morphology (Guza and Inman, 1975; Sasaki and Horikawa, 1975, 1979; Short, 1978; Wright
et al., 1979; Wright, 1987). This has led to a classification of beach types as dissipative and reflective with several morphologic intermediate varieties in a sequence from one to the other (Wright, 1982). Associated with each beach type are characteristic levels of beach and backshore mobility, beach form and zones of sediment storage. Characteristic profile shapes are ascribed to each beach type (Short and Hesp, 1982; Short and Wright, 1983). The observed beach-surfzone shape is produced by the dynamics associated with incident waves and wave generated currents and different reflected and resonant oscillation frequencies interacting with the beach gradient and sediment, coupled with antecedent morphologies (Short, 1979).

Wright and Short (1984) suggest that beach profiles are controlled by breaker height, period and grain size. It is important to note the subtle distinction realised herein between beach state and beach profile. If beach profiles were simple, as is roughly the case for the reflective and dissipative extremes, and if breaking waves were the only source of fluid motion acting to move sediment, which is not the case for any of the natural states, then predicting beach changes would probably be a relatively uncomplicated matter. The existence of complicated and widely prevalent intermediate states, such as those which prevail at Moruya and Narrabeen, make the natural environments less simple. Each observed beach form has a characteristic level of beach stability, zone of sediment storage and mode of beach and dune erosion.

The variation in wave energy reaching the inshore zone from deep water is of primary importance both spatially in determining characteristic differences between intra and inter regional coastal environments and temporally in determining the dynamic nature of the beach and inshore zones. The inshore wave regime depends upon both the offshore wave climate and the shallow water modification of the deepwater wave regime by the interaction of waves with the coastal boundary.
Profile behaviour is also significant in the study of foredune formation and the relationship of waves, beaches and dunes (Hesp, 1983, 1984; Short and Hesp, 1982). Contemporary foredune development is seen as a temporal analog of beach ridge formation in coastal embayments (Davies, 1957, 1977; Langford-Smith and Thom, 1969; Thom et al., 1973).

The profile shape is critical in effecting dune development in the backshore (Short and Hesp, 1982). Landward aeolian sediment transport of swash deposited sand is dependent on the subaerial beach topography and the aerodynamic flow regime across that topography.

3.3 Methods

3.3.1 Overview

Summary statistics, analysis of variance, least squares methods and other advanced statistical techniques (section 3.2) were used to determine the character and behaviour of profile shape. Data were normalised where required by squaring each element, summing, finding the square root of the sum and dividing each element by this number. If we denote elements of the normalised variable as $B_i$, this operation is

$$B_i = \frac{b_i}{\sqrt{\sum_{i} b_i^2}}$$  \hspace{1cm} (3.3)

Program NORMAL (appendix C-5) performs the transformation.

Analysis of variance (ANOVA) were used to test for the statistical significance of linear and curvilinear regression estimates. A complete discussion of ANOVA techniques can be found in Walpole (1982) and will not be discussed in this text.

3.3.2 Information Theory in Multivariate Classifications
Information theory groups observations on the basis of the inequality statistic $I$ (Semple et al., 1972; Johnson and Semple, 1983). The basis of the classification methodology is maximisation of between-group differences and minimisation of within-group differences in data matrices to produce the most effective grouping.

For any population there is a finite number of ways into which the $N$ individuals (observations or cases) can be classified into $K$ groups (where $K = 1, \ldots, N$). The classification algorithm searches, for each $K$ value, to determine that grouping which maximises the value of $R_m$; this being the test statistic which expresses the between-group inequality for the grouping as a percentage of the total inequality. $R_m$ therefore assesses the effectiveness of alternative groupings. $R_m$ may be defined as:

$$R_m = \left[ \frac{I_B(P)}{I(P)} \right] \times 100$$ (3.4)

where;

$I(P)$ is the total inequality for a given population

$I_B(P)$ is the between group inequality

The procedure is not hierarchial so that classification at one level does not constrain that at another. Clearly, the larger the number of groups considered, $K$, the larger the value of $R_m$; since a greater percentage of the variation is between groups relative to within groups. The decision on the optimal number of groups is largely a subjective one. A plot of the values of $R_m$ for each value of $K$ (stage) is diagnostic. Ideally, the most efficient number of groups is that number above which the rate of improvement in $R_m$ is significantly lessened.

Once identified, each group may be characterised by summary statistics; means and standard deviations. Each group mean can be compared to the overall mean by using the $Z$ statistic standardisation (Balock, 1960).

The $Z$ statistic is given by:

$$Z = (x - \mu) / (\sigma / \sqrt{N_o})$$
where:

\[ x \] is the mean of the group
\[ u \] is the total population mean
\[ \sigma \] is the total population standard deviation
\[ N\alpha \] is the size of the group

The Z statistic is not used to estimate statistical significance but is used to indicate the degree to which the characteristics of a group differ from those of the population from which they were selected. A greater Z statistic implies a greater difference between the group and population means.

Information theory was applied to variables which defined the profile shape so as to determine optimal groupings for overall profiles.

3.3.3 Wave Theory

Deep-water wave power is computed using wave parameter data from the Maritime Services Board waverider buoy. The following mathematical expressions are required for the computation of deep-water wave power \( P_0 \):

\[
P_0 = \left( \frac{\rho g H^3 C_g}{\pi} \right) / 8
\]

where, \( C_0 = \frac{g T_0}{2\pi} \)

and \( C_\alpha = C_0 / 2 \)

Power is expressed in watts/cm wave crest x 10^4. Program POWER (appendix C-9) calculated average monthly wave power from a master data file of daily wave statistics. Various forms of wave power expression were considered in comparison with profile shape indices (section 3.4.6). These include average monthly wave power, 3 and 7 day lag average wave power, survey to survey interim averaged wave power, and weighted filter estimates of power.

3.4 Results for Moruya and Narrabeen

3.4.1 Profile Statistics

Long term beach monitoring allows profile behaviour to be quantified. Profiles were analysed to provide
statistical information both on general trends and on the likely variations due to seasons or to the effects of weather in beach volume and width above ISLW. Individual profile data were analysed to provide a mean value, standard deviation and the minimum and maximum recorded values. The summary statistics results are provided in tables 3.1 and 3.2.

These values define the sweep zone or variation for representative profiles, a concept introduced by Barnes and King (1955, 1964). Appendix B illustrates profile envelopes or sweep zones for Moruya and Narrabeen. Superimposing a long series of beach profiles repeatedly surveyed at the same transect gives some indication of the variability of the beach. The sweep zone is the area between upper and lower extreme curves. Profile envelopes also indicate repetitive morphology and location. Such shape factors are discussed in greater detail in section 3.4.4.

Figure 3.1, provides a representation of selected data from tables 3.1 and 3.2. Moruya data are spatially limited (figure 1.4) and this localised monitoring is reflected in figure 3.1 by stable variances. Differences in absolute magnitude are due to arbitrary datum points fixed in the backshore; other variability arises from differences in incipient foredune development which is discussed in section 3.4.5.

Volumetric information is less variable than beach width. Cross correlations for Moruya and Narrabeen illustrate this (table 2.1).

Narrabeen data have the ability to express alongshore changes. Higher mean beach volume (Q values) are mainly due to differences in arbitrary datum positions. Profiles 3, 5 and 7 Narrabeen (table 3.2) should be discarded from total impressions because these data sets are of less duration. Profiles 1, 2, 4, 6 and 8 Narrabeen indicate that alongshore behaviour is not consistent. Mean volumes are higher where the backshore is natural or partially altered. Compare especially profiles 4 and 6. Profile 4 has the most natural
### Table 3.1 Morphometric parameters for Moruya profiles

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<tr>
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<th>Profile 1</th>
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<td>2.18</td>
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<td>132.7</td>
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<td>111.8</td>
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<td>55.8</td>
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<td>63.6</td>
<td>51.1</td>
<td>37.7</td>
<td>76.2</td>
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### Table 3.2 Morphometric parameters for Narrabeen profiles

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<td>sd2</td>
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<td>cv2</td>
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<td>max W</td>
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<tr>
<td>min W</td>
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<tr>
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<td>228.7</td>
<td>299.4</td>
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<tr>
<td>min Q</td>
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<td>63.6</td>
<td>51.1</td>
<td>37.7</td>
<td>76.2</td>
</tr>
</tbody>
</table>

- **n**: sample size
- **months**: length of survey
- **Q**: Average beach volume (m$^3$/m)
- **sd1**: Standard deviation of Q
- **cv1**: Coefficient of Variation for Q
- **W**: Average beach width (metres)
- **sd2**: Standard deviation of W
- **cv2**: Coefficient of Variation for W
- **Q/W**: Ratio of Q and W
- **max Q**: Maximum recorded beach volume
- **min Q**: Minimum recorded beach volume
- **max W**: Maximum recorded beach width
- **min W**: Minimum recorded beach width
Figure 3.1 Profile volume and width summary statistics for Moruya and Narrabeen; lines represent means, maximum and minimum and ±1 standard deviation bands.
backshore and profile 6 the least. Profiles 4 and 6 have the highest variability, which is consistent with their modal intermediate beach state (Short and Wright, 1985). This is indicated by high coefficient of variations (CV) where the CV of width provides a dimensionless backshore mobility index. As the CV increases from zero towards one mobility increases. A strong seasonal trend at profile 8 is reflected in the standard deviation of width which provides a shoreline mobility index.

Comparatively, Moruya has marginally lower CV values reflecting marginally lower mobility. Qualitatively higher modal beach state at Moruya would explain lower mobility. Cross correlation results for Moruya and Narrabeen series (table 2.1) indicate that volumetric information is less variable than beach width.

3.4.2 Profile Volume and Width relationships

Sonu (1973) analysed profile volume and profile width relationships as deterministic of profile shape. Profile behaviour can be quantified by determining these variables. Intuitively \( Q \) is proportional to \( W \) and the exact relationship of \( Q \) and \( W \) expresses changes in profile shape in time and space. As the ratio \( Q/W \) increases the profile segment gradient increases to produce a steeper, more convex upwards beach profile. Whether exact \( Q/W \) relationships exist for various profile types is assessed in section 3.4.4.

Tables 3.3 and 3.4 summarise results of simple linear regression analyses of Moruya and Narrabeen \( Q \) and \( W \) data. Results for both raw and normalised data are presented. The analysis was applied for volume as a function of width. The F test statistic was critical for all regressions indicating that significant relationships exist. As indicated previously, Narrabeen profiles 3, 5 and 7 are excluded from direct comparison because the data sets are of shorter duration.
### Table 3.3 Regression coefficients for Moruya volume as a function of width
Results are given for both original and normalised data for I SLW and half metre incremented levels above I SLW.

<table>
<thead>
<tr>
<th>Level</th>
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<td>1.020</td>
<td>0.963</td>
</tr>
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<td>0.5 m</td>
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<td>1.090</td>
<td>1.140</td>
<td>1.070</td>
</tr>
<tr>
<td>1.0 m</td>
<td>0.912</td>
<td>1.130</td>
<td>1.120</td>
<td>1.060</td>
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<tr>
<td>1.5 m</td>
<td>0.821</td>
<td>1.070</td>
<td>1.050</td>
<td>0.992</td>
</tr>
<tr>
<td>2.0 m</td>
<td>0.703</td>
<td>0.968</td>
<td>0.952</td>
<td>0.901</td>
</tr>
<tr>
<td>2.5 m</td>
<td>0.571</td>
<td>0.846</td>
<td>0.843</td>
<td>0.770</td>
</tr>
<tr>
<td>3.0 m</td>
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<td>0.795</td>
<td>0.706</td>
<td>0.643</td>
</tr>
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<td>4.0 m</td>
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<td>0.610</td>
</tr>
<tr>
<td>4.5 m</td>
<td>0.594</td>
<td>1.203</td>
<td>0.579</td>
<td>0.484</td>
</tr>
</tbody>
</table>

### Table 3.4 Regression coefficients for Narrabeen volume as a function of width. Results are given for both original and normalised data for I SLW and half metre incremented levels above I SLW.

<table>
<thead>
<tr>
<th>Level</th>
<th>Profile 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>I SLW</td>
<td>0.679</td>
<td>0.678</td>
<td>0.851</td>
<td>0.824</td>
<td>0.830</td>
<td>0.811</td>
<td>1.060</td>
<td>1.020</td>
</tr>
<tr>
<td>0.5 m</td>
<td>0.806</td>
<td>0.770</td>
<td>0.949</td>
<td>0.963</td>
<td>0.953</td>
<td>0.909</td>
<td>1.180</td>
<td>1.180</td>
</tr>
<tr>
<td>1.0 m</td>
<td>0.978</td>
<td>0.879</td>
<td>1.050</td>
<td>1.040</td>
<td>1.020</td>
<td>1.020</td>
<td>1.190</td>
<td>1.260</td>
</tr>
<tr>
<td>1.5 m</td>
<td>0.923</td>
<td>0.940</td>
<td>1.030</td>
<td>1.050</td>
<td>0.989</td>
<td>0.958</td>
<td>1.100</td>
<td>1.300</td>
</tr>
<tr>
<td>2.0 m</td>
<td>0.828</td>
<td>0.880</td>
<td>0.987</td>
<td>1.020</td>
<td>0.908</td>
<td>0.845</td>
<td>0.943</td>
<td>1.280</td>
</tr>
</tbody>
</table>
Figures 3.2 and 3.3 illustrate individual profile Q and W for original data for Narrabeen and Moruya respectively. At Moruya, regression coefficients are consistent which is expected as the data is spatially limited. Variability in the normalised relationships reflect differences in incipient foredune development. Incipient foredune morphology represents an additional subaerial storage function. This is discussed fully in section 3.4.6. Summation of the normalised data for Moruya (figure 3.4) indicates an average relationship; 
Beach volume (Q) = 0.965 Beach width (W) ,
r^2 = 75.5 ,
F_{calculated} >> F_{0.01}(1,864).
This was calculated based on the assumption of close proximity for the Moruya profiles which in the original study design was intended to allow averaging to exclude small scale topographic effects and therefore give a better indication of trends or effects.

Narrabeen data have the ability to express alongshore changes. Normalisation of data removes magnitude effects caused by arbitrary datum positions. This allows comparison of average Q/W behaviour between profiles. Interpretation suggests shape changes from profile to profile alongshore. The Narrabeen data (table 3.4) indicates alongshore profile behaviour is not consistent. Low coefficient values indicate a flatter, more concave beach profile (profiles 1 and 2). High values indicate a steeper, more convex beach profile (profile 8). These extremes and the trend is consistent with concepts of the beach model developed by Short, Wright and others with lower energy beaches having steeper morphology which occurs at the southern end of the Narrabeen embayment.

The Moruya and Narrabeen coefficients are not directly comparable. The inclusion of secondary incipient foredune morphology in Moruya surveys will raise the Q/W ratios to provide the result indicated in table 3.3.

