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What rip?
The Significance of Mega-rips Along an Embayed Coast

By

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy
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Abstract

Data were collected on flow velocity, bathymetry and suspended sediment concentration on the inner-shelf on both the upper and lower shoreface in order to identify and elucidate the phenomenon of mega-rips. Over a two year period instruments were deployed offshore of MacMasters beach, New South Wales, Australia, a micro-tidal pocket beach where mega-rips have been previously observed. In order to augment the data collected on mega-rips, data were collected on the hydrodynamics of the lower shoreface to determine processes active on the inner-shelf.

Mega-rips were found to play a significant role in the seaward transport of water and sediment within an embayed beach when waves exceeded 3m. The mega-rips typically formed adjacent to a headland with a single feeder channel running the length of the embayment. On occasions a much smaller rip was observed simultaneously at the opposite end of the embayment. Evidence presented in this thesis suggests mega-rips were driven by oblique waves, the oblique waves generating an alongshore current which was deflected offshore by the headland. The offshore extent of mega-rips was typically 1.5 times the width of the surfzone.

Average flow velocities measured within the rip-neck reached 130 cms\(^{-1}\) in water depths of 15m, with the seaward extent of the rip being observed over 900m from the shore. Pulsing was a significant feature of the velocities measured, occurring at periods of 10–15mins with a possible causal relationship being established with wave grouping. Sediment transport in association with the most severe storm during the study period was found to have deposited a total of 60,000m\(^3\) of sediment, mostly deposited in the 10–15m depth zone (up to 1m thick), with smaller amounts in water depths of 15–25m (up to 4cm thick). Photographic observations indicated that significant quantities of sediment were carried further than 1km offshore into water depths exceeding 35m.

Velocity boundary layer profiles measured in the rip-neck during the study departed significantly from the generally accepted logarithmic profile and may have been attributed to the turbulence injected into the upper water column by breaking waves. Similarly, qualitative suspended sediment concentration profiles departed from the logarithmic decrease, the upper levels of the water column having a relatively higher concentration.
Data were collected during both fair-weather and storm (high wave activity) conditions, the fair-weather data showing mean flow at the seabed was driven by internal waves (<25cms\(^{-1}\)) and tides (<5cms\(^{-1}\)). Internal waves were active all year round, however they were most active when surface water temperatures were warmest (in the summer months). A distinct link was also made between upwelling and internal wave activity, whereby internal waves were promoted by upwelling in summer, and were suppressed by upwelling in winter. Tidal flow on the inner-shelf had a pronounced K\(_1\) constituent, the source of which was unresolved.

The impact of storm conditions on the fair-weather processes varied between the upper and lower shoreface. On the upper shoreface, tidal flow was disrupted when waves exceeded 3m, while on the lower shoreface tidal flow was unaffected even during the largest storm event within the study period. On the lower shoreface, the propagation of internal waves was suppressed by mixing associated with waves exceeding 2.5m. By far the most dramatic change in the hydrodynamics observed during storm conditions was the occurrence of mega-rips.
Declaration:
I, Aaron Coutts-Smith, solemnly declare that the work presented in this thesis is my own except where referenced.

Signed: [Signature]

Aaron Coutts-Smith
Acknowledgements

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VII
Notations Used in the Text

- overbar denotes mean value

\( a_b \) — wave orbital semi excursion (m)
\( a_s \) — maximum wave orbital semi excursion (m)
\( c \) — suspended sediment concentration (gL\(^{-1}\))
\( c_0 \) — reference sediment concentration (gL\(^{-1}\))
\( D \) — characteristic grainsize (m)
\( E_i \) — echo intensity
\( E_n \) — normalised echo intensity
\( E_p \) — echo intensity profile
\( f_r \) — current friction factor
\( f_w \) — wave friction factor
\( g \) — acceleration due to gravity (ms\(^{-2}\))
\( H_b \) — breaker wave height (m)
\( H_o \) — deep water wave height (m)
\( H_{sig} \) — significant wave height (m)
\( H_{st} \) — nearshore storm wave height that is exceeded 12hrs each year (m)
\( h_c \) — depth of closure (m)
\( h_l \) — limit of significant onshore-offshore transport in a typical year (m)
\( k \) — von Karman constant
\( k_b \) — bed roughness (m)
\( R_p \) — reference echo intensity profile
\( S_{sx} \) — onshore transport of cross-shore momentum (Jm\(^{-2}\))
\( s \) — density of sediment relative to seawater
\( T_e \) — nearshore storm wave period that is exceeded 12hrs each year (s)
\( T_{sig} \) — significant wave period (s)
\( U \) — velocity in the offshore direction (ms\(^{-1}\))
\( U_{max} \) — maximum velocity in the cross-shore direction (ms\(^{-1}\))
\( u_s \) — shear velocity (ms\(^{-1}\))
\( u_{rc} \) — time dependent current friction velocity (ms\(^{-1}\))
\( u_m \) — maximum orbital velocity (ms\(^{-1}\))
\( u_{rw} \) — time dependent wave friction velocity (ms\(^{-1}\))
\( u_o \) — standard deviation of instantaneous water velocity in the cross-shore direction (ms\(^{-1}\))
\( V \) — velocity in a longshore direction (ms\(^{-1}\))
$V_{max}$ — maximum velocity in the longshore direction (ms$^{-1}$)

$z$ — height above the bed (m)

$z_0$ — hydraulic roughness length (m)

$z'_{oc}$ — hydraulic roughness of wave boundary layer (m)

$\alpha_b$ — breaker wave angle (°)

$\beta$ — seabed slope (°)

$\gamma$ — ratio of wave height to water depth

$\delta_{cr}$ — combined wave current boundary layer thickness (m)

$\delta_w$ — wave boundary layer thickness (m)

$\varepsilon_s$ — sediment diffusivity constant (m$^2$s$^{-1}$)

$\eta$ — water surface elevation (m)

$\theta$ — Shields parameter

$\theta_c$ — current contribution to Shields parameter

$\theta_t$ — total combined wave current contribution to Shields parameter

$\theta_w$ — wave contribution to Shields parameter

$\xi_s$ — surf similarity parameter

$\rho$ — water density (kgm$^{-3}$)

$\tau$ — shear stress (Nm$^{-2}$)

$\tau_w$ — wave contribution to shear stress (Nm$^{-2}$)

$\varphi$ — angle between waves and currents (°)

$\omega$ — wave radian frequency (rad)

$\omega_s$ — sediment fall velocity (ms$^{-1}$)
Chapter One

Introduction
1.1 Introduction

The inner-shelf is an important component of the coastal zone and is defined physically by Wright (1995) as extending seaward from the surfzone to depths where waves frequently agitate the seabed. Numerous processes are active across the inner-shelf and are driven by waves and large-scale oceanographic phenomena (Wright, 1995). Closer to shore (upper shoreface), waves generate mass transport (Stokes, 1880; Longuet-Higgins, 1953; Wells, 1967), bed return flow (Bagnold, 1940; Svendsen, 1984; Masselink and Black, 1995), gravity currents (Hayes, 1967; Wright et al., 1986a, 2002), alongshore currents (Longuet-Higgins, 1970a, b; Komar, 1975; Thornton and Guza, 1989) and rip circulation (Bowen, 1969a; Sonu, 1972; Smith and Largier, 1995; Brander, 1999), while oceanographic processes mainly affect the outer region of the inner-shelf (lower shoreface) and include boundary currents (Webb, 1992), tidal flow (Cox et al., 1993; Wright et al., 1997), internal waves (Cacchione and Southard, 1974; Gibbs and Middleton, 1997) and wind-driven currents (Griffin and Middleton, 1992; Madsen et al., 1993; Wright et al., 1994).

Understanding the role and impact each of the above processes have on the coastal zone is imperative to determining future changes of the coastal system. Rip currents have received a modest amount of attention in the literature (MacKenzie, 1958; Cook and Gorsline, 1972; Short, 1985; Smith and Largier, 1995; Brander and Short, 2000), and are well recognised for their ability to transport water and sediment seaward of the surfzone (Inman et al., 1971; Gruszczynski et al., 1993; Brander, 1999). The transport of water and sediment offshore by rips makes them an important component in the coupling of the surfzone and the upper shoreface. However, the extent of this coupling is considered to be limited to the upper shoreface (Johnson and Eagleson, 1966; Cowell, 1986; Wright et al., 1991), even during storms.

Few studies pertain to rips during high wave events (Brander and Short, 2000), as collection of data during high energy conditions is very difficult due to the extremely hazardous conditions of the surfzone. Circulation under high energy wave climates has been observed as both horizontal (Brander and Short, 2000) and vertical (undertow/bed return flow; Dyhr-Nielsen and Sorensen, 1970; Salenger et al., 1983). Vertical circulation appears to be restricted to dissipative beaches in the absence of alongshore variations in wave height and in the presence of uniform alongshore topography (Wright et al., 1982a; Greenwood and Osborne, 1990), while horizontal circulations in the form of rips tend to
dominate intermediate beach states due to alongshore irregularities in topography (Short, 1999). Cases of horizontal circulation with highly energetic wave climates (e.g. Murawai, New Zealand) may provide an analogue of circulation expected on less energetic coasts under high energy conditions by simple scaling, whereby rip size and spacing increases (Short and Brander, 1999). Observations off the central New South Wales (NSW) coast, Australia, have identified the presence of large topographically controlled rips (mega-rips) during high energy wave events (McKenzie 1958; Short, 1985); an example is illustrated in Figure I.1. This study will focus on mega-rip formation and hydrodynamics during high energy events on an embayed central NSW beach.

Mega-rips have been discussed in unpublished research theses (Cowell, 1975; Hall, 1984; Williams, 1992; Brander, 1996), published research (Short, 1985; Cowell, 1986b; Evans et al., 2000) and texts on coastal processes (Wright, 1995; Short and Masselink, 1999; Woodroffe, 2002). Despite being identified as a mechanism of potential significance, no process study exists for mega-rips. McKenzie (1958) documented the first observation of mega-rips on the southeast coast of Australia, in that study, with a change in normal rip circulation being noted when wave height exceeded 3m such that one rip dominated an entire embayment. Later studies (Cowell, 1975; Short, 1985) identified mega-rips elsewhere along the southeast coast of Australia, with the latter study offering a qualitative definition based purely on observation: “Mega-rips are large-scale (>1km) topographically controlled erosion rips that persist when nearshore and/or embayment topography prevents the development of the fully dissipative state by inducing wave refraction and persistent alongshore gradients in surf-zone dynamics that in turn drive the rip circulation”. Short (1985) further suggested that mega-rip formation is favoured in small embayments (<3km) under high wave energy conditions (storm conditions).

Rips can be divided into three general categories: 1) accretive, occurring under decreasing wave heights; 2) erosive, occurring under increasing wave heights; and 3) topographically controlled rips that are relatively permanent features (Short, 1999). Topographically controlled rips tend to form in fixed locations where circulation is forced through a permanent topographic feature such as an offshore reef (wave focusing), natural structures (headlands) or human-made structures (breakwaters, groins, piers etc.). The physical make-up of rips generally comprises three major components: feeder channels, a rip-neck and a rip-head (Figure 1.2). Topographically controlled rips adjacent to a structure vary by
Figure 1.1: Example of a ‘mega-rip’ at Curl Curl Beach, Sydney New South Wales, Australia in 1974. The embayment is approximately 1km long. Arrows illustrate the current direction. Source: Aerial photograph from Department of Land and Water Conservation image library.
having only one feeder channel and are directed offshore by the structure. Flow characteristics within the rip vary between each of the zones whereby flow in the feeders runs alongshore and converges turning offshore to form the rip-neck. The rip-neck occupies the rip channel across the bar and it is here that velocities are greatest. Immediately seaward of the bar the rip-head is formed by flow expansion as the flow is no longer constrained by topography or the surfzone, leading to a rapid decrease in flow velocities (Short, 1999). This rapid decrease in velocity is associated with a depositional feature known as the ‘rip-head bar’ (Figure 1.3).