Figure 3.5 illustrates the relationship for volume and distance change from survey to survey for profile 3.
Figure 3.2  Scatter diagrams for observed profile volume and width for all Narrabeen profiles
Figure 3.3 Scatter diagrams for observed profile volume and width for all Moruya profiles
MORUYA ALL PROFILES NORMALISED

Figure 3.4 Normalised relationship for beach volume and width for all observed Moruya profiles
Figure 3.5  Relationship of survey to survey changes in volume and width for Moruya profile 3
Moruya. Generally, a reduction in volume would parallel a reduction in width. While this general trend is apparent, wide scatter normal to the trend indicates positive volume change with width reduction and vice versa. This is indicative of volume redistribution rather than loss from the subaerial beach. The profile is therefore reshaping.

Tables 3.3 and 3.4 also summarise results of linear regression analyses for profile volume as a function of profile width for 0.5 metre vertically wide horizontal beach segments at Moruya and Narrabeen. Incremental analysis results for both raw and normalised data are given. Results indicate that all profiles become initially more convex above ISLW, from 0.5 to 1.5 metres above ISLW, before reverting to increasingly lower gradient tendencies. The profile above ISLW therefore adopts a 'S' shape. This is indicated by coefficient variability which reflects changing sediment storage for a given profile width as described above. Moruya profiles store more sediment as a function of width for all levels which reflects additional volume stored in dune morphology (section 3.4.5) with the exception of Narrabeen profiles 7 and 8: these are the low energy extremes and have characteristically steep profile morphology (Wright et al., 1982). The similar values do not therefore indicate similarities in profile shape in this instance. At Narrabeen lower coefficient values alongshore indicate changes in profile gradient with the flattest profiles located at the northern high energy extreme of the beach. This association of shape and energy agrees with commonly acknowledged observations in the literature (King, 1959; Komar, 1976).

3.4.3 Beach recovery

The time series of beach volume for Moruya profiles is dominated by major erosive events and subsequent beach recovery. The available data allows rates of beach volume
recovery to be assessed and comparisons to be made between the behaviour of respective field sites.

Qualitative assessment of the Moruya time series revealed a number of erosive episodes of varying magnitude (section 2.4.1). Beach recovery at Moruya is assessed for profile 3 in this section.

Differences in pre 1974 and post 1980 recovery levels of the beach volume at Moruya are evident. Such differences are attributed to a number of factors. The pre 1974 event beach was not indicative of a long term equilibrium beach. It is suggested that the present beach equals the pre 1974 beach plus a further contribution from offshore. In addition there may be possible fluvial input (Hall, 1981) and other recovery effects such as the function of debris aiding exaggerated incipient foredune growth (section 3.4.5). This is illustrated by comparing beach statistics from pre 1974 when the beach was at its most accreted state with an equivalent period in 1981 and 1986 (table 3.5).

The 1986 mean volume represents a 1981 mean volume plus an additional calculated incipient foredune storage function of 24.82 m³/m (section 3.4.5). Figures for 1973 and 1981 are comparable allowing for seasonal beach oscillations and short term microtopographic influence on surveys. A t-test was significant at the 0.10 level (t_{calculated} = -1.089 ; t_{critical} = -1.761 ) which indicates that the 1973 and 1981 mean volumes are statistically equivalent.

Further comparison was made between profiles in 1972 and 1979 (table 3.5). A t-test statistic indicates an equivalent mean volume;

(t_{calculated} = 0.1262 ; t_{critical} = 1.645)

From the time series (appendix A) the beach during these periods was still in the process of profile accretion or a recovery phase. Figure 3.6 illustrates this concept further. The profile in its most accreted pre erosion phase state is superimposed on its equivalent 1979 post erosion phase recovery profile. This enhances the concept of repetitive morphology or developmental stage. The
<table>
<thead>
<tr>
<th>Year</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>314.983</td>
<td>10.312</td>
<td>10</td>
</tr>
<tr>
<td>1981</td>
<td>322.674</td>
<td>18.240</td>
<td>6</td>
</tr>
<tr>
<td>1986</td>
<td>345.782</td>
<td>17.830</td>
<td>6</td>
</tr>
<tr>
<td>1972</td>
<td>256.459</td>
<td>23.097</td>
<td>24</td>
</tr>
<tr>
<td>1979</td>
<td>265.117</td>
<td>27.600</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 3.5 Profile statistics for Moruya profile 3
N denotes number of observations.
Figure 3.6 Profiles from pre and post erosion dominated period, Moruya profile 3
beach was essentially in the same long term stage or recovery phase. It has reattained not only volume but profile shape. Previous erosion dominated events occurred in the period 1966 - 1968 but unfortunately no survey data are available from this period. This indicates a process of progressive accretion will terminate in a stable quasi-static (seasonally wave influenced) beach unless a random storm event interrupts the sequence.

Thom and Roy (1988) have recognised two distinct periods of shoreline change and termed these as erosion and accretion dominated periods, EDP and ADP respectively. At Moruya the continuity of the accretion phase was interrupted in mid 1973 before the ADP achieved its fullest expression. The erosion events preceeded the ADP dune development stage. When the volume of sediment stored in the contemporary incipient foredune is subtracted and means compared with post erosion recovery levels (table 3.5) the values are consistent. It appears that the 1973 peak is not indicative of a stable situation.

To assess rates of subaerial beach volume recovery at Moruya regression analysis was applied to five significant recovery phases indentified from the time series. Results are contained in table 3.6. For profile 3 Moruya, linear regression results are statistically significant at the 1% level. A number of features are apparent. Rates are more rapid for recovery when volume depletion is most severe; an example is phases 2 and 3 with respective rates of 0.361 and 0.419 m$^3$/m/day. Rates decrease as beach volume increases; example phase 1 had a rate of 0.176 m$^3$/m/day.

A linear regression of 1972 and 1979 for volume as a function of time indicates:

\[
\text{Volume}_{1972} = 238.47 + 0.167 \, \text{(days)} ; \quad r^2 = 75.9\% \quad (3.6)
\]

\[
\text{Volume}_{1979} = 233.96 + 0.185 \, \text{(days)} ; \quad r^2 = 77.4\% \quad (3.7)
\]

The rates are statistically significant at the 1% level. This further indicates how the beach was in an equivalent stage of behaviour in 1972 and 1979. Both mean volumes and rates of accretion are equivalent.
<table>
<thead>
<tr>
<th>Profile Phase</th>
<th>Linear Coeff.</th>
<th>Polynomial Coeff.</th>
<th>R2</th>
<th>F calc1</th>
<th>F calc2</th>
<th>F crit</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moruya profile 3 volume</td>
<td>172.8</td>
<td>0.029</td>
<td>-0.00012</td>
<td>89.1</td>
<td>146.89</td>
<td>30.78</td>
<td>7.31</td>
</tr>
<tr>
<td>5</td>
<td>268.7</td>
<td>0.114</td>
<td>-0.00005</td>
<td>61.8</td>
<td>18.60</td>
<td>0.84</td>
<td>7.88</td>
</tr>
<tr>
<td>5a</td>
<td>156.0</td>
<td>0.040</td>
<td>-0.00023</td>
<td>87.8</td>
<td>40.96</td>
<td>10.41</td>
<td>10.04</td>
</tr>
<tr>
<td>5b</td>
<td>121.6</td>
<td>0.039</td>
<td>-0.00005</td>
<td>60.9</td>
<td>18.60</td>
<td>0.84</td>
<td>7.88</td>
</tr>
<tr>
<td>Moruya profile 3 width</td>
<td>79.8</td>
<td>0.071</td>
<td>-0.00003</td>
<td>46.6</td>
<td>15.68</td>
<td>3.39</td>
<td>7.31</td>
</tr>
<tr>
<td>5</td>
<td>62.4</td>
<td>-0.067</td>
<td>0.00050</td>
<td>60.4</td>
<td>7.61</td>
<td>2.39</td>
<td>10.04</td>
</tr>
<tr>
<td>5a</td>
<td>100.8</td>
<td>0.044</td>
<td>-0.00002</td>
<td>24.7</td>
<td>3.61</td>
<td>0.37</td>
<td>7.88</td>
</tr>
<tr>
<td>5b</td>
<td>119.3</td>
<td>0.105</td>
<td>-0.00008</td>
<td>8.4</td>
<td>1.84</td>
<td>3.52</td>
<td>7.31</td>
</tr>
<tr>
<td>Narrabeen profile 2 volume</td>
<td>78.3</td>
<td>0.551</td>
<td>-0.00091</td>
<td>60.9</td>
<td>8.57</td>
<td>5.06</td>
<td>9.65</td>
</tr>
<tr>
<td>5b</td>
<td>213.6</td>
<td>-0.376</td>
<td>+0.00038</td>
<td>56.8</td>
<td>17.06</td>
<td>25.85</td>
<td>7.72</td>
</tr>
</tbody>
</table>

Table 3.7 Results of curvilinear regression analyses for recovery phases. DOF denotes degrees of freedom. R2 denotes the coefficient of determination.
Rates of accretion dwindle as the beach volume approaches an equilibrium. The reaction rate begins rapidly and slows as the end point is reached. For example the dominant EDP to ADP recovery phase 5 (figure 3.7). Although an average rate of $0.120m^3/m/day$ was identified as significant it appears that the points approximate a curve rather than a straight line. Curvilinear regression analysis was applied to this phase. Results are contained in table 3.7.

F-test statistics indicate the increase in the degree of the polynomial has significantly improved the fit of the regression. The phase from June 1978 - November 1981 indicates peak initial rates of $0.269 m^3/m/day$ and equilibrium is attained by July 1981 when rate equalled zero. The recovery phase includes a relatively minor 1979 erosion event. Subdividing phase 5 into pre and post 1979 phases, 5a and 5b respectively, and reanalysing indicates peak initial rates of $0.406 m^3/m/day$ which compares with phase 2 and 3 values. Results of curvilinear regression analysis for phase 5b failed to provide a significant statistical improvement over simple linear regression.

At Narrabeen beach recovery is inconsistent between profiles. The Narrabeen time series also does not record the major 1974 erosive event and does not display patterns which are consistent with those observed at Moruya. An erosive event in 1980 at Narrabeen is not evident at Moruya. Narrabeen profiles do not display simple ADP - EDP behaviour identified at Moruya with the possible exception of the southern profiles 6, 7 and 8.

The results of analysis of equivalent phases in time at Narrabeen profile 2 are contained in table 3.7. F-test statistics indicate relationships are weak or non-existent. The beach at Narrabeen does not therefore respond in an equivalent echo fashion to Moruya in time. Recoveries are apparent and sometimes equivalent (phase 4). Recovery rates vary alongshore by as much as the relative severity of storm impact. This is
Figure 3.7 Time series of dominant EDP - ADP volume recovery for Moruya profile 3 with fitted polynomial
exemplified by comparison of post 1978 storm recovery for various profile series (appendix A) at Narrabeen.

At Narrabeen trends in recovery do not appear comparative in time with the magnitude of seasonal effects often obscuring real recovery. The complexity may be related to the character of intermediate beach types with high characteristic mobility in the short term obscuring longer term behaviour. This points to inherent data limitations. More mobile beaches require more frequent monitoring.

3.4.4 Definition of eroded and accreted profiles

Classification of profile shape was approached using information theory. The incremental approach was adapted to shape description. Raw survey data for each profile were reduced to distance and volumetric information for 0.5 metre (vertical width) horizontal segments of the beach profile. These segments were related to ISLW and correspond approximately with different process zones. Matrices of volumes and distances were therefore produced for each set of profile data for the length of the time series. The variation both within and between surveys in incremental volume and beach segment width expresses variations in beach shape.

The information statistics program (Johnson and Semple, 1983) grouped profiles based upon these shape criteria. The analysis of original format data produced erratic results because of magnitude effects. The data was therefore normalised (Program NORMAL, appendix C-5) before processing. The results are tabulated (table 3.8) and plotted (figure 3.8) as the test statistic R* against the number of classes or stage. The resulting curves adopted a similar shape signature suggesting a consistency in profile behaviour.

Results (figure 3.8) indicated that shape as defined by the beach segment width matrix provided a higher level of explanation than the corresponding incremental volume
<table>
<thead>
<tr>
<th>Number of classes</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Moruya Profiles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Volume</td>
<td>55.3</td>
<td>66.4</td>
<td>73.6</td>
<td>80.5</td>
<td>82.7</td>
<td>85.4</td>
<td>86.6</td>
<td>87.5</td>
<td>88.4</td>
<td>89.4</td>
<td>90.1</td>
</tr>
<tr>
<td>1 Width</td>
<td>54.3</td>
<td>63.7</td>
<td>77.5</td>
<td>80.2</td>
<td>84.2</td>
<td>87.0</td>
<td>88.5</td>
<td>89.2</td>
<td>89.0</td>
<td>90.5</td>
<td>90.9</td>
</tr>
<tr>
<td>3 Volume</td>
<td>42.2</td>
<td>57.3</td>
<td>66.8</td>
<td>74.6</td>
<td>77.9</td>
<td>81.8</td>
<td>83.9</td>
<td>85.2</td>
<td>86.2</td>
<td>86.9</td>
<td>87.6</td>
</tr>
<tr>
<td>3 Width</td>
<td>43.1</td>
<td>60.4</td>
<td>69.0</td>
<td>75.4</td>
<td>78.4</td>
<td>81.5</td>
<td>82.9</td>
<td>84.7</td>
<td>85.7</td>
<td>86.5</td>
<td>87.2</td>
</tr>
<tr>
<td><strong>Narrabeen Profiles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Volume</td>
<td>22.8</td>
<td>35.5</td>
<td>46.3</td>
<td>51.0</td>
<td>57.6</td>
<td>60.0</td>
<td>63.0</td>
<td>66.4</td>
<td>69.3</td>
<td>70.5</td>
<td>72.7</td>
</tr>
<tr>
<td>2 Width</td>
<td>28.8</td>
<td>47.5</td>
<td>57.2</td>
<td>61.5</td>
<td>66.6</td>
<td>68.0</td>
<td>72.9</td>
<td>74.1</td>
<td>75.2</td>
<td>78.2</td>
<td>80.0</td>
</tr>
<tr>
<td>4 Volume</td>
<td>33.1</td>
<td>51.2</td>
<td>56.1</td>
<td>62.9</td>
<td>65.4</td>
<td>69.1</td>
<td>71.7</td>
<td>73.4</td>
<td>73.8</td>
<td>75.3</td>
<td>76.0</td>
</tr>
<tr>
<td>4 Width</td>
<td>42.9</td>
<td>55.0</td>
<td>65.9</td>
<td>70.0</td>
<td>73.8</td>
<td>75.7</td>
<td>77.3</td>
<td>78.9</td>
<td>82.0</td>
<td>81.1</td>
<td>81.4</td>
</tr>
<tr>
<td>6 Volume</td>
<td>37.9</td>
<td>55.0</td>
<td>62.3</td>
<td>67.7</td>
<td>70.9</td>
<td>72.1</td>
<td>75.6</td>
<td>76.0</td>
<td>76.6</td>
<td>79.7</td>
<td>80.9</td>
</tr>
<tr>
<td>6 Width</td>
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<td>45.0</td>
<td>55.4</td>
<td>62.1</td>
<td>66.0</td>
<td>69.1</td>
<td>70.1</td>
<td>73.7</td>
<td>75.8</td>
<td>77.4</td>
<td>78.0</td>
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<td>8 Volume</td>
<td>59.3</td>
<td>71.8</td>
<td>75.2</td>
<td>78.3</td>
<td>81.0</td>
<td>83.0</td>
<td>84.5</td>
<td>85.7</td>
<td>86.4</td>
<td>86.8</td>
<td>87.4</td>
</tr>
<tr>
<td>8 Width</td>
<td>57.0</td>
<td>66.8</td>
<td>70.6</td>
<td>75.1</td>
<td>77.4</td>
<td>79.8</td>
<td>83.5</td>
<td>84.9</td>
<td>85.9</td>
<td>86.9</td>
<td>87.7</td>
</tr>
</tbody>
</table>

Table 3.8  Entropy classification for selected profiles.
Results indicate percentage explanation by class.
Figure 3.8  Relationship of number of classes to percent explained (Rs curve) for (A) width shape index (B) volume shape index (C) both width and volume for Moruya (1,3) and Narrabeen (2,4,6,8) profiles
matrix for each profile. Beach width therefore provides a more efficient means of shape indexing. The curve trend for Narrabeen is for a greater percentage explanation by stage for profiles successively alongshore towards lower energy conditions. Resulting curves for Moruya indicate higher levels of explanation by stage than Narrabeen. These findings have implications for profile variability in addition to those for profile shape.