The offshore extent of the mega-rip in Figure 1.1 exceeded 1km. Given the location of the rip-head and the expected location of the rip-head bar, sediment may then be delivered more than 1km offshore, beyond the sub-aerial extent of the headland. Therefore, mega-rips present a potential mechanism for the transport of nearshore sediments well seaward of the surfzone such that sediments may by-pass the headland or are deposited in deepwater where they can’t return and thus are lost from the system.

To assess the impact of mega-rips on a beach system it is important to understand the processes that are active on the inner-shelf where sediments are potentially delivered by mega-rips. A series of active processes have been identified as influencing the oceanography of the Sydney region (primarily where mega-rips have been observed). These include: the East Australian current (Hamon, 1970; Nilsson and Cresswell, 1980; Ridgway and Dunn, 2003); coastal trapped waves (Church et al., 1986; Griffin and Middleton, 1991); internal waves and tides (Griffin and Middleton, 1992; Gibbs and Middleton, 1997); wind-driven currents (Griffin and Middleton, 1991; Gibbs et al., 1998); and tidal flow (Cox et al., 1993).

The impacts of the above processes on near-bed currents on Sydney’s inner-shelf are poorly understood, largely due to an absence of long-term real process data. Studies pertaining to the confines of the inner-shelf (0–60m) are limited to work conducted by Wright et al. (1980), Gordon and Hoffman (1984), and Lawson and Treloar (1992). These studies identified tidal flows as being important adjacent to major estuaries although both tidal currents and net drift are overwhelmed by wave-orbital motions (Wright et al., 1980). Velocities near the seabed generated by internal wave activity, coastal trapped waves and the East Australian current were identified by Lawson and Treloar (1992). Of these studies, none encompass any significant storm periods. As such, storm driven processes of
Figure 1.2: Horizontal nearshore cell circulation associated with rip currents (taken from Komar, 1975)

Figure 1.3: Deposition associated with rip currents as observed by Brander, 1999 (re-drafted from Brander, 1999).
the Sydney region are inferred from sedimentological features and extrapolated from research on other coasts. It is believed that the dominant process under storm conditions is downwelling associated with strong onshore winds and onshore directed mass transport. Field and Roy (1984) surmise that sand bodies on the inner-shelf off the Sydney coast result from sediment transport associated with downwelling during storms, although the formative mechanism remains unresolved. Transport processes associated with mega-rips are not currently considered in the literature specific to the Sydney region.

There is, therefore, an absence of real process data for both fair-weather conditions and storm conditions (i.e. high energy wave events) for the Sydney coast. To adequately assess the impact of mega-rips on the inner-shelf and embayment processes of this region it is essential to understand the background fair-weather conditions from which storms deviate. Based on observation, mega-rips represent a dramatic change of circulation within an embayment during large wave events. Headlands are expected to play an integral role in forcing this circulation, therefore this phenomena is likely to be of more significance to highly embayed coasts like those of the Sydney region, particularly when exposed to a moderate wave climate punctuated by high energy events.

1.2 Aims of Thesis
The primary aim of this study is to investigate the hydrodynamic coupling between the nearshore and inner-shelf on an embayed beach system, with a focus on the role of mega-rips. The system is located at MacMasters beach, 55km north of Sydney, on the central coast of New South Wales, Australia. It is hypothesised that mega-rips have the potential to contribute to the export of sediment from the nearshore system to the inner-shelf. If disequilibrium exists between sediment export and import, this mode of transport translates to a loss of sediment from the nearshore budget and has implications for shoreline change. To evaluate this hypothesis several key objectives must be achieved:

1) Identification of the key hydrodynamic processes active in the field area during fair-weather conditions;
2) Identification of the key hydrodynamic processes active in the field area during storm events;
3) Identification of the processes that generate mega-rips in the embayment;
4) Assessment of the potential for mega-rips to transport sediment; and
5) Documentation of the hydrodynamic characteristics of mega-rips.

1.3 Thesis Objectives and Justification

Results from this thesis have many applications in process-based research, coastal hydrodynamic and sedimentological modelling, and coastal management. First and foremost this study elucidates the process of mega-rips, detailing spatial and temporal flow velocities, spatial extent, lateral positioning and their ability to transport sediment. This study will also identify mega-rips outside of the field area within the Sydney region and determine relationships that are consistent with the field area.

Due to a lack of process-based data on the inner-shelf of the Sydney region this investigation seeks to provide vital knowledge of fair-weather oceanographic processes that operate across the inner-shelf, with particular reference to near-bed flow generated by the East Australian current (EAC), coastal trapped waves (CTW), internal waves and tidal flows on steep shelved coasts, such as those of the Sydney region. The ability of fair-weather processes to ‘recover’ the system from storm-generated changes will be assessed through quantification of sediment transport under varying wave conditions across the inner-shelf. In addition, knowledge of the interaction between storm and fair-weather processes will be obtained: more specifically, the study seeks to determine whether these processes are mutually exclusive.

In the context of modeling, this study will assess the applicability of current models for embayed coasts under storm conditions, particularly hydrodynamic models that often depict a simplified vertical velocity profile as governed by the boundary layer theory. In a sediment transport context, mega-rips will be used to assess the applicability of 2-dimensional cross-shore sediment transport models to embayed coasts. The concept of embayed coasts being closed sedimentological systems will be challenged by sediment transport associated with mega-rips.

In a coastal management context, this investigation will provide insight into the impact storms have on the coasts of embayed beaches and of the long-term response of the coastal system to future changes in wave climate. It will allow previous management decisions to be assessed, particularly along the Sydney coast where real process data has been lacking and previous decisions have been based on 2-dimensional modeling (pers. comm. D. Hanslow).
1.4 Thesis Structure
The thesis objectives will be achieved through collection of data from the shoreface and from data collected by external agencies, under both fair-weather and storm wave conditions. This data will be presented in three results chapters, each addressing the major objectives as stated in Section 1.2. The thesis presents a general background on various hydrodynamic and sediment transport processes of the shoreface in Chapter Two. Chapter Three documents the characteristics of the field area and the methodology employed to obtain the results presented in later chapters. Chapter Four characterises the processes active under fair-weather conditions and identifies the relative contributions of each process. Chapter Five discusses the hydrodynamics encountered within the embayment and inner-shelf during storm wave conditions with an emphasis on the process of mega-rips. Chapter Six identifies general sediment characteristics and embayment morphology, with a focus on identifying changes in response to mega-rips. This chapter also determines the sediment transport rates associated with mega-rips and under fair-weather conditions. Chapter Seven discusses the results and the wider implications for nearshore and embayment hydrodynamics and sediment transport on embayed coasts. The final chapter (Chapter Eight) summarises the findings of the study and identifies areas for further investigation.
Chapter Two

Background to Inner-shelf and Embayment Processes
2.1 Introduction
This chapter provides background knowledge of the processes active on the inner-shelf and within embayments, with specific attention to concepts that are discussed in light of the results. A definition of the various regions of the continental shelf is provided, followed by consideration of the major concepts that define processes of the inner-shelf including general morphodynamic principles, the concept of the equilibrium profile, cross-shore and alongshore transport, nearshore and inner-shelf circulation, and the impact of storms in the context of the NSW central coast. This chapter further identifies deficiencies in the current body of research and demonstrates how the present study adds to current knowledge.

2.2 An Introduction to the Continental Shelf

2.2.1 Shelf Nomenclature
The continental shelf can be divided into three categories: the inner-shelf, the mid-shelf and the outer-shelf (Wright, 1995). The inner-shelf extends from the shoreline to a depth where waves frequently agitate the seabed. This definition is highly dependant on the regional wave climate and time-scale, which for the Sydney region corresponds to water depths of 50–60m (Wright, 1995). The mid-shelf extends from the seaward limit of the inner-shelf to a depth of ~120m (Wright, 1995). The outer-shelf extends from the seaward limit of the mid-shelf to the upper continental slope. According to this definition a general profile of a ‘typical’ shelf is illustrated in Figure 2.1. The major difference between shelves from around the world is the offshore distance each of these boundaries occurs at and is largely controlled by the tectonic history of the shelf.

The region of most importance in the context of this study is the inner-shelf, which can be further sub-divided into the upper and lower shoreface, collectively called the shoreface. Cowell et al. (1999) define the upper shoreface as extending from the shoreline to a depth where significant measurable profile change occurs, further defined as the depth of closure \( h_c \) according to Hallemeier (1981):

\[
h_c = 2.28H_{\infty} - 68.5 \left( \frac{H_{\infty}^2}{gT_e^2} \right) \text{ E2.1}
\]

where \( H_{\infty} \) is the nearshore storm wave height that is exceeded 12h each year and \( T_e \) is the associated wave period. The lower shoreface extends seaward from this point to the limit
Figure 2.1: Components of the shelf where the average offshore distances are depicted, offshore distances are typical of the NSW shelf (taken from Wright, 1995).
of significant onshore-offshore transport of sand by waves in a typical year $h_i$ (Hallemeier, 1981):

$$h_i = \left( \overline{H}_{s\text{rg}} - 0.3\sigma \right) \overline{T}_{s\text{rg}} \left( g / 5000D \right)^{1/2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots E2.2$$

where $\overline{H}_{s\text{rg}}$ and $\overline{T}_{s\text{rg}}$ are the mean annual significant wave height and period respectively and $D$ is the characteristic grain size of the lower shoreface.

2.2.2 Shelf Characteristics

General shelf characteristics are dependent on the tectonic setting and latitude of the coastal boundary, whereby tectonics control the general gradient and stability as well as the grain size and mineralogy of sediments delivered to the coast. Latitude influences the climate over both the land and ocean which in turn influences the delivery of sediments to the coast, the size, quantity and mineralogy of the sediments, and the ocean wave climate.

2.2.2.1 Tectonic Setting

Tectonics contribute to the large-scale relief of continental shelves, namely the slope and width, where passive trailing margins result in shallow wide shelves and active convergent margins result in steep narrow shelves (Inman and Nordstrom, 1971). Inman and Nordstrom (1971) further classify passive margins on an age basis into Amero, Afro and Neo (oldest to youngest). Concurrent with the decrease in age of the passive margins is a decrease in the width of the shelf, whereby Amero passive shelves are wide and beaches tend to be long and un-interrupted and Neo passive shelves are narrow. The southeast Australian margin is, in some respects, a typical Afro margin and exhibits coastal plains, a narrow shelf and alternating beach and headlands. Uncharacteristic of Afro margins, the southeast Australian margin is very steep and is the result of a paleo-subduction zone along the east coast of Australia (400–500Mybp; Li and Powell, 2001) and splitting of the Lord Howe Rise (60–80Mybp; Hayes and Ringis, 1973).

In more geologically recent times, the late Quaternary has been dominated by glacio-eustatic sea level fluctuations between +5m and -120m relative to present sea level recurring at 100,000–140,000 year cycles (Shackleton, 1987; Martinson et al., 1987). These repeated sea-level fluctuations have resulted in transgression and regression of the shoreline across the shelf, continually re-working sediments (Roy et al., 1980). The last major fluctuation in sea-level was a rise associated with the last de-glaciation and resulted in the rapid transgression of the shoreline (1m/70–80yr) reaching the present day level
6,500–6,000 b.p. (Thom and Roy, 1985; Ferland et al., 1995). This flooded the world's continental shelves, including the Sydney shelf where it also drowned a series of eroded valleys forming the coastal embayments of the present coastline.

2.2.2.2 Sediment Supply
Transgression of the shoreline results in sediment being re-worked shoreward to form the shoreface and coastal barriers (Roy et al., 1980). On shelves with a low sediment supply only a thin veneer of sediment remains to cover the shelf (Swift, 1968; Swift et al., 1991; Ferland and Roy, 1993), while on shelves with an abundant supply of sediment the shoreline progrades with rising sea level and leaves a much thicker sequence of sediments behind (Swift, 1976). These two cases are referred to as autochthonous and allochthonous respectively (Swift, 1976).

Sediment supply on the shelf also affects the across-shelf distribution of grainsizes. An abundant sediment supply often leads to a distinct seaward fining of sediments on the seafloor termed a 'graded shoreface' (Niedoroda et al., 1985; Swift et al., 1991) while shelves with a limited sediment supply often exhibit a zonation termed a 'segmented shoreface' (Roy and Stevens, 1981). This zonation, as illustrated in Figure 2.2, has led some coastal engineers to interpret the boundary between each facies as offshore limits of transport (e.g. Nielsen, 1994), however the use of geologically inherited features to imply contemporary processes has been questioned (Cowell et al., 1999).