The coefficient of variation for beach volume and width provided a relative beach mobility index (tables 3.1 and 3.2). The order of curve ranking (figure 3.8) agrees with the range of calculated coefficients with the exception of profile 2. This indicates a near consistent ranking of profile stability:

Most stable 1 3 8 4 6 2 Least stable

The ranking may be explained using the beach model (Wright and Short, 1984). Profiles 1,3 are high intermediate; profiles 8,4 low intermediate and profiles 6,2 are modal intermediate or most mobile.

The repetitive nature of plots of $R_m$ versus stage (figure 3.8) suggest that a basic number of groups or classes of profile shape may be identified. Decisions as to the optimal number of groups is largely a subjective one. A plot of $R_m$ values for each stage is diagnostic. Ideally, the most efficient number of groups is that number above which the rate of improvement in $R_m$ is significantly lessened. The turning point of the curve is therefore critical.

Figure 3.8 summarises results of $R_m$ versus stage. While it is difficult to identify a common turning point, 3,4 and 5 class groupings are dominant with Moruya indicating a higher number of optimum classes. The higher optimum number of classes for Moruya may be due to the bimodal profile population caused by ADP – EDP transfer. This will be discussed later in this section. The optimum for Moruya appears to be 4 to 5 classes and for Narrabeen 3 to 4 classes.
Figures 3.9 and 3.10 illustrate the reality of profile groupings for profile 3 Moruya and profile 8 Narrabeen respectively, by overlaying member profiles for each of the optimum classes. The resulting classification of Narrabeen is inconclusive, due to the nature of the survey data as originally collected. Attempts to classify the subaerial beach for Narrabeen are difficult because the monitored profile collects information from an arbitrary datum which is located on the berm. The survey is not inclusive of a dune function but rather emphasises the subaqueous beach profile. Increased groupings at Narrabeen merely imply a concave profile with berm dimensionalised subgroups producing an increasingly convex form (figure 3.10).

Resulting envelopes are more significant for Moruya (figure 3.9). There appears to be three dominant morphological functions. These are a concave upward primary profile shape and secondary berm and dune shapes. Intuitively, with three functions, only two of which are variable, only four possible shape combinations exist in the long term. These are: concave; concave and berm; concave and berm and dune; concave and dune. The relationship of these shape functions is illustrated in figure 3.11.

Under EDP conditions the beach fluctuates between shape types 1 and 2 (figure 3.11). In the transition to ADP shape types 3 and 4 become prevalent. Narrabeen fails to exemplify this classification because the surveys do not monitor the dune zone which has largely been altered or obliterated and the duration of surveys do not extend to pre 1974.

Normalised beach width and volume data are presented with information statistics groupings delineated for the optimum Moruya profile 3 grouping (figure 3.12). Sonu (1973) attempted a similar representation in beach face shape classification. The distinction between shapes as a function of overall profile volume and width is not clear. Figure 3.13 represents all raw profile volume and width data plotted with temporally consecutive
Figure 3.9 Profile envelopes for Moruya profile 3 grouped into 4 classes by information theory
Figure 3.10  Profile envelopes for Narrabeen profile 8 grouped into 3 classes by information theory
Figure 3.11 Profile shape classification model
Figure 3.12  Scatter diagram for normalised volume and width for (a) 4  (b) 6 classes for Moruya profile 3
Figure 3.13  Observed volume and width relationships for profiles one Moruya and Narrabeen with temporally consecutive interconnecting lines
Figure 3.14  Profile envelopes for Moruya profile 3

grouped into 6 classes by information theory
interconnecting lines for Moruya and Narrabeen. The Moruya population contrasts with the Narrabeen population in being distinctly bimodal. The two subpopulations represent the profile behaviour under distinct EDP and ADP conditions. The profile is translated onshore under EDP and is represented by the lower grouping. The profile returned to the upper group following beach recovery. Due to this bimodality the classification by information statistics is initially unclear as illustrated by attempts to isolate groups by scatter diagrams of volume and width by class (figure 3.10).

Profile envelope results for six classes aids the identification of the optimal classification which is obscured by the series bimodality (figure 3.14). From the six envelopes, four types are apparent. The represented types are (i) a concave ADP and a concave EDP profile (1a and 1b); (ii) a concave plus berm ADP and a concave plus berm EDP profile (2a and 2b); (iii) a concave plus berm plus dune profile (3); and (iv) a concave plus dune profile (4). Within the domain of EDP and ADP these represent accretion and erosion extremes. Four shape types are apparent: an eroded-eroded profile; an accreted-eroded profile; an eroded-accreted profile and an accreted-accreted profile.

3.4.5 Foredune development

Foredunes develop on the vegetated sand surface of the beach profile beyond normal wave influence. In shape, foredunes are generally shore parallel, convex ridges with concave swales commonly separating the ridges (Hesp, 1984). Incipient foredunes are the initial foredunes located in the most seaward of dune positions. They are formed by aeolian accretion in laterally continuous (alongshore) zones colonised by perennial seedlings.
At Moruya the monitoring of beach profiles has been inclusive of the incipient foredune zone. Incipient foredunes have been observed to develop by aeolian and vegetative processes and be later removed by wave incursion. The development of incipient foredunes can be assessed at Moruya from the monitored changes in surface elevation at the four profiles in a continuous trace from 1982-1986 inclusive.

At the beginning of 1982, Moruya beach had recovered significantly in width and volume from the devastating effects of erosive events during 1974-1978. The recovery morphology of the monitored profiles consisted of a low established foredune with accreted scarp, an unvegetated swale and a wide, low gradient berm. The development of an initial low terrace shaped incipient foredune the incipient foredune was based on the preceeding development of the wide low gradient berm. The incipient foredune was initiated by aeolian accretion dichotomous with the growth of Spinifex sericeus.

In contrast, at Narrabeen beach the monitored profiles are not inclusive of foredune morphology but were originally intended to indicate inshore morphological behaviour. In addition the urban environs have completely altered the original foredune beyond assessment.

Landward aeolian sediment transport of swash deposited sand is dependent on the subaerial beach topography and the aerodynamic flow regime across that topography. The profile shape is critical in affecting dune development in the backshore (Short and Hesp, 1982). Observations at Moruya indicate a critical beach width (volume) is required as a prerequisite to dune genesis. Contrastingly, other beaches located directly to the south of the Moruya beach and river had developed extremely wide stable berms by 1982 yet in the concurrent time period the incipient foredunes have failed to develop beyond a low terrace morphology. Hesp (1983) argues the relevance of debris in dune genesis. The Moruya river which divides these beaches experienced
large scale flooding in 1975 and 1976 with the result that much of the length of the Moruya beach was heavily littered with large scale debris, especially logs. This debris, not apparent on the adjacent southern beaches, was eventually buried by the accreting profile with the uppermost debris protruding from the berm and forming the basis for the incipient foredune. Hesp (1983) refers to the sand trapping ability of debris and associated shadow dunes. Personal observations of wave incursion into the incipient foredune zone have revealed the underlying debris protruding from scarps and subsequently being reburied.

The development of a large incipient foredune at the monitored sites contrasts its absence to the south. Beaches further to the north also have more developed incipient foredunes intermediate in stature to Moruya and its southern neighbours.

At Narrabeen the observed absence of an incipient foredune can be attributed to human influence and pressures literally walking on the profile, dispersing its convexity and killing the pioneering spinifex so essential to incipient foredune development. However the natural incipient foredune would develop at Narrabeen given the opportunity and interestingly observations of profile envelopes (appendix B) indicate that the incipient foredune would develop in an equivalent morphometric position.

At Moruya the stoss face (accreted scarp) of the older foredune was produced by storms in 1974 and reinforced in 1978 though not advanced upon. The beach recovered from 1978 to 1981. By 1982 a low terrace incipient foredune existed. By 1986 the characteristic morphology of convex and concave vertical growth due to aeolian movement of sand was well developed.

During the dune growth phase there was no significant wave incursion into the incipient foredune zone. On rare occasions when the frontal berm was depleted, such as during the August 1986 storms, high tide swash limits contacted the base of the incipient
foredune but with no apparent morphological effects. However personal observation beyond the spatially limited monitoring site indicated significant scarps of up to one meter magnitude in incipient foredunes at the southern extreme of the beach in August 1986.

The profile cross section sequence (figure 3.15) indicates the salient features of dune development, qualitatively indicating vertical growth of the incipient foredune and concurrent depletion of the backshore swale. Hesp (1984) proposed aerodynamic vortices as being intensified by incipient foredune elevation growth. Concurrent with growth is foredune asymmetry and onshore movement. Alongshore, the continuous incipient foredune crest elevation varies by approximately ±0.25 metres. In its present accreted state, microstructures are common as hummocks and other small slugs of sand move over the dune shape. Small scale fluctuations in the annual profile envelope attest to these features as various surveyors alternatively site readings on or besides these features.

The long term behaviour of the incipient foredune during 1982-1986 growth phase was assessed through plots and linear and curvilinear regression analysis. By considering the measured changes in surface elevations at each of the four profiles over five years, rates of accretion both maximum and average and both vertically and shore normally were determined. The time series of elevation data in the area relevant to incipient foredune morphology were plotted and regressed to calculate average point to point behaviour. The results are contained in table 3.9.

Average vertical growth rates are highest about the dune crest and decrease asymmetrically with an emphasis on onshore movement of the dune. The growth of the convex dune shape is therefore self reinforcing. Rates of vertical growth were averaged between profiles 2, 3 and 4. The replicate time series for optimum growth location at profiles 2, 3 and 4 is given in figure 3.16. A linear regression determined an average vertical growth rate of 0.207 metres/year. The regression was statistical.
Figure 3.15 Incipient foredune development

cross sectional sequence
<table>
<thead>
<tr>
<th>Profile</th>
<th>Location</th>
<th>Coefficient</th>
<th>R²**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40m</td>
<td>0.083</td>
<td>57.4</td>
</tr>
<tr>
<td>1</td>
<td>45m</td>
<td>0.083</td>
<td>45.0</td>
</tr>
<tr>
<td>1</td>
<td>50m</td>
<td>0.184</td>
<td>66.9</td>
</tr>
<tr>
<td>1</td>
<td>55m</td>
<td>0.089</td>
<td>20.3</td>
</tr>
<tr>
<td>2</td>
<td>30m</td>
<td>0.057</td>
<td>59.7</td>
</tr>
<tr>
<td>2</td>
<td>35m</td>
<td>0.178</td>
<td>81.3</td>
</tr>
<tr>
<td>2</td>
<td>40m</td>
<td>0.201</td>
<td>92.0</td>
</tr>
<tr>
<td>2</td>
<td>45m</td>
<td>0.079</td>
<td>38.0</td>
</tr>
<tr>
<td>3</td>
<td>30m</td>
<td>0.028</td>
<td>32.2</td>
</tr>
<tr>
<td>3</td>
<td>35m</td>
<td>0.097</td>
<td>81.6</td>
</tr>
<tr>
<td>3</td>
<td>40m</td>
<td>0.171</td>
<td>79.6</td>
</tr>
<tr>
<td>3</td>
<td>45m</td>
<td>0.126</td>
<td>64.2</td>
</tr>
<tr>
<td>4</td>
<td>40m</td>
<td>0.058</td>
<td>30.1</td>
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<td>0.188</td>
<td>71.2</td>
</tr>
<tr>
<td>4</td>
<td>50m</td>
<td>0.249</td>
<td>66.4</td>
</tr>
<tr>
<td>4</td>
<td>55m</td>
<td>0.145</td>
<td>65.7</td>
</tr>
</tbody>
</table>

Combined profiles 2, 3, 4

0.207 81.1

**Table 3.9** Results of linear regression analyses of incipient foredune development, Moruya. **R² denotes the coefficient of determination.**
Figure 3.16  Superimposed time series of incipient foredune development at the dune crest for Moruya profiles 2, 3 and 4
significant at the 1% level with a correlation coefficient, $r = 0.901$.

Limitations caused by the 5 metre incremental nature of data collection have a coarse filter effect on these values. It is difficult to obtain a more accurate assessment of growth rate values unless a more spatially intensive survey technique is used.

Profile 3 was assessed in greater detail as representative of overall dune behaviour. Although correlations are high and significant it was apparent from the appearance of the fitted line that a straight line does not closely approximate the data. From figure 3.15 it is visually apparent that as the dune increases in elevation it also moves onshore. Consequently it would be expected that the point of optimum growth rate would also move. Therefore at any point it may be expected that the data would approximate a smooth curve rather than a straight line as deposition rates increased initially through the optimum and then waned as the dune moved further onshore.

An analysis of variance (ANOVA) was constructed to assess the estimated growth rate equations. A polynomial curve was fitted to the data by least squares. ANOVA was applied to test if the increase in the degree of the polynomial had significantly improved the fit of the regression. The point of maximum rate of incipient foredune growth was observed to have moved onshore from 45 metres to 40 metres relative to arbitrary profile datum. The time series of surface elevation for these survey points (figure 3.17) are illustrated with the fitted polynomial curve. Calculated $F$ statistic values exceeded critical for both curves, indicating that the quadratic regression was a significant improvement over the linear regression alone.

$F_{critical} \alpha=0.01 = 7.08$
$F_{40m} = 19.34$
$F_{45m} = 28.88$

The approximating curves were:

$$y = -2.68023 - 0.00357 x + 0.03417 x^2$$  \hspace{1cm} (3.8)
Figure 3.17 Time series of incipient foredune elevations for (a) 40 and (b) 45 metre points relative to arbitrary datum for Moruya profile 3 with fitted polynomial
for the 40 and 45 metre points respectively. The curves indicate maximum vertical growth rates of 0.338 and 0.343 meters/year respectively. By considering the turning points of these curves where predicted growth rates are zero, the lateral (onshore) rate of dune movement was assessed as 1.256 metres/year.

Differences in profile envelopes between 1981 and 1986 allow the volume of sediment stored in the subaerial incipient foredune morphologies to be assessed. The primary incipient foredune volume (figure 3.15) was 13.09 m$^3$/m. In addition a secondary incipient foredune, intermediate to the established foredune and incipient foredune, was observed to develop at all profiles, having a volume, when combined with the accreted stoss face, of 11.73 m$^3$/m. The combined incipient foredune volume represents 7.8% of total sediment storage above ISLW and 17.6% above ISLW plus 2 metres.

The growth of incipient foredune volume as an additional volume storage function with a combined volume of 24.82 m$^3$/m does not account for differences in mean volume for pre - 1974 and post - 1981 accretionary dominated periods. Either additional sediment volume has been input or the pre - 1974 beach was not indicative of a long term stable accretionary dominated period volume.

3.4.6 Wave power and profile relationships

The time series of average monthly wave power for the Botany Bay wave rider is illustrated in figure 3.18. Results obtained by Trenaman(1985) (figure 3.19) for average monthly deepwater wave heights illustrate seasonality in the climate with peaks in March and June and troughs in May and September. Qualitative assessment of the original series suggested that the time series was not stationary. The series was detrended by separating linear regression estimates and residuals prior to analysis. The result of the linear regression was:

$$y = -2.72603 + 0.34329 x - 0.04256 x^2$$ (3.9)

Average Monthly Wave Power = 25.67814 + 0.00037 (days)
Figure 3.18 Time series of average monthly wave power for the Botany Bay wave rider, April, 1971 to March, 1987.
Figure 3.19 Time series of average monthly deepwater wave heights off Botany Bay (After, Trenaman, 1985)
where \( \text{day}(1) = 010171 \) and \( r = 0.054 \),

\[
F\text{-test statistic} = 0.54312, \quad F_{\text{critical}} = 6.63.
\]

Although not statistically significant as a regression the transformation creates a stationary series with mean zero which is an essential prerequisite to analysis (section 2.3.1). Average monthly wave power is therefore increasing at a rate of \( 0.135 \text{ watts/cm x 10}^4/\text{year} \) (figure 3.18).

The autocorrelation and partial autocorrelation functions were calculated for the detrended series (figure 3.20) for lags 1 to 60. These indicate that the series contains virtually no short term correlation. The lag(1) coefficient of 0.118 indicates a weak positive relationship where a month with higher or lower than average wave power will be followed by a similarly biased month. There appears to be sinusoidal behaviour in the autocorrelation of the detrended series which indicates an annual (12 month) cycle which is obscured by shorter term fluctuations. The dominant significant peak however is a biennial cycle. Series modelling (section 2.3.6) by the application of difference operators could not reduce series standard deviation below that of the original series.

Fast fourier transform (FFT) of the detrended series produced a spectral density function (figure 3.21) which formed a wide band across the range of frequencies with peaks at the biennial, annual, 9 and 3 month periods. The wave power time series therefore has a dominant biennial/annual signal with noise or short term oscillations (particularly in the 3 month period) complicating the longer term pattern.

To enhance the understanding of the temporal qualities of the average monthly wave power time series a 12 month seasonal filter (Program SEASON, appendix C-6) was applied. This separated the series into temporal components acting as a high pass filter for periods less than 12 months. The autocorrelations, partial autocorrelations, and FFT were evaluated for these series. The autocorrelation function for the 12 month
Figure 3.20  Autocorrelation and partial autocorrelation as a function of lag (months) for detrended average monthly wave power time series.
Figure 3.21 Spectral density as a function of frequency for detrended average monthly wave power series
smoothed series (figure 3.22) clearly identifies the dominant biennial cycle. With the removal of fluctuations of period of less than 12 months the smoothed series demonstrates a consistent sinusoidal behaviour with high positive correlation between successive months. The partial autocorrelation for the smoothed series fluctuates rapidly initially and decays with a mixture of damped sinusoids and exponentials which implies a mixed ARMA(1,1) model (section 2.3.6) with parameters $\theta$ and $\phi$ both positive would be appropriate for its description. Dominant peaks at 12 and 24 lags indicates filter bypass caused by using a 12 month filter when a 24 month cycle was dominant. The autocorrelation for 12 month filter residual series (figure 3.23) indicates randomness as lag(1) is not statistically significant. The short term wave climate fluctuations are therefore highly variable or random.

The spectral density function for the smoothed and residual series (figure 3.24) emphasises the 24 month peak, 12 month peak in residuals and a broad band across all frequencies with the 3 month period of marginally greater significance.

King(1959) considered the distinction of destructive and constructive waves as a function of wave steepness. It was suggested that the more frequent the profile survey interval, the better changes could be correlated with the frequently changing patterns of wave action. Sonu and Van Beek(1971) did not agree with this conclusion. They questioned how beach changes were related to waves. Their attempts to correlate wave parameters and profile characteristics were unsuccessful. Sonu and Van Beek compared wave heights and 12 hour changes in sediment storage and failed to find a significant correlation. Their results indicated that both erosion and accretion would result for waves of identical height. No significant distinction in wave steepness was recognised between waves associated with erosion and those associated with accretion. Sonu and Van Beek suggested that the classification of constructive
Figure 3.22  Autocorrelation and partial autocorrelation as a function of lag (months) for deseasonalised smoothed time series of average monthly wave power
Figure 3.23  Autocorrelation and partial autocorrelation as a function of lag(months) for deseasonalised residual time series of average monthly wave power.
Figure 3.24  Spectral density as a function of frequency for deseasonalised average monthly wave power for (A) smoothed (B) residual time series
and destructive waves by means of wave steepness (King, 1959) was an oversimplification. They did however find better correlation when wave direction was considered but could determine little explanation. No directional data are reliably available for the Sydney wave climate.

To relate available wave data to profile shape as a means of explaining observed changes requires selection of suitable wave power and shape indexes to ratify shape as a function of power. Power indexes initially considered were average monthly power, 3 and 7 day wave averages, and survey to survey interim wave averages. The profile was initially quantified as the total volume time series and profile to profile volume change as a function of power was considered.

Narrabeen profile 2 was assessed (figure 3.25) because of close proximity to the wave data source and because of the profiles open ocean aspect. Results are as inconclusive as those obtained by Sonu and Van Beek (1971). Log relationships were no more explanatory. Both positive and negative changes in total subaerial beach volume were observed for comparative average power indexes. This is not altogether unexpected given the monitoring interval of one month. Wright et al., (1985) suggest beach response is much more sensitive. Fluctuations in the survey to survey interim may be greater in magnitude than suggested by the end product surveyed. This is particularly evident in the inherent variability of day to day wave statistics.

When both wave conditions and beach morphology are constantly changing, as observed both at Moruya and Narabeen, the degree of association between instantaneous profile form and wave power is poor owing to the response lag of the beach morphology (Wright et al., 1985). The association may be improved by employing a weighted filter estimate of wave power, \( P_w \), to account to some degree for the role of antecedent conditions. The weighted filter power estimates were calculated from;
Figure 3.25 Scatter diagram of relationship of observed profile volume change and average interim wave power
\[ P_w = \left[ \sum_{i=1}^{D} 10^{-\frac{D}{10}} \right]^{-1} \sum_{i=1}^{D} \left( P_i 10^{-\frac{i}{10}} \right) \] (3.11)

where \( i = 1 \) on the day prior to the survey and \( i = D \) on \( D \) days prior to the survey.

The value of \( \varnothing \) depends on the rate of memory decay of the system. Wright et al., (1985) developed this weighted filter for Dean's dimensionless fall velocity parameter (Dean, 1973). They repeated the association analyses to relate beach type to Dean's parameter using different combinations of temporal parameters.

The character of the beachface was considered by quantifying the character of a 2 metre (vertical width) horizontal segment above ISLW and seaward of the profiles 2 metre datum intersect. In this way the most dynamic or active portion of the beach was related to wave power. Beachface shape descriptors for the active zone were volume, width, average slope and the \( Q/W \) ratio (section 3.4.2). The weighted filter was determined for 5, 7, 14 and 30 day lags and applied to produce a weighted estimate wave power for each observed group of shape parameters (Program WEIGHT, appendix C-10). Results (figure 3.26) proved inconclusive with both positive and negative changes in beachface shape observed for equivalent wave power. Wright et al., (1985) found the best explanation to be obtained for \( \varnothing = 5 \), and \( D = 30 \) days for beach type - Dean's parameter relationships using equation 3.11. Results failed to find improvement using various lags although \( D = 7 \) days was the most significant.

Because of the monthly interval of surveys and the observed rates of beach change (Wright et al., 1985) the shape parameters based on volume and width descriptors may not be representative. The beachface could have achieved the observed end product via many intermediate pathways.

Plotting the relationship of \( P_w \) to average beachface slope (Narrabeen profile 2 data) also proved inconclusive. However when the observations were divided upon the
Figure 3.26 Scatter diagram for active beach zone and power relationship for (A) width (B) volume (C) Q/W ratio
criterion of observed erosion or accretion (indexed by decreases or increases in active zone volume) results (figure 3.27) indicated a coarse cluster of accretion types for lower gradient average beachfaces while erosion types were observed for all slopes but with a bias towards higher $P_w$ and steeper slopes. The behaviour of the beachface in response to erosive wave action was to create steeper beachface slopes and in response to accretive wave action was to create flatter beachface slopes. This is opposite to widespread observations in the literature (e.g. Komar, 1976). Explanation lies in the nature of definition of beachface volume where even in the event of overall subaerial volume loss volume could increase in this zone. Further, because slope can only be determined as an average derived from a coarse 10 metre survey interval the estimates could often be inaccurate. The steeper recorded slope under erosive waves indicates beach face scarping. Lower gradients under accretionary waves are due to onshore bar movement. In addition deepwater wave estimates often do not accurately index inshore wave conditions (Trenaman, 1985). If changes of less than $5 \text{ m}^3/\text{m}$ are considered to be effectively zero and the slope and $P_w$ replotted with these excluded the subdivision of accretion and erosion types becomes more distinct (figure 3.27).

Beachface volume was plotted against beachface width following the techniques of Sonu (1973) to attempt to identify beachface profile shape types. Results (figure 3.28) fail to isolate obvious groups of shapes identified by Sonu, probably because of the poor efficiency of monthly shape estimates mentioned above.

Further attempts were made to relate volume to power by cross spectral analysis (CSA). Series were detrended and filtered to remove background and irregular disturbances. Profiles 2, 4, 6 and 8 Narrabeen and profile 3 Moruya were considered. Results of CSA between wave power and the transformed volume series indicate higher levels of coherence in the annual than the biennial for all profiles (figure 3.29). Consistent phase behaviour
Figure 3.27 Scatter diagram for relationship of active beachface slope as a function of weighted wave power for (A) erosion and accretion subgroups (B) erosion and accretion subgroups with stable observations deleted
Figure 3.28 Scatter diagram of beachface volume and width observations
Figure 3.29 Cross spectral analyses of wave power and detrended and deseasonalised volume series for Narrabeen (2, 4, 6, 8) and Moruya (3)
indicated that the annual cycle of volume peaks lags the power peaks by 5.5 months at Narrabeen and 5.8 months at Moruya. For the biennial the lags were 10.3 and 10.9 months respectively. This implies that higher wave power levels are associated with lower volume levels with a delay effect operating in profile response if wave power is the responsible forcing. However this analysis cannot rationalise this question. Other attempts to relate volume series directly to wave power by CSA proved inconclusive because of noise effects.
4. Implications of the study

4.1 Discussion

This study was essentially two-faceted in aiming to determine both the spatial and temporal behaviour of profiles as described by two large datasets. Chapter 2 undertook to determine via TSA the temporal components of profiles observed in the field. Chapter 3 undertook to statistically characterise and classify profile shape. The aims were therefore to develop an understanding of both the shapes which profiles will adopt under varying circumstances and when such changes will occur.

TSA determined that beneath an secular trend and irregular or random short term fluctuations there existed a profile to profile recognisable low frequency signal. Similarities indicate that these may be responses to large scale regional processes. Wright (1987) has suggested that bidirectional shore normal sediment transport across the shoreface may be a key factor affecting both short and long term fluctuations of the beach profile. Eliot and Clarke (1982a) suggest that 'lags between offshore deposition of sediment by storm rip activity and subsequent subaerial beach recovery may produce a long period quasi-cyclic pattern of beach change'. Annual and biennial periodic oscillations were also identified from the analyses.

Results (section 3.4.4) indicate that the natural subaerial beach shape can be classified based upon long term profile behaviour. The profile was determined to consist of a primary erosive function with a concave upwards shape and secondary accretive functions with convex upwards shapes. The complete range of profile forms and volume levels continues to recur despite occurrences of severe erosion. Monitoring of the subaerial beach at Moruya indicates that distinct phases of shoreline change occur. These have been termed erosion and accretion dominated periods (Thom and Roy, 1988). Deficiencies in the Narrabeen dataset and local factors such as urban pressures are considered to be responsible
for a lack of clear recognition of the erosion-accretion phase signature in the Narrabeen series.