2.2.2.3 Latitudinal Effects
The effect of latitude on the shoreface is varied. Firstly, latitude controls regional wind patterns which are responsible for the generation of waves and secondly it influences the sediment characteristics. Warm water is prevalent at low latitudes and can result in high rates of biogenic sediment production and a predominance of carbonate in the sediments. These sediments undergo high rates of chemical weathering and frequently form beach rock in the inter-tidal zones (Short, 1999). Wave energy is often very low due to low regional winds and the reefs that protect the coast. At high latitudes physical weathering dominates and results in coarse sediments often composed of unstable minerals due to slowed chemical activity. At the very extreme, a total absence of wave energy can exist due to the presence of sea ice slowing the evolution of the coast. Mid-latitude beaches are well studied and highly diverse. Many are composed of fine to medium grained quartz sediment, although some arid coasts have large contributions of shelf-carbonate sediments.
Figure 2.2: Schematic illustration of across-shelf sediment zonation: a) shoreface of southeast Australia; b) graded shoreface exhibiting seaward fining (taken from Cowell et al., 1999).
2.2.3 Effect of Shelf Slope on Oceanographic Processes
Shelf slope affects several oceanographic processes including tidal range, storm surge and wave climate. Tidal range increases proportionally with shelf width and is inversely proportional to shelf depth so that wide, shallow gradient shelves exhibit large tidal ranges and steep, narrow shelves exhibit micro-tidal ranges (Davies, 1980). Similarly, storm surge effects are felt greatest over wide, shallow shelves. The wave climate at the shoreline is also influenced by shelf gradient as shallow shelves tend to dissipate the energy of larger waves well before nearing the coast (Wright, 1995).

While tides are considered a non-essential beach component their impact on the shoreface is important (Short, 1999). Changes in water elevation results in migration of the various morphodynamic zones by altering the location of wave shoaling, breaking and run-up. Additionally, the rate of change of the water elevation (which is in direct proportion to the tide range) affects the length of time over which the waves can act at any given point on a profile and thus may be an important element in the shoreface morphodynamics. Tide range is classified into three stages; micro-tidal (<2m), meso-tidal (2–4m) and macro-tidal (>4m) after Davies (1964). The direct effect of tides on upper shoreface morphodynamics is the recurrent oscillation of hydrodynamic processes across the profile whereby a point along the profile may experience aeolian, swash, surfzone and shoaling waves (Masselink and Turner, 1999). An indirect effect of tides is to change the water table that has been shown to control the shape of the equilibrium profile (Masselink and Turner, 1999).

2.3 Physical Setting of the Sydney Region
2.3.1 Geological Setting
Many of the factors influencing the circulation in the Sydney region are artifacts of its geological history, climate and latitude. The southeastern margin of Australia is now essentially passive and has been for the last 2my (Marshall and Thom, 1976) and was formed by rifting in the Tasman Sea during the late Cretaceous and early Tertiary, 80–60mybp (Hayes and Ringis, 1973; Roy and Thom, 1991). As such, the southeast coast of Australia is narrow (30km near Sydney) and steep (Roy and Thom, 1991), the width of the shelf increasing northward. This section of coast is characterised by bedrock headlands that alternate with coastal barriers and estuaries that fill drowned river valleys (Roy and Thom, 1981). The composition of the bedrock headlands varies between Hawkesbury Sandstone and Shales of the Wiannamatta Group formed during the Triassic (Roy and Thom, 1981).
The bedrock comprising these headlands is specifically part of the Terrigal formation on the central coast (equivalent to the Narrabeen group of Sydney) and is relatively resistant to weathering resulting in minimal supply of sediments to the coastal compartments. This supply is estimated to be approximately 100–200 m$^3$km$^{-1}$yr$^{-1}$ for the Sydney coast (Chapman et al., 1982).

2.3.2 Recent History
As stated in Section 2.2.2.1 the late Quaternary was dominated by glacio-eustatic sea level fluctuations. These repeated fluctuations in the sea-level have resulted in transgression and regression of the shoreline across the shelf, continually re-working sediments such that the oldest known sequence of sediments on the shelf along the southeast coast of Australia is positively identified at 0.2 mybp (Roy et al., 1980). The last major fluctuation in sea-level was a rise associated with the last de-glaciation, resulting in a rapid transgression (1 m/70–80 yr) to reach the present day level 6,500–6,000 ybp (Thom and Roy, 1985; Ferland et al., 1995). This marine transgression was followed by a period of barrier building and progradation that varied significantly between different sectors of the coast, and continues today where sediments are available.

2.3.3 Sediment Characteristics
Sediments on the Sydney shelf are distributed in four shelf-parallel zones: 1) nearshore sands; 2) inner-shelf sands; 3) mid-shelf sands and muds; and 4) outer-shelf calcareous sands (Figure 2.2; Roy and Stephens, 1981). Of particular interest to this study are the nearshore and inner-shelf sands, the former being further divided into two components; a coarser inner nearshore sand and finer outer nearshore sand. The boundary between the two nearshore units is difficult to distinguish while the boundary between the nearshore sands and the inner-shelf occurs between 20–30 m water depths and is often well-demarcated. The inner-shelf sands are typically coarser and less wellsorted than the nearshore sands and extend to water depths of 50–60 m. This zonation of sediments is believed to be the result of marine transgression and from sediments supplied to the shoreface from winnowing of the finer sediment fraction of the inner-shelf sands (Chapman et al., 1982).

Sedimentological studies of the inner-continental shelf of the Sydney region have revealed the presence of convex sand bodies of nearshore origin (Field and Roy, 1984). Field and Roy's 1984 study detected 10–30 m thick sand bodies of nearshore origin stretching for
40km along the Sydney coast. These sand bodies lay between the 30m and 80m isobaths with the seaward edge being re-worked by shore parallel currents. Field and Roy (1984) surmised that the sand bodies were likely a result of wave stirring and downwelling associated with storm events as the sediments that composed these bodies were likely to be derived from the upper shoreface, however Field and Roy (1984) also suggest that rips were a possible mechanism.

2.3.4 Controls on Regional Wave Climate
Because of the steep narrow shelf of the NSW central coast, tides undergo minimal amplification resulting in a micro-tidal (1–2m) regime and exposing the coast to a relatively high energy deepwater wave climate that undergoes very little attenuation across the shelf (Wright, 1976). These factors, combined with the absence of major river systems, result in this region of the coast being wave dominated. The modal wave climate along the coast is \( H_s = 1.5 \text{m} \) and \( T_s = 8 \text{s} \) arriving from the southeast, with high energy conditions dominated by southerly storms and long period swells from the south Tasman Sea. These swells are generated by mid-latitude cyclones with waves having been reported in excess of 10m (Short and Trenaman, 1992). Large seas and swells are also generated by east coast cyclones and tropical cyclones that typically result in waves arriving from the east and northeast respectively. Many of the high energy wave events are driven by storms located great distances (100’s of kilometres) away and the narrow steep nature of the shelf minimises the impact of storm surge along this section of the coast.

2.4 Physical Oceanographic Processes of the Sydney Region
While waves may dominate the upper shoreface their impact on the seabed is reduced seaward as water depths increase. At some depth the waves cease to be the major at which point other oceanographic processes may be responsible for the generation of mean currents on the lower shoreface. As such, these other oceanographic processes have the potential to transport sediments, particularly in the presence of waves and must be considered. It follows that quantification of currents associated with these processes is imperative to understanding the response of the shoreface to extreme wave and current conditions.

2.4.1 Boundary Currents
The first of the large-scale processes active on the east coast of Australia is the East Australian Current (EAC, Figure 2.3). The EAC transports warmer water poleward and is
strongest on the shelf proper in northern NSW, where it persists adjacent to the coast with a notable deflection to the east at Seal Rocks (Middleton et al., 1997). South of Seal Rocks (30°S) a portion of the current persists southward with small separations from the coast, mirroring the behaviour of the EAC to the north (Ridgeway and Dunn, 2003). In addition to the main flow of the current, the regular formation of anticyclonic eddies off the NSW central coast makes currents in the region around Sydney (34°S) highly variable (Huyer et al., 1988; Morrow et al., 1992).

Current speeds associated with the EAC approach 1–2 ms⁻¹ along the north coast of NSW (Nilsson and Cresswell, 1980; Webb, 1991, 1992; Ridgeway and Dunn, 2003). When the EAC flows past Sydney it creates strong flows of up to 1.5 ms⁻¹ in the shallower depths of 20–50 m within 1 km of the coast (Cresswell, 1994), while flow associated with eddies shed from the main EAC have been measured up to 1 ms⁻¹ (Gibbs et al., 2000). The EAC has also been linked to coastal upwelling driven by flow encroachment, acceleration and separation along the coast (Roughan and Middleton, 2002).

2.4.2 Shelf Waves
Coastal Trapped Waves (CTW) have been shown to exist along the east coast of Australia generated in the Tasman Sea by the passage of low pressure systems and trapped on the shelf by the Coriolis effect. CTW's along the southeast Australian coast have small amplitudes (<20 cm), are characterised by time scales of 7–20 days and have spatial scales of alongshore variability of many hundreds of kilometres (Church et al., 1986). They manifest as a current oscillation that moves equatorward from its source in the Bass Strait, affecting Sydney waters two days after being generated by storm winds in the Strait (Griffin and Middleton, 1991). These waves are, therefore, predictable to an extent and can produce strong north-south directed currents (<0.5 ms⁻¹) in the nearshore region (Middleton et al., 1997, Figure 2.4). Higher frequency CTWs have also been identified by Freeland (1988) and occur in the diurnal frequency band, although no causal link was established with tidal forcing. Similarly, Gibbs and Middleton (1997) identified diurnal oscillations in near-bed currents (±4 cm s⁻¹); the cause of these currents also remains unresolved.

2.4.3 Tidal flows
The continental shelf of the east coast of Australia is narrow (10–20 km) resulting in a micro-tide range (1–2 m) along the east coast. Therefore, barotropic tidal flow, a direct
Figure 2.3: Thermal image of sea surface temperatures (in degrees Celsius) in the south Pacific Ocean, showing the East Australian Current and an eddy associated with it (obtained from RSMAS, 2004).
result of sea surface elevation, over the inner-shelf is minimal with a dominant $M_2$ (semi-diurnal) constituent (Easton, 1970). Observations by Gibbs and Middleton (1997) identified the presence of a strong diurnal constituent, the cause of which was unresolved due to suspected contamination of CTWs and local daily wind patterns at diurnal frequencies. Baroclinic tides (propagating along density variations) are also known to exist off the coast of Sydney and contribute to velocities at the seabed of up to 10cmsg$^{-1}$. Tidal flows are also driven by tidal exchange from the larger estuaries. The largest estuary in the Sydney region is Broken Bay, which includes the Hawkesbury River, Pittwater and Brisbane Water has a total area of 144.6 km$^2$ (Middleton et al., 1997) and is located 10km to the north of the study site. Velocities associated with tidal exchange decrease with increasing distance from the estuary mouth and have strong semi-diurnal components.

### 2.4.4 Wind-Driven Currents

Wind-driven currents manifest themselves as upwelling and downwelling of coastal waters. These currents have many impacts on the coastal system, the major one being upwelling of nutrient water from below the photic zone that often coincides with increased biological activity (Roughan and Middleton, 2002). The ability of winds to generate mean currents, the direction of which is governed by the wind direction, is of primary importance to this study. Two effects are active in the generation of these currents. Firstly, alongshore winds (in the context of the Sydney coast) from the northeast drive surface waters offshore through Ekman transport. This produces a lower water surface at the coast which is replaced by deeper water — this is upwelling. The second effect is shelf flow driven poleward by an internal pressure gradient. In contrast, winds from the southwest create onshore directed Ekman transport and elevate the water surface at the coast which forces coastal waters down — this is downwelling (Figure 2.5). Similarly, a secondary flow is generated along the coast in the direction of the wind, equatorward (Griffin and Middleton, 1992; Gibbs et al., 1996).

When considered in the context of this investigation, which focusses on the shoreface, it is important to note that it is friction-dominated. Put more simply the surface boundary layer affects the seabed and the seabed boundary layer affects the surface boundary layer (Wright, 1995). The impact is that winds, in the absence of Ekman transport (due to depth limitations), from northeast anticlockwise through the southwest can produce offshore surface flow and upwelling, while winds from southwest anticlockwise through northeast
Figure 2.4: Measured current velocities on the mid-shelf of the east coast of Australia, associated with coastal trapped waves (taken from Middleton et al., 1997).

Figure 2.5: Schematic illustration of wind-driven currents on the inner-shelf for a coast in the southern hemisphere (adapted from Wright, 1995).
can produce onshore directed surface flow and downwelling. Water temperatures vary significantly between these two types of events, whereby upwelling brings cooler deeper water to the surface, stratifying coastal waters, while downwelling drives warm surface water down to lower depths, homogenising coastal waters (Middleton et al., 1997) and may have implications for internal wave activity (presented in the following section).

2.4.5 Internal Waves
Internal waves propagate along density contrasts within the coastal water column. The density of sea water is governed by salinity and temperature and it is along differences in these two properties that internal waves typically form. Off the coast of Sydney stratification of the water column occurs mainly due to temperature differences, with the intensity of internal waves being governed by the degree of stratification (Wright, 1995). Stratification increases from September with a maximum range of 10°C in late summer, decreasing to March with the winter months typically resulting in isothermal conditions (Middleton et al., 1997). Intrusions of the EAC, and eddies associated with it, have however been noted to elevate surface temperatures and induce stratification in the winter months (Middleton et al., 1997). The energy of internal waves is contained in two bands; tidal frequencies (baroclinic tides) and high frequencies (10–30mins, internal waves), an example of which is shown in Figure 2.6. As for surface waves, internal waves manifest as orbital motion at the seabed and result in oscillation of both water velocity (20–30cms⁻¹) and temperature and are thus important considerations in the generation of near-bed currents.

2.4.6 Rip Currents
Rip currents are active on the upper shoreface in the surfzone and form an integral part of horizontal circulation on intermediate beach states where variations in alongshore morphology exist. Typically, the number of rips decreases with increased wave energy. This reduction in number is countered by an increase in their size and intensity (Shepard et al., 1941; Shepard and Inman, 1951; Inman and Quinn, 1952; McKenzie, 1958; Bowen and Inman, 1969; Hino, 1974; Short, 1985; Huntley and Short, 1992; Short and Brander, 1999). Huntley and Short (1992) demonstrated that rip spacing was primarily dependent on wave height and sediment fall velocity, increasing with increases in wave height and decreases in sediment fall velocity. Their study did not adequately account for all variation and cited antecedent beach morphology as influential to the observed rip spacing. Short and Brander
Figure 2.6: Measured temperatures on the mid-shelf of the east Australian coast associated with Internal Waves (taken from Middleton et al., 1997).

Figure 2.7: Primary components of coastal morphodynamics illustrating the feedback between morphology and hydrodynamics (taken from Cowell and Thom, 1994).
(1999) considered antecedent beach morphology and identified a strong relationship between rip density and regional wave climates. Short and Brander's study showed west coast swell dominated regions exhibit larger rips (typically 2 rips per km), east coast swell dominated regions exhibit moderately sized rips (typically 5 rips per km) and moderate wind sea regions exhibit small rips (typically 12 rips per km). Hence, rip spacing is strongly dependent on the incident wave conditions and the pre-existing beach conditions.

The offshore extent of rips, and the offshore extent of their coupling with the inner-shelf, is largely governed by the width of the surfzone. Surfzone width is in turn a result of the beach slope and incident wave characteristics. The control that surfzone width has on the offshore extent of rips, is through flow deceleration seaward of the surfzone.

2.4.7 A Summary of Current Understanding
A general paucity of data and research exists for the impact of oceanographic processes on the hydrodynamics of the inner-shelf. The current understanding of oceanographic processes on the inner-shelf is limited to the context of the outer-shelf of the Sydney region, with only inferences for their importance closer to shore. Although a large body of research exists for the role that rips play in the coupling of the upper and lower shoreface, little of the work pertains to the extent of the coupling under high energy conditions.

2.5 Inner-shelf Morphodynamics
The form and process of the shoreface are inter-related and present understanding is that an equilibrium state exists for each set of environmental conditions. The difference between the present state of the system and the ideal state for the present forcing conditions is the driving force for change. This section will describe the concept of morphodynamics and equilibrium states as they pertain to the shoreface.

2.5.1 General Morphodynamics
The general principle of morphodynamics is based on the interdependence of hydrodynamics and morphology, whereby hydrodynamics respond instantaneously to morphology, and morphology responds to the hydrodynamics with a time lag that is dependant on the volume of sediment to be transported and is inversely proportional to the energy of the hydrodynamic process (Figure 2.7; Wright, 1995). Changes in external conditions drive morphodynamics and produce evolution of the coast (Wright and Thom, 1977; Wright, 1995; Woodroffe, 2002), the present state being a combination of antecedent morphology and the present hydrodynamic conditions.
Three core aspects of the nearshore system were identified by Wright (1995) as requisite for the determination of morphodynamic processes: 1) the environmental conditions; 2) the fluid dynamic and morphodynamic processes; and 3) the coastal response over various time-scales (evolutionary sequence). Environmental conditions include the pre-existing solid-state boundary conditions, nature and abundance of sediments and the oceanographic forcing conditions that induce change. Fluid dynamic and morphodynamic processes are best defined as the way in which the forcing conditions and solid state interact and, via their co-dependence, induce change in the system. Evolutionary sequence is the ultimate goal of morphodynamic study; it is the identification of the net sum of the processes as viewed in stratigraphic records and provides insight into the response of the coast to changes in environmental conditions.

Equilibrium states are often achieved by feedback loops between the morphology and the hydrodynamics and may be either positive (self-organising) or negative (self-regulating) (Cowell and Thom, 1994). An example of a positive feedback mechanism is the progressive infilling of rip feeder channels under decreasing wave conditions as observed by Brander (1999). An example of negative feedback on a short time-scale is beach cusps initiated by edge waves and maintained by topographic relief that ultimately suppresses the edge waves (Guza and Bowen, 1981). On a longer time-scale maintenance of the equilibrium profile is also a self-regulatory system (Dean, 1991). Equilibrium is a product of negative feedback and takes three forms: 1) steady state; 2) periodic; and 3) chaotic (Phillips, 1992).

2.5.2 The Equilibrium Profile
The concept of an equilibrium profile is based on the frequent observation of a concave-up shoreface profile. The general slope of this profile is associated with the energy of the wave climate and the characteristics of the sediment that compose the shoreface. Higher energy wave climates and fine sands result in flatter, wider shorefaces and lower wave energy and coarser sediments result in steeper, narrower shorefaces. Attempts to define the physical processes active in defining the shape of the profile, and to hence develop deterministic equations, was initiated by Cornaglia (1889). This study suggested the concave-up shape of the profile was the result of a balance between the shoreward asymmetry in wave orbital velocity and gravity acting on the sediments. This theory is known as the null point hypothesis as a null point exists for each sediment grainsize where
onshore-offshore forces are balanced, with null points for coarser sediments being closer to the shoreline. This model adequately explains the seaward fining observed on many profiles, however the model predicted that a distribution of grainsizes placed on the seabed would result in one grainsize remaining, the coarser sediments moving offshore and finer sediments onshore, which countered other observations (Zenkovich, 1946; Murray, 1967) and led to the development of new hypotheses.

One of the more recent hypotheses is based on measured profiles which correspond with:

\[ h = Ax^m \]  
\[ A = 0.067 \omega_s^{0.44} \]

where \( h \) is water depth and \( x \) is offshore distance, with \( A \) being defined by Equation 2.4 and \( m \), typically between 2/5 and 4/5, with empirical definitions of \( A \) as the scale factor and \( m \) as the shape factor (Dean, 1977). It was later hypothesised that this formulation was associated with the uniform dissipation of energy across the profile and is implemented as the rate of dissipation per unit area of the seabed (Bruun, 1954) or by the uniform dissipation per unit volume (Dean, 1977).

A weak relationship has been established between beach state (beach slope) and the shape factor \( m \); Kotvojs and Cowell, 1991). While attempts have been made by Dean (1991, 1997) to make \('A' \) a semi-empirical factor (as in Equation 2.4) by the introduction of sediment fall velocity, its application to data on southeast Australian profiles was not particularly useful in a predictive sense (Cowell and Kotvojs, 1987). Cowell and Kotvojs (1987) and Meleo (1994) both suggest that \( A \) and \( m \) should be derived from direct measurement of the profile and Cowell et al. (1995) found its use best in general shoreface modelling.

2.5.3 Beach States
Beach states are classified for natural beaches by Wright and Short (1984) using the dimensionless fall velocity developed by Gourlay (1986):

\[ \Omega = H_b / (\omega_s T) \]

where \( H_b \) is breaker height, \( \omega_s \) is sediment fall velocity, and \( T \) is wave period (Figure 2.8). Values of \( \Omega \leq 1 \) result in reflective beaches and values of \( \Omega \geq 6 \) result in dissipative beaches. Beaches where \( 6 \geq \Omega \leq 1 \) are 'barred profiles' and are referred to as intermediate type
beaches. As $\Omega$ increases above 6 no change to the general morphodynamics is noted, however an increase in surfzone width is apparent.

In the beach state model of Wright and Short (1984) offshore sand transport is manifest as the seaward movement of the bar under increasing wave energy, while the reverse is also true with decreasing energy conditions being associated with the onshore migration of the bar. An erosional and accretionary sequence was compiled by Short (1999) whereby beach states reflect the changes in profile shape according to the models proposed by Short (1979) Wright and Short (1984), Sunamura (1988), and Lippman and Holman (1990).

2.6 Embayed Beaches

All beaches at some point have a terminal boundary; these termini may take the form of an inlet or sandy foreland, a product of wave and tidal processes, or formed by rocky headlands or structural elements such as groynes, independent of formative beach processes. It is the latter that classifies embayed beaches and exert a significant influence on the processes active within the embayment. This is the case for the beaches of the Sydney region and the NSW and Victorian coastline where rocky headlands segment the coast into 1280 beaches of an average length of 1.4km (Short, 1993).

2.6.1 Planform of Embayed Beaches

Beach planform of embayed beaches is attributed to the refraction and diffraction of waves, such that the beach is typically shaped the same as the pattern of the refracted waves, as observed by Davies (1958). Generally, these beaches have an asymmetric planform due to the incidence of the modal wave climate being oblique to the chordline of the embayment, the chordline being defined as the line between the seaward extremities of the headlands (Figure 2.9). In the lee of the sheltered headland the embayment is typically highly arcuate, while down drift of the wave field the embayment is typically long and straight. The asymmetry at the sheltered end of the embayment is well defined by a zeta form (Yasso, 1965), however the straighter portion of the beach does not conform well and a parabolic shape has been applied by Hsu et al. (1987) which better predicts the embayment shape.

The planform of an embayment in equilibrium with the incident wave climate has been shown to match the wave refraction pattern. When waves arrive from angles other than the modal direction the planform of the embayment is no longer in equilibrium and a net alongshore current is generated, resulting in an adjustment of the planform. The alongshore
Figure 2.8: Sensitivity plot of the contribution grainsize, wave height and wave period have to beach type as specified by the dimensionless fall velocity of Gourlay (1986) (taken from Short, 1999).
Figure 2.9: Planform of an embayed beach showing the effect oblique waves have on the shape of the shoreline.
currents generated result in an adjustment that corresponds to the refraction pattern of the new wave conditions. Such changes in wave climate over prolonged periods (decadal) have resulted in beach rotation (Bird, 1993; Short et al., 1995; Short and Trembanis, in press).