4.2 Modelling profiles

Many researchers have indicated that high energy conditions promote beaches which approach a parabola in form (Bruun, 1954; Dean, 1973; Vellinga, 1982). These theoretical studies have been constrained so as to describe only the subaqueous profile. Results indicate (section 3.4.4) that the subaerial beach shape can be classified based on long term behaviour. The commonly accepted concave upwards erosion profile was found to occur as the primary profile shape. With accretion secondary morphologies would develop (berm and dune functions) which were convex upwards in shape and independent of the primary profile. Research by Hayden et al., (1975) and others, using empirical orthogonal function analysis, have determined similar morphological independence from a primary profile function. The beach shape was found to translate shore normally as the beach moved from accretion to erosion dominated phases. The accretion and erosion phase distinction was clearly demonstrated by bimodality in the beach volume and width populations for Moruya beach (figure 3.13). During both periods the full range of observed beach types were observed. With subsequent recovery repetitive morphology was observed to develop as profile shape in the recovery phase followed a strict morphological sequence. Results suggest that the basement concave profile function supports a suite of secondary convex functions from dune to berm to low tide terrace and finally single or multiple bars. The basement profile is indicative of equilibrium associated with current sea level (Bruun, 1954). The secondary morphologies are accretionary features. The relative disposition of sediment volume in each of these independent morphologies has important implications for intermediate term beach stability.
Temporal domain results indicated that the series are dominated by low frequency signals with high frequency disturbances which are statistically random. Data transformation and filter applications were necessary to remove these effects. However random elements, which are a consequence of the monthly survey, interval continue to obscure periodic behaviour in varying degrees related to individual profile stability. The detrended and filtered series for comparable time windows for Moruya and Narrabeen were determined (section 2.4.3) and found to be remarkably similar. The implication is that when site specific trends (due to long term sediment budget imbalances) and high frequency random elements (due to irregular storm events) are removed the underlying signal can be identified (figure 2.5). This signal confirms that a common environmental forcing possibly related to waves or sea-level effects exists.

Results of attempts to apply conventional time series modelling to series proved inconclusive and otherwise over elaborate. These results (section 2.4.4/2.4.5) suggest a predictability which is over complex and these series could be more readily represented by a simple model such as a linear combination of trend, seasonality and error terms. Observations however indicate that it is the complete unpredictability of the error term - which may vary from minor storm impact to a major cluster of storms leading to severe erosion of the subaerial beach - which frustrates attempts to successfully model the temporal behaviour of beach profiles. Prediction of future behaviour is further complicated because the driving forces and system responses continue to change through time. Temporal models remain elusive and if they could be determined would need to be continually adjusted.
4.3 Beach erosion and recovery

The documentation of long time series of subaerial beach volume allows the nature and magnitude of profile change to be assessed. Erosion is evident as a persistent problem along many coastlines. Gordon (1987) indicates that most of the New South Wales coast is presently undergoing long term recession and suggests that examples of coastal embayments experiencing long term accretional trends and/or stability are rare. However results indicate that Moruya represents a stable embayment shoreline while in contrast the Narrabeen embayment long term trends indicate recession in the north to accretion in the south for the study period.

In the short time domain beach fluctuations occur in response to random storm wave activity. Storms produce rapid profile responses and are well documented in the literature (Ziegler et al., 1959; Birkemeier, 1979; FitzGerald, 1979; Vellinga, 1982; Sunamura, 1983; Lins, 1985; Kriebel and Dean, 1985; Takeda and Sunamura, 1986) and generally lead to erosion. When storms are severe, or when a sequence or persistence of storms occurs, large scale beach erosion can occur with subaerial beach volume being moved offshore to form surfzone bars. Subsequent low wave power conditions promotes an accretionary phase and the beach volume redevelops.

Cycles of shore normal sediment exchange without net loss have been attributed to periodic behavioural shifts in wave climate and mean sea level. Contrastingly the secular behaviour of profiles has been attributed to a net loss or gain from the active zone of the coastal system. The persistence or groupiness of storms over time has led to the concept of storminess (Bryant, 1987, in press; Thom and Roy, 1988). Thom and Bowman (1980) commented on beach erosional periods involving ‘clusters’ of storms. Such sustained periods of erosion are of irregular incidence with similar events observed on the New South Wales coast in 1912, 1950, 1967 and 1974; the 1974 event is documented in the Moruya time series (appendix A). Bryant (1983) determined similar erosional and accretional phases, operating on Stanwell Park beach.
on the south coast of New South Wales, based on a time series of high tide position.

Results (section 3.4.3) indicate that accretion is a much less rapid process. Time series of beach volume (appendix A) allowed rates of volume recovery to be assessed and comparisons to be made between the study sites. Results for Narrabeen indicated that alongshore behaviour of beach volume through time was not consistent. The Moruya series indicated a different signature dominated by major erosional events and subsequent beach recovery. Attempts to relate concurrent volume behaviour proved inconclusive. When an accretionary phase persisted at Moruya it could not be assumed that a similar phase would be observed at Narrabeen. Erosion could be observed at Narrabeen profiles while Moruya profiles accreted and vice versa. Much of the irregularity can be attributed to short term fluctuations caused by a monthly sampling interval being affected by topographic transitions and minor storm events. A comparison of filtered series proved more conclusive (section 2.4.3).

Additional recovery factors observed at Moruya included site specific effects such as possible fluvial input (Hall, 1981), and the effects of debris in accelerating incipient foredune development. Results (section 3.4.3) for Moruya indicate that the process of progressive accretion will terminate in a stable equilibrium beach unless a random storm event(s) interrupts the sequence. The strength of the Moruya recovery signal also enabled the concept of repetitive morphology or developmental stage in profiles to be explored (section 3.4.3). Results of curvilinear and simple regression analysis quantified rates of recovery of subaerial beach volume for Moruya and Narrabeen. Recovery was observed to be initially more rapid and of greater magnitude when depletion was most severe. Beach erosion and recovery in this context therefore refers to a low frequency domain phenomena. Thom and Roy (1988) have
4.4 Foredune behaviour

Results (section 3.4.5) indicated the nature and function of incipient foredune development in beach profile behaviour. Incipient foredune behaviour was dimensionalised and the contribution of the incipient foredune to profile shape as a secondary morphology was determined. The salient features of incipient foredune shape development were defined by an uninterrupted survey data time series of five years duration from 1982 - 1986 inclusive at Moruya. A temporal assessment of incipient foredune data led to estimation of rates of accretion vertically and shore normally both averaged and maximum.

The incipient foredune shape is a unique component of the observed beach profile through its representation of a purely subaerial function. The incipient foredune is purely aeolian derived although it depends directly on swash deposited sediment as a source for accretion. The incipient foredune shape is also unique as it is indicative of an accreted, stable endpoint in long term profile behaviour. A condition which currently exists at Moruya.

Profile shape is critically linked to incipient foredune development in the backshore (Short and Hesp,1982). Onshore aeolian transport of swash deposited sediment is dependent on the subaerial beach topography and the aerodynamic flow regime across that topography with beach gradient and width being prominent factors. The morphodynamic model of beaches (Short and Wright,1985) proposes that the gradient and width of beaches is related to the mode of wave approach and degree of dissipation and that in the long term most beaches tend towards occupying a modal beach state with a particular subaerial morphology. Potential aeolian sediment transport depends upon the preliminary and
sustained provision of a wide, low gradient berm. At Moruya the accretionary phase satisfied this criterion by 1982. The berm must extend or widen to also provide a basement or substrate for the incipient foredune to develop upon as the stable segment of the berm transforms itself into a new backshore area. If a satisfactory wind source exists (onshore and of velocity in excess of sediment threshold values) a flow regime will develop across the topography. The smoother the surface the less the velocities fluctuate or are reduced and the greater the potential for sediment movement. Abrupt topographic changes induce changes in the velocity fields such that separation, internal boundary layers and large scale dissipative vortices may be created. These act to reduce the velocity and consequently the volume of sand transported (Hesp, 1983). Subaerial morphology or profile shape of a beach therefore has a direct effect on the volume and rate of onshore sediment transport.

Qualitative appraisal of incipient foredune growth from profile plots for Moruya indicates an initial low, terrace-shaped, incipient foredune. With time this feature grew vertically, moved onshore, became increasingly asymmetric and increasingly convex upwards from dune peak to concave upwards in the dune swale (figure 3.15). Once the incipient foredune shape irregularity is established, probably by pioneering Cakile and Spinifex seedlings deposited by high tide swash limits, the process became self reinforcing in shape development. The onshore wind flows across the berm surface mobilising sediment. The flow then characteristically increases in velocity up the dune face, detaches or separates at the dune crest and reattaches a distance downwind dependent upon free stream velocity (Hesp, 1984). In this way the crest accretes asymmetrically as sediment is lost from both suspension and bedload transport as the flow detaches suddenly and because sediment bearing flow is generally only onshore. Therefore, since the rate of deposition increases downwind an asymmetric deposit
forms. The observed morphology of convex and concave vertical growth at Moruya confirms this behaviour.

Observations at Moruya indicated that a critical berm width was required prior to incipient foredune development presumably both as a basement for incipient foredune stabilisation and as a source of aeolian borne sediment. Contrasting observations at nearby beaches indicated low terrace shaped dunes typifying an early stage of development or failure to develop further in view of existing stable, low gradient, wide berms. It was proposed that flood debris which was extremely localised in deposition was in some way contributory in respect of flow disturbances related to debris induced deposition.

Results of cross section sequences (figure 3.15) indicated the features of dune shape development with vertical crest growth, backshore swale depletion, foredune asymmetry and onshore movement. Through the application of curvilinear and simple linear regression analyses the average and maximum vertical growth rates and onshore movement rates were determined. In this way the temporal components of shape evolution were quantified.

Profile comparison (section 3.4.5) enabled isolation of the incipient foredune as an independent, secondary sediment storage function, which for Moruya profile 3 contained 7.8 % of total subaerial volume above ISLW. This has implications for volume reserves contained in dunes which form buffers in major erosion events. The isolation of incipient foredune volume for the 1982-1986 time series does not account for differences in stable volume between this period and the preceeding ADP (pre mid 1973). This implies that the pre mid 1973 beach was not indicative of what could be termed the equilibrium beach. In addition to the incipient foredune recent profiling indicates the development of an additional subaerial foredune in the lee of the incipient foredune and partially overidding the accreted stoss face of the original backshore relict foredune.
At Moruya and many other coastal embayments series of shore parallel, convex upwards ridges form plains in the coastal embayments. Commonly termed beach ridges they are well documented in the literature on the south-east Australia (Davies, 1957; Langford-Smith and Thom, 1969; Davies, 1977; Thom et al., 1981; Short and Hesp, 1982). Several modes of beach ridge formation have been proposed including accreted bars and berms (Hine, 1979) and storm built berm and beach deposits (Psuty, 1966). Hesp (1983, 1984) proposes that these are relict foredunes and therefore implies that an understanding of incipient foredune behaviour is important in the context of understanding the formation of these coastal ridges.

4.5 Wave power and profile behaviour

Results of analyses which aimed to relate wave data to profile shape as a means of explaining observed changes generally proved inconclusive (section 3.4.6). Both the morphologic and dynamic nature of the beach are process - response linked directly or indirectly with wave action. The beachface is the location of the final energy dissipation of waves. Intuitively relationships are expected to exist between wave and profile indices.

Statistical and time series analysis identified the trend and temporal components of the wave power data. The deepwater wave power recorded off Sydney is increasing and is dominated by biennial and annual cycles with superimposed irregular or random elements creating a highly variable, complex character. TSA indicated no short term correlation in the series. Previous work on the Sydney wave climate by Trenaman (1985) and Trenaman and Short (1987) statistically characterised the deepwater and breaker wave characteristics and also detected consistent seasonality beneath apparent high variability.

Specific aims to determine whether profiles eroded, accreted or reshaped for a given initial beachface slope and subsequent wave input generally proved inconclusive.
Simple associations such as wave power and volume change (figure 3.25) failed and suggested the inapplicability of available survey data to these analyses. Earlier literature assertions about simple wave classifications as erosive or accretionary were not always supported by field observations. Field studies by Sonu and Van Beek (1971) tested how beach changes were related to waves. Correlations between wave height and sediment storage were not significant. Results (figure 3.25) indicated a similar result to that obtained by Sonu and Van Beek (1971) for such simple associations. Contrastingly, Thompson and Harlett (1968) found good correlations between deepwater wave steepness and wave power and observed profile changes. However, their work was confined to a simple low energy, linear reflective beach. Theoretical studies have correlated wave steepness thresholds to offshore/onshore sediment movement (Saville, 1957; King, 1972) and field studies continue to attempt to verify this relationship. The determination of a simple parameter describing incipient shore normal sediment movement would prove extremely beneficial to engineers and planners but remains to be rigidly defined.

Trenamen (1985) has determined that the Sydney deepwater wave climate contains a significant seasonal directional behaviour. Sonu and Van Beek (1971) determined that better correlation in their associations were possible when wave direction was considered. Results of TSA for volume and width series for Narrabeen beach (section 2.4.3) indicate alongshore inconsistency in the behaviour of temporal components. The notion of direction in wave approach being significant was further supported by the clearly annual behaviour of Narrabeen profile 8 (section 2.4.3). The isolated two-dimensional profile fails to relate to wave power because sediment movement in the shore parallel is not described in the absence of a third dimension.

Results of TSA of beach profile series (section 2.4.3) and wave power series (section 3.4.6) identified a common dominant biennial cycle when the series were
filtered to remove high frequency disturbances. In the wave power series such fluctuations in the high frequency band were shown to be statistically random. In the profile series the monthly sampling interval was shown to be also prone to short term variability due to the migration of various topographic features such as rip channels and cusps. Eliot et al.,(1982) and Eliot and Clarke(1982a) suggested that long term trends and short term fluctuations are superimposed on periodic shoreline fluctuations which occur in response to regular shifts in mean sea level and wave climate. The obvious question was whether the biennial signal in the observed wave series was responsible for the biennial response in the profile series. To test the assertion the series were detrended and filtered to remove background and irregular disturbances and cross spectral analyses applied (section 3.4.6). Results of CSA of the transformed power and volume series indicated varying degrees of coherence in the biennial band. Generally coherence was lower for the biennial than for adjacent bands and the interpretation of the analyses was limited by the application of CSA to a small dataset (N=132) such that results were inconclusive.

The inshore wave regime depends upon both the deepwater wave climate and the shallow water modifications caused by the interaction of deepwater waves with the coastal boundary (Wright and Thom,1977). Variations in inshore wave regime are important spatially in determining characteristic differences between intra and inter regional coastal environments. The complexities of the Narrabean nearshore topography (figure 1.4) and evidence of variable directional climate indicate that a spatially and temporally complex situation exists. Results of simple direct associations of power and profile indices are therefore poor.

Inconclusive results of wave power and profile indices association can further be attributed to the inapplicability of the survey data. Deepwater wave statistics are not directly indicative of inshore wave
character (Trenaman, 1985). The inshore wave regime is clearly complicated by nearshore boundary effects and in liaison with directional components becomes even more unpredictable. Profile indices based on data derived from a monthly sample interval may be temporally secondhand. Profile indices are also based on a 5 or 10 metre survey interval which often results in loss of detail particularly on the beachface where slope response has been shown to be maximal (section 2.4.2). It is hardly surprising that clear relationships cannot be found especially when Sonu and Van Beek (1971) failed using a 12 hourly sampling interval.