2.6.2 Alongshore Sediment Transport
Headlands hinder the continuity of alongshore currents and alongshore transport (littoral drift) along the east coast of Australia, the degree being largely dependent on the degree of embaymentisation. Along this coast the direction of transport is northward, the result of the dominant southeast wave climate (Chapman et al., 1982), although other coastal processes may influence the direction of mean currents. Often the only means for significant alongshore transport of sediment between embayments is via the process known as headland sand by-passing. Little research has been undertaken on this process and the mechanisms responsible, although beach rotation is expected to play a role (Short, 1999).

Beach rotation may periodically allow sediments to be released to the down drift embayment when that end of the embayment is built out (Short, 1999). Chapman et al. (1982) used the distribution of nearshore sands on the southeast coast of Australia as an indicator of the potential for alongshore transport via headland sand by-passing, whereby the alongshore continuity of the nearshore sands indicates a strong likelihood that significant quantities of sediment are by-passing the headlands, while alongshore discontinuity of nearshore sands due to rocky reef headlands indicates insignificant amounts of sediment by-passing the headland.

2.6.3 End Effects
Due to the refraction and diffraction pattern of the waves around the headland into the sheltered section of the beach, a distinct difference in beach state can be observed between the exposed and sheltered ends of the embayment (Short, 1985). In addition, the associated decrease in energy results in a change in rip spacing such that rips spacing decreases towards the sheltered end of the embayment. The structural elements (headlands) of the embayment typically result in the formation of a rip adjacent to them (Short and Masselink, 1999) this introduces the idea of end effects created by the presence of headlands. This concept of end effects introduces the notion of their ability to affect the entire embayment (in short embayments under high energy conditions) and this is said to
occur when rip spacing approaches embayment width (Martens et al. referenced in Short 1999).

2.7 Surfzone Circulation
Water circulation in the surfzone is the result of waves breaking and is driven by three mechanisms: 1) alongshore variations in wave setup; 2) alongshore currents due to oblique wave approach; and 3) bed return flow.

2.7.1 Wave Setup Gradients
The concept of wave setup was introduced by, and has been demonstrated theoretically and experimentally by, Bowen and Inman (1969). This concept predicts a setup shoreward of the break point and set-down seaward of the breakpoint with the slope in water surface producing a pressure gradient that balances the onshore directed momentum generated by the waves. The radiation stress in shallow water is given by:

$$S_{xx} = \frac{3}{16} \rho g H^3 \quad \text{E2.6}$$

where $\rho$ is the water density. To balance the onshore directed momentum and the pressure gradient the following relationship must hold true:

$$\frac{dS_{xx}}{dx} + \rho g (\bar{\eta} + h) \frac{d\bar{\eta}}{dx} = 0 \quad \text{E2.7}$$

whereby the difference between the water surface elevation ($\eta$) in the presence of waves and the absence of waves is equated using:

$$\frac{d\bar{\eta}}{dx} = \left( \frac{1}{1 + 8/3 \gamma^2} \right) \tan \beta \quad \text{E2.8}$$

where $\gamma$ is the ratio of wave height to water depth and $\beta$ is the slope of the shoreface.

When considering variations in the wave height in an alongshore direction concurrent with the subsequent variation in wave setup, a pressure gradient is established. This pressure gradient is unbalanced and flow is established such that flow is directed toward areas of low setup. Alongshore variation in wave setup is governed by:

$$\frac{\partial S_{yy}}{\partial y} = \frac{1}{4} \rho g H \frac{\partial H}{\partial y} \left[ \frac{kh}{\sinh(2kh)} \right] \quad \text{E2.9}$$

where $k$ is the wave number.
Variations in wave height alongshore are generated by changes in topography typically associated with bar and rip morphology, where deeper water in the rip channels produces a lower setup gradient than over the shallower bars creating the pressure gradient required to generate flow. In a similar manner, offshore topographic features can generate zones of higher or lower wave setup by wave refraction (Shepard and Inman, 1951). Under these circumstances rips generated in response to such wave setup gradients can be topographically controlled.

2.7.2 Oblique Waves
Waves arriving oblique to the shoreline generate an alongshore directed current, the strength of which is modulated by the wave angle and wave height. Modern analysis of these currents is based on work by Bowen (1969b), Longuet-Higgins (1970a,b) and Thornton (1971), with the driving force being the oblique component of radiation stress, \( S_{xy} \). Current velocities, \( v_i \), can be defined for the mid surfzone position by (Komar, 1979):

\[
\bar{v}_i = 1.17 (gH_o)^{1/2} \sin \alpha_b \cos \alpha_b \quad \text{...............E2.11}
\]

where \( H_o \) is the breaker wave height and \( \alpha_b \) is the breaker wave angle. These currents are well researched given their ability to transport sediment (Komar, 1979). A series of cross-shore velocity distributions associated with the alongshore current as developed by Longuet-Higgins (1970a,b) is shown in Figure 2.10. The quantity \( P \) is a horizontal mixing term and results in the alongshore current being observed further seaward than the break point, as for where there is no mixing (\( P=0 \); Figure 2.10).

2.7.3 Bed Return Flow
Bed return flow (undertow) consists of a strong seaward flowing bottom current and was first observed in the wave channel experiments of Bagnold (1940). These currents are generated by the water transported toward the shore by breaking waves in the process of setup, as previously discussed, and are best observed in the absence of three-dimensional circulation. Observations of bed return flow have been made on natural beaches by Wright et al. (1982) and Masselink and Black (1995). Bed return flows have been observed on both planar and barred beaches with flows peaking around the mid surfzone position on planar beaches and over the bar on barred beaches.
2.7.4 Characteristics of Rip Current Flow

Horizontal circulation in the form of rip currents dominates the intermediate beach zone, as seen on many dissipative beaches and absent from reflective beaches (Wright et al., 1992). Flow within the rip channels leads to the rip head, which is shown to modulate with the tides due to a variation in the cross-section of the rip channel area and changes in wave breaking (McKenzie, 1973; Longuet-Higgins, 1995; Brander, 1999). Ripping in flow has also been observed in several mixtures in response to infragravity waves and/or bottom subaerial erosion (McKenzie, 1985; Brander, 1999). The impact such flow characteristics have on the beach can be studied using the example of the rip current model shown in Figure 2.10.

Figure 2.10: Group of longshore current profiles across the surfzone where X and V are both normalised components. The value P indicates the horizontal mixing where 0 = no mixing (taken from Longuet-Higgins, 1970a).

2.8 Boundary Layer and Sediment Transport Processes

The boundary layer, a logarithmic velocity defect layer, can be shown to develop across the near-surface zone of the beach, as shown in Figure 2.11. The logarithmic layer model is used to describe the variation of the near-surface flow by Equations 2.15 and 2.17, with the identification of the logarithmic profile of the near-surface flow. The implications that arise from the development of the boundary layer on sediment transport and beach dynamics in response to changes in wave direction and wave height (Wright, 1991). Their height is used to define the

Figure 2.11: Idealised logarithmic profile showing various regions of the current boundary layer (taken from Wright, 1989).
2.7.4 Characteristics of Rip Current Flow
Horizontal circulation in the form of rip currents dominate the intermediate beach states, are rare on fully dissipative beaches and absent from reflective beaches (Wright et al., 1982). Flow within the rip channels has been shown to modulate with the tides due to a reduction in the cross-section of the rip-neck area and changes in wave breaking (McKenzie, 1958; Sonu, 1972; Masselink and Hegge, 1995; Brander, 1999). Pulsing in flow has also been observed at periods of 30s to several minutes in response to infragravity waves and/or wave grouping (Sonu, 1972; Short, 1985; Brander, 1999). The impact such flow characteristics have on the structure of the boundary layer is unknown yet highly significant in accurate quantification of surfzone circulation.

2.8 Boundary Layer and Sediment Transport Processes

2.8.1 Boundary Layers
The concept of the boundary layer is based on friction arising from the relative motion between a fluid and a solid. Friction is restricted to a layer known as the boundary layer adjacent to the interface between the two surfaces and can be divided into three regions: the bed layer, a logarithmic layer and an outer layer (Figure 2.11).

Identification of the logarithmic layer allows determination of the shear stress (τ) via Equations 2.12 and 2.13:

\[ U_z = \frac{u_z}{k} \ln \left( \frac{z}{z_0} \right) \] ............E2.12

\[ \tau = \rho u_z^2 \] .................E2.13

where \( z \) is height above the bed, \( z_0 \) is the hydraulic roughness length and \( k \) is the von Karman constant (\( k=0.4 \)). The importance of shear stress is the force it applies to the particles that make up the seabed that leads to their entrainment and subsequent transport. Implicit in the definition of the boundary layer is the assumption of steady flow i.e. flows that are not accelerating (or decelerating). In the presence of waves this assumption is invalid as it is continuously oscillating. As the shoreface is dominated by oscillatory flow associated with surface waves, it is important to consider an oscillating boundary layer.

Oscillating boundary layers are thin and rarely extend more than 10cm above the seabed (Wright, 1995). Their height is defined by:
\[\delta_w = K_\delta \frac{K u_{**}}{\omega} \quad \text{E2.14}\]

\[u_{**} = \sqrt{\tau_w / \rho} \quad \text{E2.15}\]

where \(\omega\) is the wave radian frequency, \(u_{**}\) is the time dependant wave friction velocity and \(K_\delta\) is a constant between 1 and 2. Above the boundary layer the 'free stream' orbital velocity as defined by wave theory exists. As \(u_{**}\) varies with wave orbital velocity so too does the thickness of the boundary layer, however a time averaged shear stress can be defined by:

\[\langle \tau_w \rangle = \frac{2}{3\pi} \rho f_w \bar{u}_{b, max}^2 \quad \text{E2.16}\]

\[f_w = e^{[5.21 (k_b/\omega) \rho^{0.18} - 5.97]} \quad \text{E2.17}\]

where \(a_b\) is the orbital semi-excursion and \(k_b\) is the roughness of the bed. At times both waves and mean currents are expected to be present on the lower shoreface, and it is also important to consider the combined action of wave and current boundary layers.

Typically, the thin wave boundary layer is nested within the bed layer of the current boundary layer and acts to enhance the bottom friction (Grant and Madsen, 1979; Sleath, 1990). Three shear velocity components can be distinguished: 1) mean current shear velocity; 2) oscillatory in the absence of mean currents; and 3) a combined wave-current. Their co-dependency is defined by Equations 2.20–2.23 and requires iterative solving of simultaneous equations in order to be determined. The thickness of the combined wave current boundary layer is given by:

\[\delta_{cw} = K_\delta \frac{K u_{*w}}{\omega} \quad \text{E2.18}\]

Above this layer, in the mean current logarithmic layer, velocities conform to (Grant and Madsen, 1986):

\[u_c = \frac{u_{*c}}{\kappa} \ln \frac{z}{z'_{ac}} \quad \text{E2.19}\]

where \(z'_{ac}\) is the apparent roughness above the wave boundary layer that equates to:
\[ z' = \delta_{yw} \left( \frac{z_{yw}}{\delta_{yw}} \right)^{\gamma} \] \hspace{1cm} \text{E2.20}

\[ \gamma = \frac{u_{yw}}{u_{yw}} \] \hspace{1cm} \text{E2.21}

The co-dependency of \( u_{yw} \) and \( u_{yw} \) lies in the following set of equations (Grant and Madsen, 1986):

\[
u_{yw}^2 = \frac{k \delta_{yw} u_{y,\text{max}}}{\left[ \ln \left( \frac{k \delta_{yw}}{z_{yw}} \right) - 1.15 \right]^2 + \left( \frac{\pi}{2} \right)^2} \] \hspace{1cm} \text{E2.22}

\[
u_{yw} = u_{yw} \left[ 1 + 2(u_{y_1}/u_{yw})^2 \cos \phi_{yw} + (u_{y_1}/u_{yw})^4 \right]^{1/4} \] \hspace{1cm} \text{E2.23}

The combined effect of wave and current boundary layers enhances the bed stresses imposed on the sediments and is greater than simple linear addition (Wright, 1995).

### 2.8.2 Sediment Transport Processes

The movement and transport of sediment is governed by the forces acting on the individual grains, which are derived from the sediments that compose the seabed and the fluid that is working on the sediments. The initiation of motion is a difficult concept due to its definition being dependent on whether one in a thousand sand grains or one in a hundred sand grains is moving (Nielsen, 1994). In addition, antecedent bed roughness also plays a significant role in the suspension of sediments. These factors aside, Shields (1936) developed a parameter, \( \theta \), which measures the balance between the disturbing and stabilising forces acting on a sediment grain and is defined by the skin friction Shields parameter:

\[ \theta = \frac{\tau'}{\rho(s-1)gD} \] \hspace{1cm} \text{E2.24}

where \( \tau' \) is the effective stress defined by Equations 2.13 and 2.16, \( s \) is the density of sediment relative to water and \( D \) is the grain diameter. A critical value for \( \theta' \) exists for each grainsize where sediment motion is initiated and for sand is typically around 0.05.
2.8.3 Gravity-Driven Flows
A unique situation of auto-resuspension can be achieved when sediment concentrations are high enough to increase the density of the fluid near the bed. Under such conditions, gravity results in the downslope movement of a high density sediment plume. This action is initiated by high sediment concentrations increasing the density of the fluid-sediment mixture, which in turn increases the effective shear stress that enhances re-suspension (Wright, 1995). When the rate of re-suspension equals the rate of deposition it is said to be 'auto-suspending'. When values exceed that required to auto-suspend, the flow accelerates downslope. These events are well documented on the outer-shelf and shelf slope where sediments are much finer, however their observation on the inner-shelf is limited (Wright et al., 2002). In the study of Wright et al. (2002) gravity-driven sediment transport was episodic and related to the wave grouping, whereby the largest waves in the wave group were responsible for the formation of the currents. These currents may have contributed to drapes of finer sediment over coarse sediments on the inner-shelf, as observed in the earlier study of Wright et al. (1991).
Chapter Three

Methodology
3.1 Introduction
The data for this study was collected as part of a SPIRT funded grant investigating "Rip current dynamics — social and shoreline implications and management". All experiments for this study were conducted at MacMasters — Copacabana beach on the New South Wales Central Coast (Figure 3.1) in collaboration with the former Department of Land and Water Conservation. Experiments were semi-continuous, commencing July 1999 and concluding July 2001. This chapter details: the Holocene history and the local environment of the field site; the design of the experiments in context with their requirements to achieve the objectives; the working principles of the instrumentation and their calibration; and the recovery and reduction of the acquired data.

3.2 Field Site
MacMasters — Copacabana beach forms a mid bay barrier located on the New South Wales Central Coast approximately 50km north of Sydney (Figure 3.1). The beach is 1500m long with prominent headlands that extend 900m offshore (aerial extent) at both ends of the embayment. The headlands compartmentalise the beach, limiting sediment supply by removing littoral transport between embayments (Short and Wright, 1981). The embayment faces 127° approximately southeast, exposing it to the dominant southeast wave climate that exists in this region.

The embayment can be divided into two regions: the first, MacMasters beach, is a minor bay head beach situated at the southern end; and the second, Copacabana beach, is a mid-bay barrier beach that forms a barrier at the northern end. The barrier encloses Cockrone Lake, a usually closed shallow brackish water lagoon. The two beaches connect to form a continuous stretch of sand running the entire length of the embayment. For the purpose of this study the system described above is hereafter termed MacMasters beach in this document.

MacMasters beach lies on the eastern edge of the Sydney Basin, which extends from Port Stephens (in the north) to Wollongong (in the south). The Sydney Basin is typically composed of massive horizontally-bedded Triassic sandstone with various groups in the sequence containing shale interbeds. These sandstone units produce the prominent headlands that compartmentalise the beaches and characterise the coastline so indicative of this region. MacMasters beach lies within the Narrabeen Group, specifically the upper Gosford Formation, typically referred to as shaley sandstone.
The study site is located at 33°29'00" latitude and 151°25'30" longitude and is exposed to a periodic moderate swell and local wave climate (1-5m, 40%) with few calendar days (10%). A significant wave height is 2-3m (21%), 3-4m (21%) (Treadwell and Short, 1997). The study site is in the Tasman Sea by Tropical cyclones. East Coast cyclones and Mid-Latitude cyclones. A strong seasonal trend for northerly sea

Figure 3.1: Location of MacMasters beach, NSW, Australia, with inset of bathymetry and instrument site locations (Department of Land and Water Conservation).
The field site is located at 33°30'00" latitude and 151°25'30" longitude and is exposed to a persistent moderate swell and wind wave climate (1–2m, 63%), with few calms, (<1m, 10%) and a significant occurrence of high waves (2–3m, 21%; 3–5m, 5%) (Trenaman and Short, 1987). The wave climate is generated in the Tasman Sea by Tropical cyclones, East Coast cyclones and Mid-Latitude cyclones. A strong seasonal trend for northeasterly sea breezes and hot northwesterly winds during summer is well documented (Short, 1993). The modal grain size is 1.5 phi, which has a fall velocity of 3.85 cms^{-1}, and gives the beach a steep offshore profile of 0.022 that extends ~1.9km offshore and flattens to 0.002 seaward of 2km. MacMasters beach is typically a transverse bar and rip with the bar being dissected by 6–8 rips (Short, 1993).

3.3 Instrumentation, Calibration and Data Reduction
As for many studies, availability of instrumentation was a limitation and was largely due to the hazardous conditions they were to be deployed in. Much of the equipment needed to be robust and capable of handling large seas and have the ability to collect data remotely. This study was limited to two sontek hydramas, each consisting of an Acoustic Doppler Velocimeter (ADV) and two Optical Backscatterance Sensors (OBS), and two Acoustic Doppler Current Profilers (ADCP). Funding allowed for the collection of sidescan data and two hydrographic and topographic surveys. This section outlines the instrumentation used and the techniques employed to obtain the data used in this study. The following section (Section 3.4), explains the experimental setup and design and defines the placement and sampling strategies employed throughout the study.

3.3.1 Hydrodynamic Instruments
Eulerian hydrodynamic data were collected from the 6th of June 1999 to the 26th of April 2001 over 8 deployments using two ADVs (Figure 3.2a) and two ADCPs (Figure 3.2b). The two ADVs (Sontek Hydra) were used to obtain high resolution, near-bed current velocities in three dimensions (east, north and up) and to determine the water temperature and hydrostatic pressure. LaGrangian estimates of surface flow velocity and mega-rip size and position were determined using oblique digital video footage and photographs.

ADVs and ADCPs use a high frequency acoustic pulse which is reflected by minute sediment particles, air bubbles etc. that act as passive tracers for current velocity. The reflected pulse is received and used to determine water velocity by measuring the change in wavelength of the returning signal (Doppler Shift). A zero change in wavelength
Figure 3.2: Photos of: a) acoustic doppler velocimeter; and b) acoustic doppler current profiler in trawl-proof frame.
indicates a zero velocity, while an increase in wavelength indicates a velocity away from
the receiver and a decrease in wavelength indicates a velocity towards the receiver. The
ADV and ADCP vary by use of a technique called ‘range gating’, which allows the ADCP
to determine the water velocity at various heights. The received signal is broken into
successive segments, each successive time segment corresponding to an increased distance
from the instrument, thus allowing a profile of water velocity to be measured. As the
ADCP has a combined emitter/receiver the transducer has to stop ringing before a
returning signal could be heard and, this time corresponds to distance termed the blanking
distance of 0.5m was created. The advantage of using acoustic instruments is their ability
to remotely sample water velocity in three dimensions. In addition, the use of self-
contained acoustic instruments provided a means of collecting long-term data in a hostile
environment. These factors made them ideal for use in this study.

Local wave heights were determined using the ADV, through and onboard pressure gauge
and the post-processing software utility ‘View Hydra Pro™’. This software determined
wave parameters using the PUV technique (SonTek, 2001) Offshore wave height and
direction data were obtained from the Department of Public Works and Services’ Manly
Hydraulics Laboratory. Their Datawell Waverider buoy system uses an accelerometer
mounted on a loose tethered buoy to measure vertical and horizontal accelerations as the
buoy moves with the water surface.

3.3.2 Hydrographic and Beach Surveys
Surveys of the bathymetry were used to determine bathymetric features such as sediment
bodies, channels and general morphological characteristics of the field area. More than two
surveys allowed for the identification of bathymetric change that may have resulted from
hydrodynamic processes. The sub-aerial beach and surfzone (+5m to -3m) was surveyed
using a total station (geodometer), while the outer-surfzone (-3m) to the inner-shelf (-40m)
was measured using an echo sounder.

The bathymetry is a surface and, as such, required three components (XYZ) to be
identified. Horizontal co-ordinates (XY) were determined using an Ashtec Z12 GPS with
differential corrections from Omnistar using a base station located at Bathurst (accurate to
±3m), while the third, vertical (Z) dimension was determined using an Odom Echotrac
MkI 200KHz echo sounder (accurate to ±1cm). The most problematic issue with regard to
sampling via echo sounding was the presence of waves on the water surface. Waves
resulted in the pulse being emitted in a non-vertical direction, the pulse thus overestimating the depth to the seabed. Similarly, waves placed the receiver higher and lower than the sea level, again resulting in over- and underestimation of depth respectively. Both errors were compensated for by a TSS 323 heave compensation sensor that corrected for the deviation of the emitted pulse from the vertical and horizontal (accurate to ±10cm). Finally, a correction for the tide was required. Tidal elevation is accurately known along the entire coast of Australia, thus tide correction was achieved by post-processing of the data for the time the sample was taken.

The sub-aerial beach and inner surf-zone morphology were measured by a geodometer (computerised theodolite), into which a series of known locations were programmed. Placing the geodometer at one of these known locations and triangulation with another known location allowed its position and orientation within the programmed co-ordinate system to be derived. Accuracy of this system was in the order of millimeters in three dimensions, however placement of the reflector on sand introduced error in the order of 1–2cm.

3.3.3 Seabed Mapping and Characteristics
The echo sound surveys did not provide full coverage of the seabed nor did they determine the nature of the seabed (rock/sand). Thus sidescan sonar was employed to provide greater detail on the nature of the seabed to produce a quasi-3 dimensional image. The system used was a Klein 595 towfish (Figure 3.3) with transmitter/receiver transducers operating at 384kHz, an Isis system for collection of the data, and DelphiMap for mosaicing, with positional fixing gained through DGPS as described in Section 3.3.2. The transmitters emitted a high frequency (10Hz) acoustic pulse whose slant range was 75m either side of the vessel, with an across-track resolution of 75mm. Along-track resolution was governed by the vessel speed set at 4–5knots giving a resolution of 250mm, the system having a pixel resolution of 75x250mm. As different materials have different reflective properties, which correspond to changes in the intensity of the returning signal, sediment characteristics smaller than the pixel resolution could be quantified with ground truthing.

Sediment characteristics were determined for 25 sediment samples taken from various positions within the embayment. The grainsize fractionations were determined using a column by sieving at 0.25 phi intervals. Each column was agitated for a total of 22 minutes to separate the various size fractions. The composition of the sand grains was in three
ion categories, the major abundance (70%) was quartzose sands, followed by biogenically derived calcareous carbonates (20%) and trace amounts of heavy minerals. To determine the relative contribution of quartzose sands and carbonate sands to the bulk composition, a simple strong acid digestion was used to remove the carbonate fraction. The remaining material was subjected to the same processing process to yield the quartzose fraction with the carbonate fraction being determined by a difference method. These samples were used to ground-truth the sidescan sonar, the results of which are presented in Chapter 6.

3.3.4 Suspended Sediment Concentration

D.O. A-Instruments 9 CRS-4 were used to measure suspended and also concentrations (SSC) at two intervals above the substrate. Each sample consisted of a high intensity lathe-near mixing with the substrate and was collected at regular intervals. From these measurements, it was possible to calculate the loads of sediments transported within the estuary and the sensitivity of the system to changes in the input of sediments from the river.

Long-term remote deployments were used for two reasons: firstly, knowledge of the hydrodynamics under all conditions was required to identify both the estuarine and coastal processes; and secondly, to eliminate the costs associated with monitoring the stable sediments within the estuary. The impact on the coast associated with increased sediment load was studied and the impact of future changes and the potential of future changes was assessed.