Further results (section 3.4.6) indicated broad relationships between beachface slope and filtered wave power when erosion and accretion subpopulations were distinguished (figure 3.27). The best association using filtered wave power was found using a seven day lag. Similarly, Aubrey et al., 1980 found weekly mean wave energy to be the best predictor of beach change.

4.6 Field site comparisons

Differences in local study environments and profile monitoring techniques and their application at Moruya and Narrabeen have produced two distinct datasets. Results indicate that this has had important implications for the applicability or usefulness of the datasets.

At Moruya the original prime objective of monitoring was to relate beach face morphology to seasonal and longer term changes in wave and atmospheric climate (Thom and Bowman, 1980). At Narrabeen the emphasis has been to develop a model of three dimensional beach behaviour. The Moruya study therefore emphasises the subaerial beach while the Narrabeen study design has emphasised the inshore zone. Differences in sampling intervals (section 1.5.1) both spatially and temporally have directly affected the applicability of the data to various analyses in this study.
Results (section 3.4.5) indicate that it was not possible to develop a comparative profile shape classification for Moruya and Narrabeen because of the exclusion (or obliteration) of the backshore zone from Narrabeen surveys.

TSA (section 2.4.1) described series for all profiles (appendix A) which initially appeared quite distinct. However, application of TSA techniques resulted in the determination of an underlying low frequency signal (section 2.4.3; figure 2.5) which indicated remarkable similar temporal behaviour between the two sites. In the high frequency domain results indicated that it is not possible to relate immediate beach responses. This was due to a discrete monthly sampling interval where observed fluctuations caused by transitional morphologies often exceeded in magnitude other behaviour. Results indicated profile oscillations with a common biennial and seasonal component operating at both field sites. This temporal component was later detected in the wave data time series (section 3.4.6).

Inter and intra regional beach behaviour differs owing to spatial variations in boundary configurations, exposure to incident wave energy and available sediment sources (Wright et al., 1979). Personal observations suggest that Moruya beach occupies a slightly higher modal beach state than Narrabeen. Profile behaviour is influenced also by the influence of riverine input of sediment (Davis and Hayes, 1984) and other debris. Due to sediment deficiencies along the New South Wales coast (Roy, 1983) local areas of input become important in determining profile recovery. The physiography of the Moruya Heads-Broulee beach is clearly influenced by the Moruya (Deua) river located adjacent to its southern extreme (figure 1.3). This river is one of the few fluvial systems actively dispersing sediment onto the New South Wales coast (Hall, 1981). However, the precise role of fluvial input to beach recovery at Moruya remains to be determined. The Narrabeen-Collaroy beach has only the
Narrabeen lagoon (figure 1.4) which makes only a negligible if not negative contribution.

McLean and Thom (1975) have suggested that natural, open beaches are more elastic and subject to less short-term noise than modified beaches because beach management structures interfere with natural coastal processes and responses; further, long-term trends can be more easily detected on natural beaches where profile geometry more accurately reflects the general beach condition. Eliot et al., (1982) have noted that it is not possible to distinguish between beach oscillation components related to ocean processes such as wave climate, mean sea-level changes and those dependent on local topographic controls such as bay seiching from singular studies. A first step towards identifying processes that are of a regional or local significance is through comparative studies examining similar data sets by using the same analytical techniques.
5. Conclusion

5.1 Study conclusions

Statistical and time series analysis enabled both the characterisation and classification of subaerial profile shape and the identification of temporal components of profile behaviour for the Moruya and Narrabeen survey datasets. Subaerial profiles have basic shape elements which recur through time. These shape elements were found to be superimposed upon shore normal profile translation as the profile moved from distinct erosion to accretion dominated periods. Results indicate that it is possible to decompose complex time series of subaerial profile beach behaviour into temporal components. These components were attributed to both localised and regional scale effects. In the short time frame profile fluctuations were attributed to infrequent storm wave activity which was observed to promote rapid profile response. Combined with a discrete monthly sampling interval the short time frame behaviour included transitional morphologies and was determined to be irregular, statistically random and unpredictable. This was supported by the absence of short term correlation in the Sydney wave dataset.

Long term trends were identified in the Moruya and Narrabeen datasets. The central Moruya embayment was found to be stable in the long term. The Narrabeen embayment contains a trend from net erosion in the north to net accretion in the south for the study period. Local effects and especially the function of fluvially derived material input including logs was suggested as causing observed differences in long term behaviour between the study sites. The character of the dominant 1974 erosion event was documented in the Moruya dataset. Secularity was attributed to net imbalances in the sediment budget for the active zone of these coastal embayments.

In the intermediate term annual and biennial period components were found in both the Moruya and Narrabeen datasets with the biennial generally dominant. It was
suggested that periodicity reflects regular shifts in wave climate and mean sea level.

To determine if regional forcings existed it was found necessary to remove both the short term random and local environment effects described above. An underlying low frequency domain signal was found which indicates profile response to large scale regional processes. Causality was tentatively approached but results were found to be inconclusive. The problem is to resolve the relative impact of storms, waves, sea level effects, rainfall and other environmental forcings. Only if these factors can be resolved can models of shoreline change be developed and the problem of recent worldwide coastal erosion realistically approached.

5.2 Survey data limitations and problems

Times series monitoring of profiles requires repetitive measurement of survey transects which is both laborious and expensive. Profile surveying involves determining elevations relative to a datum along a linear transect (Owens, 1982). For Moruya and Narrabeen two distinct techniques were used (section 1.5.1). To reduce operator variance and maintain data uniformity survey profile elevations were taken at constant fixed intervals. At Moruya the transect spatial interval was 5 metres and at Narrabeen 10 metres.

Phillips (1985) proposed a methodology to determine the minimum number of elevation readings needed to achieve a given accuracy. The method involved use of the semivariance function which reveals spatial dependencies in survey data. This enabled estimates of the optimal profile sample interval to be made and may justify less intensive surveys in the shore normal direction. However the technique proved applicable only where profiles are monitored to establish sediment volume changes and is distinct to surveys designed to record details of shoreline processes where the identification of
particular morphologies is important. Results of analyses of incipient foredune behaviour (section 3.4.5) and wave power - profile associations (section 3.4.6) indicate that additional spatial detail is required and this emphasises the problem of applying fixed increment data to microtopographic studies. A mixed profiling strategy may prove to be the optimal recommendation for shore normal, spatial sampling density where additional detail is recorded but only in a limited zone. The monitoring of profiles would then provide data suitable to a wide range of applications. It should be noted that it has been practice at Moruya to record intermediate breaks of slope so that the problem has in some ways been approached.

Further problems were observed between the Moruya and Narrabeen data sets in the absolute range of surveys. The Moruya survey begins in the natural backshore above the accreted stoss face of the established foredune and extends across the beach to at least ISLW. In contrast the Narrabeen survey emphasises the inshore employing a survey technique applicable in this zone. The Narrabeen survey has a coarser sampling density than Moruya and is prone to lose detail particularly between the berm crest or scarp if present and ISLW; this is an area where slope changes have been shown to be most evident (section 3.4.2). In the inshore the accuracy of the Narrabeen survey may prove dubious in bad weather and/or wave conditions. The Narrabeen survey records the profile beginning at a floating datum and fails to incorporate incipient dune morphology. Although this is because the incipient foredune morphology is essentially absent at Narrabeen its exclusion from the surveys has made it impossible to successfully apply a classification of profile types (section 3.4.4) as was applied at Moruya. This is because the incipient foredunes were shown to be an important secondary morphology effecting profile shape.

Clarke and Eliot(1988) considering causality in the low frequency domain of sediment volume change on the beachface note that existing beach survey records do not
match the detail of available meteorologic information. They conclude that the reliability of sediment budget analyses is highly dependent on the sampling density which is a function of the time lapse between successive surveys, the number of profiles along the beach and the length of time over which the surveys have been repeated.

The long beach survey record from Moruya represents only a small area of a much longer sandy beach (figure 1.3). Studies by Eliot et al.,(1982a) and Bryant(1983) have demonstrated that spatially restricted surveys do not yield reliable representation of total beach change. Clarke and Eliot(1988) suggest that survey records from isolated profiles or groups of profiles have a low signal to noise ratio such that responses to localised foreshore and nearshore processes such as rip cells and rhythmic topography, may exceed the total beach variance. The possible implication is that high frequency beach changes could be of higher amplitude than other periodic variability. The Moruya series clearly cannot represent total beach change. However, results from surveys at central Moruya indicate consistent profile behaviour between the three closely spaced profiles and the nearby test profile (section 2.4.1). The original survey design by Thom and McLean was intended to allow averaging of the three adjacent profiles and to provide information on three dimensional beach changes with the nearby single profile to provide a standard for comparison. Moruya beach has a modally high intermediate beach state (Wright and Short,1985) and the effects of localised morphologies on profile survey variance are consequently often small. TSA of the Moruya series indicated the effects of noise; nevertheless an underlying signal was still recognisable (section 2.4.3). Clearly the spatial isolation of the profiles has not significantly worsened the noise-signal ratio but rather it is the temporal sampling interval which could be responsible.

The Narrabeen profiles are spaced along the full extent of the beach (figure 1.4). However profiles 3,5 and 7 were discontinued in 1982 and the profiles are
generally spaced approximately 400 metres apart. Studies at Warilla by Eliot and Clarke have determined that a profile interval not exceeding 100 metres is required if shore parallel sediment movement is to be determined. Thus while alongshore trends are apparent from results (section 3.4.1), it is not possible to clearly quantify shore parallel sediment behaviour at Narrabeen with the present dataset. Clarke and Eliot (1988) conclude that further advances in the understanding of low frequency beach changes depends on the acquisition of longer, more detailed and geographically more extensive datasets. In addition there is a need for more direct information on nearshore wave statistics if causality is to be accurately approached. McLean and Thom (1975) considered that studies of low frequency beach changes must be applied to natural beaches. Unfortunately beaches such as Narrabeen and the more intensive study of Warilla (Eliot and Clarke, 1982a) have been heavily influenced by urban design and may not therefore reflect the natural response of a beach to environmental factors such as waves, tides and sea level effects.

Comparability between Moruya and Narrabeen is difficult because of differences in monitoring techniques and their application at each field site. Objectives such as appraisals of incipient foredune development at Moruya and profile-wave interaction at Narrabeen may be overambitious or exceed data capabilities because these are objectives not originally foreseen in the design of these studies. At Narrabeen the failure to include the vital backshore in surveys makes attempts to document low frequency changes dubious and jeopardises study design although at Narrabeen this is of necessity as the established foredune area has been completely obliterated by human intervention.
5.3 Further work

The study aim to identify characteristic patterns of variation in the volume of sediment stored in the subaerial beach is the necessary first step towards the quantitative evaluation of the several processes contributing to beach change. Investigation is required into the possible causes of the temporal components of profile behaviour which have been identified. Eliot and Clarke (1982a) have suggested that changes in mean sea level are at least as important as changes in the wave climate. All processes which affect sediment transfer between the subaerial beach and inshore zones such as processes affecting beach water tables need to be addressed before the modelling of changes is possible. Further modelling of the subaerial profile is required particularly short term responses of the beachface. The dynamic relationship of the primary concave profile and secondary convex morphologies needs to be determined to provide a better understanding of the coastal zone.

ANDERSON, T.W., 1976. THE STATISTICAL ANALYSIS OF TIME SERIES. 2ND ED. WILEY N.Y.


ANON., 1975. SHORE PROTECTION MANUAL. 2ND ED. U.S. COASTAL ENGR. RES. CENTRE. FORT BELVOIR, VA.

ANON., 1986. SPSSX USERS GUIDE, 2ND ED. MCGRAW-HILL, N.Y.


BALOCK, H.M., 1960. SOCIAL STATISTICS. MCGRAW HILL, NEW YORK.


BLOOMFIELD, P., 1976. FOURIER ANALYSIS OF TIME SERIES: AN INTRODUCTION. WILEY N.Y.


BRUUN, P., 1954. COASTAL EROSION AND THE DEVELOPMENT OF BEACH PROFILES. US ARMY BEACH EROSION BOARD TECH.MEMO. 44: 75PP


BRYANT, E.A., 1987, IN PRESS. STORMINESS AND HIGH TIDE BEACH CHANGE, STANWELL PARK, AUSTRALIA, 1943-1978. MAR.GEOL.


CERC, 1975. SHORE PROTECTION MANUAL. U.S. ARMY CORPS OF ENGINEERS, WASHINGTON.


Chatfield, C. 1984. THE ANALYSIS OF TIME SERIES: AN INTRODUCTION. 3RD. ED. CHAPMAN AND HALL PUBL. NEW YORK.


Cowell, P.J., 1986. GUIDELINES FOR BEACH NOURISHMENT: ATHOL BAY, SYDNEY HARBOUR. COASTAL STUDIES UNIT TECH.REP. 86/4 UNIV. OF SYDNEY. 41PP
COWELL, P.J. AND KOTVOJS, F., 1987. DESIGN RELATIONSHIPS FOR ARTIFICIAL BEACHES IN ROCKY BAYS. PROC. 8TH AUST. CONF. ON COASTAL AND OCEAN ENGR.


DRAPER, N.R., 1981. APPLIED REGRESSION ANALYSIS.
2ND. ED. JOHN WILEY AND SONS, INC.


ELIOT, I.G., THOM, B.G. AND CLARKE, D.J., 1980. A COMPARISON OF SHORELINE CHANGE ON MORUYA AND WARILLA BEACHES, NSW. (UNPUBL)


GOTTMAN, J.M., 1981. TIME SERIES ANALYSIS. CAMBRIDGE UNIVERSITY PRESS.


HALL, D.C., 1981. SEDIMENT DISPERSAL ON THE SOUTHERN NEW SOUTH WALES CONTINENTAL SHELF. B.A.HONS. THESIS UNPUBL. DEPT. OF GEOG. FACULTY OF MILITARY STUDIES. UNIV. OF NSW. RMC, DUNTRON, CANBERRA.


HAYDEN, B.P., FELDER, W., FISHER, J., RESIO, D., VINCENT, L. AND DOLAN, R., 1975. SYSTEMATIC VARIATIONS IN INSHORE BATHYMETRY. ONR TECHNICAL REP., 10: 64PP.


HINE, A.C., 1979. MECHANISMS OF BERM DEVELOPMENT AND RESULTING BEACH GROWTH ALONG A BARRIER SPIT COMPLEX. SEDIMENTOLOGY., 26: 333-351.


JENKINS, G.M. AND WATTS, D.G., 1968. SPECTRAL ANALYSIS AND ITS APPLICATIONS. HOLDEN DAY. 525PP.


KENDALL, M.G., 1976. TIME SERIES. 2ND ED. LONDON, GRIFFIN.

KING, C.A.M., 1959. BEACHES AND COASTS. EDWARD ARNOLD PUBL, LONDON, 403PP.