Figure 3.3: Sidescan sonar towfish and vessel used to collect hydrographic data at MacMasters Beach.
broad categories; the most abundant (70%) was quartzose sands, followed by biologically derived calcium carbonates (30%), and trace amounts of heavy minerals. To determine the relative contribution of quartzose sands and carbonate sands to the bulk composition, a simple strong acid digestion was used to remove the carbonate fraction. The remaining material was subjected to the above sorting process to yield the quartzose fraction with the carbonate fraction being determined by a difference method. These samples were used to ground truth the sidescan sonar, the results of which are presented in Chapter 6.

3.3.4 Suspended Sediment Concentration
D & A Instrument Co. OBS-3 were used to measure suspended sediment concentrations (SSC) at two heights above the substrate. Each sensor consisted of a high intensity infrared emitting diode, a detector comprising four photodiodes, and a linear solid-state temperature transducer. Their working range was 0–5000mgL⁻¹ and 0–50gL⁻¹ for mud and sand respectively, with a 2% maximum deviation of response from a least squares straight line in both cases. Individual sensors were calibrated by immersion in a dispersion of the substrate sediment in water. Through addition of known amounts of sediment a linear line of best fit was calculated (Figure 3.4) and subsequently applied to the raw data to convert it from a voltage (V) to a concentration (gL⁻¹).

In addition to the OBS, the ADCPs provided a qualitative measure of sediment in suspension via the echo intensity. As this instrument relied on a return signal from particles within the water the greater the particulate concentration the stronger the intensity of the return signal. Thus high return signal intensities correlated to high SSCs, permitting qualitative assessment of SSCs.

3.4 Experimental Design
Long-term remote deployments were used for two reasons; firstly, knowledge of the hydrodynamics under all conditions was required to identify both fair-weather and storm-weather processes; and secondly to minimize the cost associated with retrieval of the instrumentation. In addition, processes active both on the inner-shelf and in the nearshore within the embayment also needed to be identified to determine the role and impact of mega-rips. To avoid the inherent dangers associated with collecting data during high seas and the poor predictability of storm events, self-contained instrumentation was used and deployed for long periods. Deployment and servicing of the instrumentation was conducted
Figure 3.4: Lines of best fit for calibration of OBS with dry weight of sediment.
during low swell (<1.5m), which allowed the capture of data during the extensive fair-weather conditions and also the short episodic storm events with minimal risk.

3.4.1 Experimental Design — Hydrodynamics

3.4.1.1 Embayment Hydrodynamics
Experimental design for the hydrodynamics of the field site had to encompass both nearshore and inner-shelf processes and determine variations in embayment hydrodynamics at both ends of the embayment. These data were required for all types of weather conditions, however the specific aim was to capture mega-rips during storm events. Rip current hydrodynamics are highly variable in time and space. While the degree of variability of mega-rips in horizontal space is reduced due to a preference to form adjacent to headlands the hydrodynamic variability, in the vertical direction, is likely to be very similar to that of rip currents. It was therefore necessary to determine the velocity throughout the water column.

To identify the presence of mega-rips a disparity in current velocities between the two ends of the embayment was required. Therefore an instrument capable of measuring current velocity at multiple water depths was needed at either end of the embayment, adjacent to the headlands. These instruments (ADCPs) were placed seaward of the bar on the 10m contour to minimize the potential burial of the instruments.

Eulerian current velocities provided information on the flow immediately above the instruments, however they provided very little information on the offshore extent of mega-rips. This offshore information was crucial in determining the currents’ ability to transport sediments to the inner-shelf. This limitation was overcome through the use of photographs and digital video footage to map the offshore extent of mega-rips. Additionally, LaGrangian current velocities associated with mega-rips were determined by tracking the movement of points within space for successive video images.

3.4.1.2 Inner-shelf Oceanography
Existing literature identified several important oceanographic phenomena as having the ability to contribute to the hydrodynamics of the inner-shelf in the study area (Middleton et al., 1997; Griffin and Middleton, 1991). These phenomena consisted of coastal trapped waves, the East Australian current, tides, wind-driven upwelling and downwelling and internal waves, all having characteristic signatures:

1. Coastal trapped waves — Long period (2–10 days) oscillation in velocity N to S;
2. East Australian current — Variable water temperature high velocity currents;
3. Tides — 12 hourly oscillation in velocities;
4. Upwelling — Strong NW to NE winds and flow separation of EAC uplifted cooler water;
5. Downwelling — Strong S to SW winds and storm surge can push warmer water down; and
6. Internal Waves — sub-tidal (down to 10mins) oscillations in temperature and current velocities.

The presence and magnitude of these phenomena can be monitored by measuring mean currents on an hourly basis along with water temperature and wind velocities. The location of the outermost instrument (ADV) was just inshore of the position of the inner-shelf and outer surfzone sedimentary boundary (24m), which was classified by Roy and Stevens (1981) and identified along the southeast coast of Australian by the Department of Public Works and Services (Bathymetric Charts). This boundary corresponded to the 32m contour in the study area and represented the landward extent of the inner-shelf. It, therefore, provided a site to monitor inner-shelf oceanographic processes.

Local and deepwater wave data were required as waves play a dominant role in forcing rip current hydrodynamics. While deepwater data were obtained from the Manly Hydraulics Laboratory’s deepwater wave rider buoy located off Sydney (33° 46' 54" S 151° 25' 29" E), local wave heights were determined in situ by ADVs for both the inner-shelf and the nearshore regions. Measurement of wave characteristics at the nearshore site required an additional ADV placed in close proximity to the ADCP.

3.4.2 Experimental Design — Sediment Mobility
Assessing the ability and extent to which mega-rips transport sediment to the inner-shelf was one of primary aims of the study. This was achieved by several means:

1. Determining changes in bathymetry;
2. Mapping the seabed;
3. Determining the characteristics of sediments; and
4. Determining suspended sediment concentrations associated with mega-rip currents.

Bathymetry data were collected out to the 35–40m contour, where a significant decrease in profile gradient occurred. This allowed determination of the sub-aqueous extent of the
headlands, detection of any complicating rocky reef that could focus waves or alter current patterns, and identification of the presence of transport pathways. In addition, hydrographic surveys undertaken pre- and post-storm event allowed determination of volumetric changes associated with storm activity, thereby facilitating identification of changes to the bathymetric profile that were a direct result of mega-rips.

Mapping variations in the sediment character provided important information on the association of bathymetric features with sediment types. This allowed for positive identification of rocky reef and sediment type i.e. nearshore sands or inner-shelf sands. The grain size population and juxtaposition of sediment types can provide important insight into the source of the sediments and hence the mechanism likely to be responsible for their placement. The collection of sediments from units identified by sidescan reflectance was also required to ground truth the seabed map.

Sediment transport rates can be determined by measurement of suspended sediment concentrations and current velocities. Ideally, sediment concentrations and current velocities should be measured over the full water depth to accurately reflect changes in sediment concentration. While current velocities were measured over the full water depth the study was limited to four OBSs, preventing the quantification of suspended sediment concentrations across the full depth range. Qualitative concentrations were provided by the ADCPs, their usage being limited to relative changes in suspended sediment concentration. Suspension of sediments by waves and currents was assessed using high sampling rates of the OBS (2Hz), allowing the relative contribution of wave re-suspension and current re-suspension to be determined.

3.5 Experimental Setup

3.5.1 Experimental Setup — Hydrodynamics

Four pods carrying a total of eight instruments were deployed within the MacMasters embayment (Figure 3.5). Pods 1a and 2 comprised of a SonTek ADCP and an R&D Instruments ADCP respectively in trawl-proof frames (Figure 3.2), while pods 1b and 3 comprised of an ADV and 2 OBS in large pyramidal frames (Figure 3.4). The geodetic locations of pods as shown in Figure 3.6 are listed in Table 3.1. To maintain the position of the pods the large pyramidal frames were secured using weights, while the trawl-proof frames were secured using an anchor on each of the four corners. As external battery packs were used to power the instruments a minimum separation of 1m was maintained between
Figure 3.5: Location of instrument sites within the MacMasters beach embayment.
the batteries and the instruments to ensure the magnetic field of the batteries did not interfere with the internal compass used to determine instrument orientation.

<table>
<thead>
<tr>
<th>Pod Number</th>
<th>Easting (AGD 66)</th>
<th>Northing (AGD 66)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a-b — Nearshore N</td>
<td>354482</td>
<td>6292536</td>
</tr>
<tr>
<td>2 — Nearshore S</td>
<td>353999</td>
<td>6292030</td>
</tr>
<tr>
<td>3 — Inner-shelf</td>
<td>354744</td>
<td>6292043</td>
</tr>
</tbody>
</table>

A total of eight deployments over the 30 month period were conducted (Tables 3.2 and 3.3). The first deployment of pods 1b and 3 was the most labor intensive, as the large pyramidal frames had to be lowered and anchored to the seabed using a barge (Figure 3.6). The later deployments required a team of divers to retrieve the instruments, leaving the frames in place. The smaller pods containing the ADCPs were raised to the surface and returned on re-deployment of the ADCP.

<table>
<thead>
<tr>
<th>ADV</th>
<th>Run Name</th>
<th>Start Date</th>
<th>Start Time</th>
<th>Finish Date</th>
<th>Finish Time</th>
<th>Sampling Regime</th>
<th>Total Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1I</td>
<td>10:00</td>
<td>6/07/1999</td>
<td>15:00</td>
<td>18/08/1999</td>
<td>15:00</td>
<td>2048@2Hz</td>
<td>1038</td>
</tr>
<tr>
<td>D1O</td>
<td>10:00</td>
<td>6/07/1999</td>
<td>15:00</td>
<td>18/08/1999</td>
<td>15:00</td>
<td>2048@2Hz</td>
<td>1038</td>
</tr>
<tr>
<td>D2I</td>
<td>9:00</td>
<td>20/08/1999</td>
<td>1:00</td>
<td>25/10/1999</td>
<td>1:00</td>
<td>2048@2Hz</td>
<td>1577</td>
</tr>
<tr>
<td>D2O</td>
<td>9:00</td>
<td>20/08/1999</td>
<td>1:00</td>
<td>25/10/1999</td>
<td>1:00</td>
<td>2048@2Hz</td>
<td>1577</td>
</tr>
<tr>
<td>D3I</td>
<td>12:00</td>
<td>22/11/1999</td>
<td>6:00</td>
<td>21/01/2000</td>
<td>6:00</td>
<td>2048@2Hz</td>
<td>1435</td>
</tr>
<tr>
<td>D3O</td>
<td>12:00</td>
<td>22/11/1999</td>
<td>6:00</td>
<td>21/01/2000</td>
<td>6:00</td>
<td>2048@2Hz</td>
<td>1435</td>
</tr>
<tr>
<td>D4I*</td>
<td>12:00</td>
<td>3/02/2000</td>
<td>14:00</td>
<td>28/03/2000</td>
<td>14:00</td>
<td>2048@2Hz</td>
<td>1299</td>
</tr>
<tr>
<td>D4O*</td>
<td>12:00</td>
<td>3/02/2000</td>
<td>14:00</td>
<td>28/03/2000</td>
<td>14:00</td>
<td>2048@2Hz</td>
<td>1299</td>
</tr>
<tr>
<td>D5I*</td>
<td>12:00</td>
<td>14/04/2000</td>
<td>14:00</td>
<td>25/05/2000</td>
<td>14:00</td>
<td>2048@2Hz</td>
<td>986</td>
</tr>
<tr>
<td>D5O*</td>
<td>12:00</td>
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<td>13:00</td>
<td>25/05/2000</td>
<td>13:00</td>
<td>2048@2Hz</td>
<td>987</td>
</tr>
<tr>
<td>D6I*</td>
<td>12:00</td>
<td>26/05/2000</td>
<td>14:00</td>
<td>27/06/2000</td>
<td>14:00</td>
<td>2048@2Hz</td>
<td>771</td>
</tr>
<tr>
<td>D6O*</td>
<td>12:00</td>
<td>26/05/2000</td>
<td>14:00</td>
<td>27/06/2000</td>
<td>14:00</td>
<td>2048@2Hz</td>
<td>771</td>
</tr>
<tr>
<td>D7I</td>
<td>12:00</td>
<td>28/06/2000</td>
<td>4:00</td>
<td>2/09/2000</td>
<td>4:00</td>
<td>2048@2Hz</td>
<td>1577</td>
</tr>
<tr>
<td>D7O</td>
<td>12:00</td>
<td>28/06/2000</td>
<td>4:00</td>
<td>2/09/2000</td>
<td>4:00</td>
<td>2048@2Hz</td>
<td>1577</td>
</tr>
<tr>
<td>D8I</td>
<td>12:00</td>
<td>19/02/2001</td>
<td>2:00</td>
<td>26/04/2001</td>
<td>2:00</td>
<td>2048@2Hz</td>
<td>1575</td>
</tr>
<tr>
<td>D8O</td>
<td>12:00</td>
<td>19/02/2001</td>
<td>2:00</td>
<td>26/04/2001</td>
<td>2:00</td>
<td>2048@2Hz</td>
<td>1575</td>
</tr>
</tbody>
</table>

* loss of data due to faulty instrument.