KOMAR, P.D., 1976. BEACH PROCESSES AND SEDIMENTATION. PRENTICE-HALL, ENGLEWOOD CLIFFS, N.J., 429PP.

KOTVOJS, F., 1987. FACTORS IN THE APPLICATION OF DEAN’S MODEL FOR EQUILIBRIUM BEACH PROFILES. B.SC. (HONS) THESIS GEOGR. DEPT. UNIV. OF SYDNEY.


LING, R.F. AND ROBERTS, H.V., 1980. IDA: A USERS GUIDE TO THE IDA INTERACTIVE DATA ANALYSIS AND FORECASTING SYSTEMS. MCGRAW-HILL, N.Y.


RADOK, R., 1976. AUSTRALIAN COAST: AN ENVIRONMENTAL ATLAS GUIDE WITH BASE-LINES. RIGBY ADELAIDE, 100 PP.

READ, L., 1964. A PRELIMINARY STUDY: BEACH PROFILE CHANGES AND WIND/WAVE CONDITIONS ON THREE SYDNEY BEACHES. B.A. (HONS) THESIS. GEOGR. DEPT. UNIV. SYDNEY.


SASAKI, T. AND HIRIKAWA, K., 1975. NEARSHORE CURRENT SYSTEM ON A GENTLY SLOPING BOTTOM. COASTAL ENGR. IN JAPAN., 18: 123-142.


SHEPARD, F.P., 1950. BEACH CYCLES IN SOUTHERN CALIFORNIA. U.S. ARMY CORPS OF ENGRS., BEACH EROSION BOARD TECH. MEMO. NO. 20. 26PP.


SHORT, A.D., 1980. BEACH RESPONSE TO VARIATIONS IN BREAKER HEIGHT. PROC. 17TH INT. CONF. ON COASTAL ENG, SYDNEY.


SHORT, A.D. AND WRIGHT, L.D., 1984. MORPHODYNAMICS OF HIGH ENERGY BEACHES: AN AUSTRALIAN PERSPECTIVE. IN: THOM, B.G. (ED) COASTAL GEOMORPHOLOGY IN AUSTRALIA. ACADEMIC PRESS AUST.


THOM, B.G. AND ROY, P.S., 1988, IN PRESS. SEA-LEVEL RISE AND SHORELINE CHANGE: LESSONS FROM THE HOLOCENE.


VELLINGA, P., 1982. BEACH AND DUNE EROSION DURING STORM SURGES. DELFT HYDRAULICS LAB. PUBL. NO. 276, 31PP.

VELLINGA, P., 1986. BEACH AND DUNE EROSION DURING STORM SURGES. DELFT HYDRAULICS COMM. 372: 169PP.

WALPOLE, R.E., 1982. INTRODUCTION TO STATISTICS. 3RD ED. COLLIER MACMILLAN, PUB.

WEIGEL, R.L., 1964. OCEANOGRAPHICAL ENGINEERING.PRENTICE-HALL INT. SERIES IN THEORETICAL AND APPLIED MECHANICS. PRENTICE-HALL, CANADA. 532PP.

WESTRUPP, E., 1984. TWO DIMENSIONAL PROFILE MODELS AND BEACH STATES. B.SC. (HONS) THESIS. GEOGR. DEPT. UNIV. SYDNEY. 600PP.


WRIGHT, L.D. 1987 SHELF-SURFZONE COUPLING: CROSS-SHORE TRANSPORT MECHANISMS ON THE SHOREFACE. COASTAL SEDIMENTS., 87 (1) 25-40


APPENDIX B-2

MORUYA BEACH, SOUTH COAST, N.S.W
PROFILE 3
NUMBER OF SURVEYS 219
JANUARY 1972-JANUARY 1987

MORUYA BEACH, SOUTH COAST, N.S.W
PROFILE 4
NUMBER OF SURVEYS 213
JANUARY 1972-JANUARY 1987
APPENDIX B-3

NARRABEEN BEACH, N.S.W.

PROFILE 1
NUMBER OF SURVEYS 144

NARRABEEN BEACH, N.S.W.

PROFILE 2
NUMBER OF SURVEYS 143
APPENDIX B-4

NARRABEEN BEACH, N.S.W.
PROFILE 3
NUMBER OF SURVEYS 89

NARRABEEN BEACH, N.S.W.
PROFILE 4
NUMBER OF SURVEYS 143
APPENDIX B-5

NARRABEEN BEACH, N.S.W.
PROFILE 5
NUMBER OF SURVEYS 89

NARRABEEN BEACH, N.S.W.
PROFILE 6
NUMBER OF SURVEYS 142
APPENDIX B-6

NARRABEEN BEACH, N.S.W.

PROFILE 7
NUMBER OF SURVEYS 90

NARRABEEN BEACH, N.S.W.

PROFILE 8
NUMBER OF SURVEYS 143
PROGRAM DATASORT(IN,OUT,INPUT,OUTPUT,TEMP,
+TAPE5=INPUT,TAPE6=OUTPUT,TAPE1=IN,
+TAPE2=OUT,TAPE3=TEMP)
DIMENSION DATA(225,20),DATAX(225,20)
PRINT*, 'HOW MANY CASES'
READ(5,*)IOBS
PRINT*, 'HOW MANY VARIABLES'
READ(5,*)NVAR

ENTER INPUT DATA

DO 1 I=1,IOBS
  READ(1,*) (DATA(I,J),J=1,NVAR)
  CONTINUE

L=0
MVAR=0
PRINT*, 'SELECT 1 TOTAL DATASET., 2 DATA SUBSET'
READ(5,*)IOPT
IF(IOPT.EQ.1)GOTO 9
PRINT*, 'SELECT VARIABLES'
READ(5,*)SVAR
WRITE(3,*)SVAR
IF(SVAR.NE.0)GOTO 7
REWIND 3
READ(3,*)K
IF(K.EQ.0)GOTO 6
L=L+1
MVAR=MVAR+1
DO 3 I=1,IOBS
  DO 4 J=1,NVAR
    IF(K.EQ.J)DATAX(I,L)=DATA(I,J)
  CONTINUE
  CONTINUE
GOTO 2

DO 5 I=1,IOBS
  WRITE(2,*) (DATAX(I,L),L=1,MVAR)
  CONTINUE
GOTO 10

DO 9 I=1,IOBS
  WRITE(2,*) (DATA(I,J),J=1,NVAR)
  CONTINUE
GOTO 10
STOP
END
PROGRAM MORVOL(IN, OUT, INPUT, OUTPUT, TAPE2=IN, TAPE4=OUT, TAPE5=INPUT, TAPE6=OUTPUT)
DIMENSION X(100), Y(100), Y1(100)
REAL LEVEL, M
I = 0
RCT = 0.
READ(2, 30, END=99)ID, IM, IY, IDAYNU, IPROF, A, B
IF(A.EQ.999.99)GOTO 99
IF(A.EQ.666.66)STOP
I = I + 1
X(I) = A
Y(I) = B
K = I
GOTO 20
99 CONTINUE
IDATE = (IY*10000) + (IM*100) + ID
1 IF(IPROF.EQ.1)LEVEL = 6.61
IF(IPROF.EQ.2)LEVEL = 5.67
IF(IPROF.EQ.3)LEVEL = 6.40
IF(IPROF.EQ.4)LEVEL = 6.60
LEVEL = LEVEL - RCT
2 IF(IPROF.NE.1)GOTO 3
TVOL = 0.
VOL1 = ((LEVEL - 1.06) * 8.5)
VOL2 = ((LEVEL - 1.06) * 6.7)
VOL3 = (((LEVEL - 1.06) * 11.7) + (11.7 * 1.06/2))
IF(IDATE.GE.740614)GOTO 21
TVOL = TVOL + VOL1 + VOL2 + VOL3
LEVEL = LEVEL - 1.06
GOTO 6
21 IF(IDATE.GE.740621)GOTO 22
TVOL = TVOL + VOL2 + VOL3
LEVEL = LEVEL - 1.06
GOTO 6
22 IF(IDATE.GE.801222)GOTO 6
TVOL = TVOL + VOL3
LEVEL = LEVEL - 1.06
GOTO 6
3 IF(IPROF.NE.2)GOTO 4
TVOL = 0.
VOL1 = ((LEVEL * 8.1) + (8.1 * 0.35/2))
VOL2 = (LEVEL * 6.9)
IF(IDATE.GE.740531)GOTO 31
TVOL = TVOL + VOL1 + VOL2
LEVEL = LEVEL + 0.35
GOTO 6
31 IF(IDATE.GE.740621)GOTO 6
TVOL = TVOL + VOL2
GOTO 6
4 IF(IPROF.NE.3)GOTO 5
TVOL = 0.
VOL1 = (((LEVEL - 1.36) * 9.4) + (5.0 * 0.36/2) + (4.4 * 0.52/2))
VOL2 = ((LEVEL - 1.00) * 5.3) + (5.3 * 1.0 / 2)

IF (IDATE.GE.740614) GOTO 41
TVOL = TVOL + VOL1 + VOL2
LEVEL = LEVEL - 0.84
GOTO 6

41 IF (IDATE.GE.740621) GOTO 6
TVOL = TVOL + VOL2
LEVEL = LEVEL - 1.00
GOTO 6

5 IF (IPROF.NE.4) GOTO 55
TVOL = 0.0
VOL1 = (((LEVEL - 1.23) * 7.6)
VOL2 = (((LEVEL - 1.23) * 2.3) + (0.23 * 2.3 / 2))
VOL3 = (((LEVEL - 1.0) * 10.0) + (1.0 * 10.0 / 2))

IF (IDATE.GE.740614) GOTO 51
TVOL = TVOL + VOL1 + VOL2 + VOL3
LEVEL = LEVEL - 1.23
GOTO 6

51 IF (IDATE.GE.740621) GOTO 52
TVOL = TVOL + VOL2 + VOL3
LEVEL = LEVEL - 1.23
GOTO 6

52 IF (IDATE.GE.750705) GOTO 6
TVOL = TVOL + VOL3
LEVEL = LEVEL - 1.00
GOTO 6

55 WRITE (6, 59)
GOTO 9

CONTINUE

IF (Y(K).LT.LEVEL) GOTO 8

64 DO 65 I = 1, K
Y1(I) = LEVEL - Y(I)
IF (Y1(I).GT.0.) GOTO 65
Y1(I) = 0.0
KOUNT = I
GOTO 66

65 CONTINUE
66 CONTINUE

VOL = 0.
DO 7 I = 2, KOUNT
D = (X(I) - X(I-1)) * ((Y1(I) + Y1(I-1)) * 0.5)
VOL = VOL + D
CONTINUE

7 TVOL = TVOL + VOL

IF (RCT.EQ.0.0) TV1 = TVOL
IF (RCT.EQ.0.5) TV2 = TVOL
IF (RCT.EQ.1.0) TV3 = TVOL
IF (RCT.EQ.1.5) TV4 = TVOL
IF (RCT.EQ.2.0) TV5 = TVOL
IF (RCT.EQ.2.5) TV6 = TVOL
IF (RCT.EQ.3.0) TV7 = TVOL
IF (RCT.EQ.3.5) TV8 = TVOL
IF (RCT.EQ.4.0) TV9 = TVOL
IF (RCT.EQ.4.5) TV10 = TVOL
RCT = RCT + 0.5
IF (RCT.LT.5.) GOTO 1
WRITE (4, 76) IPROF, TV1, IDAYNU, TV2, TV3, TV4, TV5, TV6, TV7, TV8, TV9, TV10

121
GOTO 15

8  M = (Y(K) - Y(K-1)) / (X(K) - X(K-1))
    Y(K+1) = LEVEL
    X(K+1) = (Y(K+1) - Y(K)) / M + X(K)
    K = K + 1
    GOTO 64
STOP

30  FORMAT(3I2, 1X, I6, 1X, I1, 4X, 2F8.2)
59  FORMAT('INCORRECT PROFILE NUMBER')
76  FORMAT(I1, 1X, F7.2, 1X, I6, 1X, 9F7.2)
9   END
PROGRAM NARVOL(INPUT, OUTPUT, NARDAT, TEMPF, 01, 02,
+ TAPE5 = INPUT, TAPE6 = OUTPUT, TAPE2 = NARDAT,
+ TAPE4 = TEMPF, TAPE8 = 01, TAPE9 = 02)
DIMENSION X(25), Y(25), Y1(25)
REAL LEVEL
LEVEL = 0.
PRINT*, 'SELECT PROFILE'
READ(5, *) IPROF

SET ARBITRARY DATUMS
IF (IPROF.EQ.1) Y(1) = 6.25
IF (IPROF.EQ.2) Y(1) = 5.00
IF (IPROF.EQ.3) Y(1) = 4.50
IF (IPROF.EQ.4) Y(1) = 4.00
IF (IPROF.EQ.5) Y(1) = 4.50
IF (IPROF.EQ.6) Y(1) = 6.44
IF (IPROF.EQ.7) Y(1) = 4.50
IF (IPROF.EQ.8) Y(1) = 3.22

ENTER DATA
I = 0.
XP = 0.
LEVEL = 0.
RR = 0.
READ(2, 10, END=69) ISUR, M, IPROF2, ISUR2, ID, IM, IY
READ(2, 11)(Y(I), I = 2, 21)
IF (M.EQ.0 . . . .AND. IPROF2.EQ.IPROF) GOTO 7
GOTO 1
IF (ISUR2.EQ.1) ISUR = ISUR + 100

CALCULATE DAY NUMBER
KOUNT = IY - 76
KOUNT2 = KOUNT * 365
IF (IM.EQ.1) KOUNT2 = KOUNT2 + 0
IF (IM.EQ.2) KOUNT2 = KOUNT2 + 31
IF (IM.EQ.3) KOUNT2 = KOUNT2 + 59
IF (IM.EQ.4) KOUNT2 = KOUNT2 + 90
IF (IM.EQ.5) KOUNT2 = KOUNT2 + 120
IF (IM.EQ.6) KOUNT2 = KOUNT2 + 151
IF (IM.EQ.7) KOUNT2 = KOUNT2 + 181
IF (IM.EQ.8) KOUNT2 = KOUNT2 + 212
IF (IM.EQ.9) KOUNT2 = KOUNT2 + 243
IF (IM.EQ.10) KOUNT2 = KOUNT2 + 273
IF (IM.EQ.11) KOUNT2 = KOUNT2 + 304
IF (IM.EQ.12) KOUNT2 = KOUNT2 + 334
KOUNT2 = KOUNT2 + ID

FILL X ARRAY
DO 8 I=1,21
  X(I)=XX
  XX=XX+10.
8 CONTINUE
DO 2 I=2,21
  IF(Y(I).EQ.0.)GOTO 3
2 CONTINUE
3 R=I-1
C CORRECT DATAFILE TO ISLW
  IF(IPROF.EQ.1)LEVEL=LEVEL-0.89
  IF(IPROF.EQ.2)LEVEL=LEVEL-0.94
  IF(IPROF.EQ.3)LEVEL=LEVEL-1.10
  IF(IPROF.EQ.4)LEVEL=LEVEL-0.90
  IF(IPROF.EQ.5)LEVEL=LEVEL-0.90
  IF(IPROF.EQ.6)LEVEL=LEVEL-0.86
  IF(IPROF.EQ.7)LEVEL=LEVEL-0.94
  IF(IPROF.EQ.8)LEVEL=LEVEL-1.23
20 IF(RR.GT.0.)LEVEL=LEVEL+0.5
18 DO 21 I=1,R
  Y1(I)=-1.*(LEVEL-Y(I))
  IF(Y1(I).GT.0.)GOTO 21
  Y1(I)=0.
  KOUNT=I
  GOTO 22
21 CONTINUE
22 CONTINUE
  VOL=0.
  DO 16 I=2,KOUNT
  D=(X(I)-X(I-1))*(Y1(I)+Y1(I-1))*0.5
  VOL=VOL+D
16 CONTINUE
  WRITE(4,12)IPROF,VOL,KOUNT2,ISUR
  RR=RR+0.5
  IF(RR.GT.5.)GOTO 23
  GOTO 20
17 YM=(Y(R)-Y(R-1))/(X(R)-X(R-1))
  Y(R+1)=LEVEL
  X(R+1)=(Y(R+1)-Y(R))/YM + X(R)
R=R+1
  GOTO 18
23 CONTINUE
GOTO 9
69 REWIND 4
18 READ(4,13,END=99)IPR,V1,K1,ISR,V2,V3,
  +V4,V5,V6,V7,V8,V9,V10
  WRITE(8,14)IPR,V1,K1,V2,V3,V4,V5,
  +V6,V7,V8,V9,V10
  WRITE(9,15)V1,V2,V3,V4,V5,V6,V7,V8,V9,V10
  GOTO 18
99 STOP
10 FORMAT(I2,F1.0,I1,I1,3I2)
11 FORMAT(S1,F3.2,20F4.2)
12 FORMAT(I1,F10.2,I6,I4)
13 FORMAT(I1,F10.2,I6,I4,9(/,1X,F10.2))
14 FORMAT(I1,1X,F7.2,1X,I6,1X,9F7.2))
15 FORMAT(10F8.2)
END
PROGRAM INTER(IN, DDAY, OUT, INPUT, OUTPUT, 
+TAPE1=IN, TAPE2=DDAY, TAPE3=OUT, TAPE5=INPUT, 
+TAPE6=OUTPUT) 
DIMENSION VAL(300, 7), DAY(300), RR(7) 
DO 6 I = 1, 298 
   READ(1, 10, END=69) PROF, VAL(I, 1), DAY(I), 
   +(VAL(I, J), J=2, 5) 
   CONTINUE 
6 CONTINUE 
69 CONTINUE 
C 
  I = 0 
1 I = I + 1 
2 READ(2, 11, END=99) DAYS 
3 IF(DAY(I).EQ.DAYS) THEN 
   WRITE(3, 10) PROF, VAL(I, 1), DAY(I), (VAL(I, J), J=2, 5) 
   GOTO 1 
ELSE IF(DAY(I).GT.DAYS) THEN 
   R1 = DAYS - DAY(I-1) 
   R2 = DAY(I) - DAY(I-1) 
   DO 8 J = 1, 5 
   R3 = VAL(I, J) - VAL(I-1, J) 
   RX = (R1/R2)*R3 
   RR(J) = RX + VAL(I-1, J) 
8 CONTINUE 
   WRITE(3, 10) PROF, RR(1), DAYS, (RR(J), J=2, 5) 
   GOTO 2 
ELSE 
   I = I + 1 
   GOTO 3 
3 END IF 
99 STOP 
10 FORMAT(I1, 2X, F10.3, 2X, F6.0, 6X, 4F7.2) 
11 FORMAT(6X, F6.0) 
END
APPENDIX C-5

PROGRAM NORMAL(IN1, OUT1, TAPE1=IN1, TAPE9=OUT1)
DIMENSION DATIN(250,12), DATOUT(250,12)
DO 1 I=1,248
  READ(1,10,END=69)(DATIN(I,J), J=1,10)
1 CONTINUE
69 NVAR=I-1
  DO 2 J=1,10
    SUMX2=0.
    DEN=0.
    DO 3 I=1,NVAR
      X2=DATIN(I,J)*DATIN(I,J)
      SUMX2=SUMX2+X2
    3 CONTINUE
    DEN=SQRT(SUMX2)
  DO 4 I=1,NVAR
    DATOUT(I,J)=DATIN(I,J)/DEN
  4 CONTINUE
  DO 5 I=1,NVAR
    WRITE(9,11)(DATOUT(I,J), J=1,10)
  5 CONTINUE
STOP
10 FORMAT(2X,F7.2,8X,9F7.2)
11 FORMAT(10F8.5)
END
PROGRAM SEASON(IN,OUT1,OUT2,INPUT,OUTPUT,
+TAPE1=IN,TAPE8=OUT1,TAPE9=OUT2,
+TAPE5=INPUT,TAPE6=OUTPUT)
DIMENSION VAL(300),RES(300),SM(300),DAY(300)

READ INPUT DATA
DO 1 I=1,298
READ(1,10,END=2) VAL(I),DAY(I)
CONTINUE
N=I-1
NN=N-6

APPLY FILTER
DO 3 I=7,NN
SM(I)=((0.5*VAL(I-6))+VAL(I-5)+VAL(I-4)+
+VAL(I-3)+VAL(I-2)+VAL(I-1)+VAL(I)+VAL(I+1)+
+VAL(I+2)+VAL(I+3)+VAL(I+4)+VAL(I+5)+
+(0.5*VAL(I+6)))/12
CONTINUE

DO 4 I=7,NN
RES(I)=VAL(I)-SM(I)
WRITE(8,10) SM(I),DAY(I)
WRITE(9,10) RES(I),DAY(I)
CONTINUE
STOP
FORMAT(3X,F10.3,2X,F6.0)
END
PROGRAM SMOOTH(IN1,OUT1,OUT2,OUT3,INPUT,OUTPUT,
+TAPE1=IN1,TAPE2=OUT1,TAPE3=OUT2,TAPE4=OUT4,
+TAPE5=INPUT,TAPE6=OUTPUT)
DIMENSION XIN(300),XOUT(300),DAY(300),XRES(300)

C
C READ INPUT DATA

DO 1 I=1,298
READ(1,10,END=2)PROF,XIN(I),DAY(I)
1 CONTINUE
N=I-1
PRINT*,XIN(I),XIN(N),N
PRINT* 'INPUT M'
READ(5,*)M

C
C CALCULATE NEW SERIES

IE=N-M+1
IK=(M+1)/2
IJ=IK
DO 3 I=1,IE
SUM=0.
DO 4 J=1,M
K=I+J-1
SUM=SUM+XIN(K)
4 CONTINUE
XOUT(I)=SUM/FLOAT(M)
DAY(I)=DAY(IK)
IK=IK+1
3 CONTINUE
DO 5 I=1,IE
WRITE(2,10)PROF,XOUT(I),DAY(I)
5 CONTINUE
DO 6 I=1,IE
XIN(I)=XIN(IJ)
XRES(I)=XIN(IJ)-XOUT(I)
WRITE(4,10)PROF,XRES(I),DAY(I)
IJ=IJ+1
6 CONTINUE

C
C CALCULATE STATISTICS

SY=0.
SYY=0.
DO 7 I=1,N
SY=SY+XIN(I)
SYY=SYY+XIN(I)**2
7 CONTINUE
SYS=0.
SYYS=0.
SYC=0.
SYYC=0.
SSD=0.
DO 8 I=1,IE
   J=I+M/2
   SYS=SYS+XIN(J)
   SYYS=SYYS+XIN(J)**2
   SYC=SYC+XOUT(I)
   SYYC=SYYC+XOUT(I)**2
   SSD=SSD+(XIN(J)-XOUT(I))**2
8 CONTINUE
   SSO=SYY-SY*SY/FLOAT(N)
   SSOS=SYYS-SYS*SYS/FLOAT(IE)
   SSS=SYYC-SYC*SYC/FLOAT(IE)
   PSS=(SSS/SSOS)*100.
C
C WRITE OUTPUT DIAGNOSTICS
C
   WRITE(3,11)SSO
   WRITE(3,12)SSOS
   WRITE(3,13)SSS
   WRITE(3,14)SSD
   WRITE(3,15)PSS
STOP
10 FORMAT(I1,1X,F7.2,1X,F6.0)
11 FORMAT('SUMS OF SQUARES OF ORIGINAL DATA ',F20.8)
12 FORMAT('SUMS OF SQUARES OF TRUNCATED DATA ',F20.8)
13 FORMAT('SUMS OF SQUARES OF SMOOTHED DATA ',F20.8)
14 FORMAT('SUMS OF SQUARES DUE TO DEVIATION ',F20.8)
15 FORMAT('%GOODNESS OF FIT ',F20.8)
END
APPENDIX C-8

PROGRAM ACFPLOT(IN,INPUT,OUTPUT,TAPE1=IN,
+TAPE5=INPUT,TAPE6=OUTPUT)
DIMENSION X(65),Y(65),Y2(65),Y3(65)
CHARACTER *40 TITLE1,TITLE2
CALL PLOTLIB
CALL PLOTS(34,25,0)
PRINT*,'SELECT 1 SCREEN 2 PLOTTER'
READ(5,*)IOPT
IF(IOPT .EQ. 1)CALL FACTOR(0.70)
PRINT*,'TITLE LINE 1'
READ(5,8)TITLE1
PRINT*,'TITLE LINE 2'
READ(5,8)TITLE2
NPTS=0
X(1)=0.
Y(1)=0.
DO 1 NPTS=1,60
READ(1,* ,END=69)X(NPTS),Y(NPTS),Y2(NPTS)
1 CONTINUE
69 NPTS=NPTS-1
X(NPTS+1)=0.
X(NPTS+2)=2.
Y(NPTS+1)=-1.
Y(NPTS+1)=.125
CALL PLOT(2.,2.,3)
CALL AXIS(2.,2.,' ',-1.,30.,0.,X(NPTS+1),X(NPTS+2))
CALL SYMBOL(14.,0.2,0.4,'LAG K',0.,5)
CALL AXIS(2.,2.,' ',1.,16.,90.,Y(NPTS+1),Y(NPTS+2))
CALL SYMBOL(1.,7.,0.4,'AUTOCORRELATION',90.,15)
CALL SYMBOL(6.,20.,0.4,'AUTOCORRELATION FUNCTION',
+0.,24)
CALL SYMBOL(6.,19.5,0.4,'VARIABLE = ',0.,11)
CALL SYMBOL(999.,999.,0.4,TITLE1,0.,40)
CALL SYMBOL(6.,19.,0.4,TITLE2,0.,40)
CALL PLOT(2.,2.,-3)
CALL LINE(X,Y,NPTS,1,0,0)
CALL PLOT(0.,-8.,-3)
CALL PLOT(0.,-8.,-3)
Y2(NPTS+1)=-1.
Y2(NPTS+2)=.125
CALL LINE(X,Y2,NPTS,1,0,0)
DO 4 I=1,NPTS
Y3(I)=Y2(I)*(-1.)
4 CONTINUE
Y3(NPTS+1)=-1.
Y3(NPTS+2)=.125
CALL LINE(X,Y3,NPTS,1,0,0)
CALL PLOT(33.9,24.9,999)
STOP
8 FORMAT(A40)
END
PROGRAM POWER(INI,OUT1,TAPE1=INI,TAPE9=OUT1)
REAL PWR,HSIG,TSIG
C
C READ INPUT DATA
C
1 READ(1,10,END=69)ID,IM,IY,DAY,HSIG,TSIG
IF(HSIG.EQ.99.99.OR.TSIG.EQ.99.99)GOTO 1
C
C CALCULATE WAVE POWER
C
PWR=(HSIG*HSIG*TSIG)*0.976713616
C
WRITE(9,11)ID,IM,IY,DAY,HSIG,TSIG,PWR
GOTO 1
69 STOP
10 FORMAT(3I2,16,2(1X,F5.2))
11 FORMAT(3I2,16,2(1X,F5.2),1X,F7.2)
END
APPENDIX C-10

```fortran
PROGRAM WEIGHT(IN, OUT, INPUT, OUTPUT, TAPE1=IN,
+ TAPE9=OUT, TAPE5=INPUT, TAPE6=OUTPUT)
DIMENSION POW(32), FILT(32)
REAL PW
PW=0.
SUMF=0.
PRINT*, 'SELECT FILTER'
READ(5,*) NOBS
DO 3 I=1, NOBS
PW=(I/5.)*(-1.)
FILT(I)=10.*PW
SUMF=SUMF+FILT(I)
SUMFF=1./SUMF
3 CONTINUE
SUMP=0.
DO 2 I=1, NOBS
READ(1,10,END=69) DAY, POW(I)
SUMP=SUMP+(POW(I)*FILT(NOBS-I))
2 CONTINUE
WPM=SUMP*SUMFF
WRITE(9,*) DAY, WPM
GOTO 1
69 STOP
10 FORMAT(12X,F6.0,F10.2)
END
```
APPENDIX D

TITLE <<< TIME SERIES ANALYSIS FILE=NV8I IDENTIFY >>>
FILE HANDLE NV8I/
DATA LIST FILE=NV8I/VOL 4-13
SET WIDTH=80
BOX-JENKINS VARIABLE=VOL/DIFFERENCE=0 THRU 2/
   SDIFFERENCE=0 THRU 2/PERIOD=12/LAG=60/
   PLOT=DSE,PAC/IDENTIFY
FINISH

TITLE <<< TIME SERIES ANALYSIS FILE=NV8I ESTIMATE >>>
FILE HANDLE NV8I/
DATA LIST FILE=NV8I/VOL=4-13
SET WIDTH=80
BOX-JENKINS VARIABLE=VOL/DIFFERENCE=1/SDIFFERENCE=1/
   PERIOD=12/LAG=60/Q=1/SQ=1/
   BFR=13/PLOT=RAC,RES/ESTIMATE
FINISH

TITLE <<< TIME SERIES ANALYSIS FILE=NV8I FORECAST >>>
FILE HANDLE NV8I/
DATA LIST FILE=NV8I/VOLUME 4-13
SET WIDTH=80
BOX-JENKINS VARIABLE=VOL/DIFFERENCE=1/SDIFFERENCE=1/
   PERIOD=12/Q=1/SQ=1/FO=(.33538)/FSQ=(.84531)/
   FCON=(-0.17188)/ORIGIN=-24/PLOT=FCF,FLF,CIN/
   FORECAST
FINISH