Data were collected by the ADV in hourly bursts of 2048 samples at a frequency of 2Hz, which equated to a duration of 1024s. Higher sampling rates and longer sample periods would have been ideal for higher accuracy data, however instrument memory and power limitations required to deploy the ADVs for 60 days precluded the sampling of data for more than 2048 samples per hour. A sample frequency of 2Hz was adequate given the
observed wave periods at the field site were 5-12s. The length of the data series also allowed longer period fluctuations to be resolved (up to ~34mm), whilst the hourly interest between bursts allowed for hourly average statistics to be generated.

Table 3.1: ADCP Deployment History

<table>
<thead>
<tr>
<th>Run Name</th>
<th>Time</th>
<th>Date</th>
<th>Time</th>
<th>Day</th>
<th>Sampling</th>
<th>Total Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>D104</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
<tr>
<td>D105</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
<tr>
<td>D106</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
<tr>
<td>D107</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
<tr>
<td>D108</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
<tr>
<td>D109</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
<td>12:00</td>
<td>2/01/2000</td>
</tr>
</tbody>
</table>

3.4.2 Experimental Setup — Sediment Mobility

Sampling rates of the OBS were governed by the ADVs, hence samples were collected at 2Hz for 105s each burst. Heights of the OBS varied with deployment. One OBS was always placed at the same height as the ADV sampling volume 22m, while the second OBS was deployed on the 21st May 1999, the second on the 26th of August 1999, and the third on the 11th of September 2000. The latter of these three surveys was undertaken.

Figure 3.6: Barge deploying large pyramidal frame used to hold ADV and OBS.
observed wave periods at the field site were 5–17s. The length of the data series also allowed longer period fluctuations to be resolved (up to ~ 4mins) whilst the hourly interval between bursts allowed for hourly average statistics to be generated.

<table>
<thead>
<tr>
<th>ADP</th>
<th>Start Date</th>
<th>Finish Date</th>
<th>Sampling Regime</th>
<th>Total Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D1S</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D2N</td>
<td>12:15 8/19/99</td>
<td>8:23 10/16/99</td>
<td>120@2Hz</td>
<td>34705</td>
</tr>
<tr>
<td>D2S</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D3N</td>
<td>12:00 22/11/1999</td>
<td>12:00 3/01/2000</td>
<td>120@2Hz</td>
<td>30503</td>
</tr>
<tr>
<td>D3S</td>
<td>12:00 22/12/1999</td>
<td>15:38 8/02/2000</td>
<td>120@2Hz</td>
<td>34730</td>
</tr>
<tr>
<td>D4N†</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D4S§</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D5N†</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D5S§</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D6N†</td>
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<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D6S§</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D7N</td>
<td>12:00 28/06/2000</td>
<td>1:50 28/06/2000</td>
<td>120@2Hz</td>
<td>30656</td>
</tr>
<tr>
<td>D7S†</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D8N</td>
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<td>22:58 3/04/2001</td>
<td>120@2Hz</td>
<td>31204</td>
</tr>
<tr>
<td>D8S</td>
<td>12:00 19/02/2001</td>
<td>18:50 17/04/2001</td>
<td>120@2Hz</td>
<td>41283</td>
</tr>
<tr>
<td>D9N</td>
<td>--/--/--</td>
<td>--/--/--</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>D9S</td>
<td>13:00 22/04/2001</td>
<td>10:52 28/05/2001</td>
<td>120@2Hz</td>
<td>25888</td>
</tr>
</tbody>
</table>

* loss of data due to faulty seal on battery pack.
§ loss of instrument.
† loss of data due to faulty transducer head.

Vertical velocity data were sampled in 2 minute bursts of 120 samples at a frequency of 1Hz. Depth bins varied between 1m, 0.75m or 0.5m; northern end deployments typically being every 1m, and southern end deployments being either 0.75m or 0.5m. Similarly, higher sampling rates would have been ideal, however a trade-off between deployment length, vertical resolution, data storage and accuracy of the data dictated the sampling regime.

3.4.2 Experimental Setup — Sediment Mobility
Sampling rates of the OBS were governed by the ADVs, hence samples were collected at 2Hz for 1024s each hour. Heights of the OBS varied with deployment. One OBS was always placed at the same height as the ADV sampling volume (20cm), while the second was placed approximately 40 or 100cm above the seabed. Three hydrographic surveys were undertaken: one on the 28th of May 1999; the second on the 26th of August 1999; and the final on the 11th of September 2000. The latter of these three surveys was conducted
after an extreme storm event early in July 2000. In addition to these surveys bathymetry was determined during mapping of the seabed, which was conducted on the first day that swell was below 0.5m (9th of September 1999). This seabed mapping survey was followed by collection of sediments used to ground truth the sidescan results. Sampling of the sediments was conducted using a grab every 200m along three shore-normal transects approximately 250m apart, resulting in a total of 32 grab samples (with the inclusion of samples collected from the instrument locations).

3.6 Data Recovery and Analysis

3.6.1 Data Recovery

Tables 3.2 and 3.3 outline the history of deployments throughout the study period and the instruments recording data during each deployment. Large breaks in recorded data occurred as a result of three factors. Firstly, gaps between deployments were a function of weather and the inability to retrieve and/or re-deploy instruments due to hazardous wave conditions. Secondly, the absence of individual instruments during a deployment due to instrument malfunctions or misplacement precluded data collection. Of particular note was the lack of the two ADVs from September 2000 to February 2001, encompassing a period of 22 weeks. Additionally, data in three of the four preceding deployments was lost due to poor data quality. Other periods of notable inactivity were from February 2000 to May 2000 where the ADCP was temporarily misplaced after a severe storm event, and February 2000 to February 2001 due to a faulty transducer. The total data recovery over the study period was 41% (7,200 hours in two years).

Sediment concentration data were unusable toward the end of each deployment due to fouling attributed to growth of biota which resulted in grossly overestimated sediment concentrations (Figure 3.7). The error associated with the fouling occurred gradually at first and then rapidly toward the end of the deployment. This eliminated approximately half the recorded data and significantly reduced the number of high sediment suspension events captured by this study.

Data collected by MHL was semi-complete with 2.5 % downtime. Unfortunately, the majority of the downtime was associated with high wave activity resulting in loss of data for the most important sampling periods. During some of these periods wave data determined by the outer field site was used to supplement the voids.
Figure 3.7: OBS records for all deployments at the inner site showing fouling of the OBS by biota.
3.6.2 Descriptive Statistics
Statistics including mean and standard deviation were computed using inbuilt MATLAB functions. These are particularly important statistics as the mean of the velocity records indicates the quasi-steady state currents ($\bar{u}$), the mean of water surface elevation ($\bar{\eta}$) indicates the water depth ($h$), while the standard deviation of cross-shore velocity can indicate the maximum orbital velocity (Equation 3.1):

$$u_{rms} = 2\sqrt{2\sigma_u}$$

and water surface elevation can indicate the significant wave height, $H_s$ (Equation 3.2).

$$H_s = 4\eta_{\sigma}$$

3.6.2 Data Analysis: Spectral Analysis, Harmonic Analysis and Filtering
Spectral analysis and filtering was conducted using MATLAB, specifically the PSD and FILTER functions. Power spectrum estimates were determined using PSD in the form:

$$[Pxx,Pxc,Fxx]=\text{psd}(\text{data},NFFT,Fs,W,'linear')$$

where $Pxx$ are the spectral estimates, $Pxc$ is the 95% confidence level of the spectral estimates, $Fxx$ is the frequency at which the estimates were made, data is the time series for which the spectral estimates were required, NFFT determines the number of frequencies at which to output the spectral estimates, $Fs$ is the sampling frequency, $W$ is the length of segment, and linear denotes the de-trending of the segments.

Harmonic analysis was used to extract tidal frequencies from water surface elevations and near-bed water velocities. This analysis was applied using a script obtained from the Institute of Ocean Sciences website (2003) and was applied in the form:

$$[\text{nameu},\text{fu},\text{tidecon},\text{xout}]=\text{t_tide}(\text{xin})$$

and does not appear in the appendices as it is comprised of over 800 lines of code.

Lowpass, highpass and bandpass filtering was applied to the data using a script (Appendix A1) used in the form:

$$[\text{output}]=\text{lowpass}(\text{data},Fs,Fc,N)$$

where output is the lowpass filtered time series, data is the time series prior to filtering, $Fs$ is the sample frequency, $Fc$ is the cutoff frequency and $N$ is the order of the filter. The order of the filter determined the sharpness of the frequency cutoff band - the higher the
order the shorter the cutoff. It is important to note that N/2 data points are lost from the end of the time series. Highpass filtering was achieved via subtraction of the lowpass data from the original time series. Bandpass filtering was achieved by using the same script, whereby two values were input for Fs, indicating the band limits. Typical cutoffs used in the application of the filter were 20s to remove or highlight surface wave frequencies and 10–15 hrs and 20–28 hrs to retain semi-diurnal and diurnal tidal frequencies respectively.

3.6.3 Data Analysis: Image Rectification
Rectification of the captured video frames was achieved using a series of three MATLAB scripts: invpersp.m, imTrans.m and digiplane.m (Appendices A3–6). The first of these scripts creates a transformation matrix:

\[
[T, \text{err}] = \text{invpersp}(	ext{refpts, pts})
\]

requiring locations known in the real world co-ordinate system (refpts) and the image co-ordinate system (pts), called ground control points (GCPs). The second script performed the transformation on the image based on the transformation matrix determined by:

\[
[\text{newim, newT}] = \text{imTrans}(	ext{im, T, region, sze})
\]

The third script (digiplane) allowed selection of points within the rectified image and returned the real world co-ordinates for that point:

\[
\text{pts} = \text{digiplane}(\text{im, newT, xij})
\]

where \(\text{im}\) is the rectified image and \(\text{newT}\) is the inverse transformation matrix. A fourth script was created to plot instrument locations on the images (digiplot):

\[
\text{digiplot}(	ext{im, newT, pts,xyij})
\]

where \(\text{pts}\) are real world co-ordinates to which the image has been rectified.

3.6.4 Data Analysis: Bathymetric Data
Golden Software's Surfer 7 was used to grid raw data, produce bathymetric surfaces and construct cross-shore profiles. Raw data were imported to ASCII XYZ format followed by gridding using one of two interpolation methods; Krigging, and Triangulation with linear
Figure 3.8: An example of image rectification used to determine spatial aspects of mega-rips: a) image prior to rectification; and b) rectified image. White dots indicate the location of control points used to rectify image and red lines define the mega-rip.
interpolation. Krigging was used to produce data for maps as it produced more subtle changes to topography. Triangulation was used to produce the surfaces for changes in bathymetry as data close to the real data measured was required for more accurate results.

Transects and profiles taken from the bathymetric data were computed in Surfer by selection of the end points of the desired profile for input into a blanking file. Surfer then computed the water depth between the two points at each location that the profile crossed a gridline.
Chapter Four

*Embayment and Inner-Shelf Fair-Weather Hydrodynamics*
4.1 Introduction
In this study of mega-rip hydrodynamics it is necessary to understand first the nature and role of fair-weather hydrodynamics, second, the changes that take place during storm conditions, third, the role of embayments during both fair-weather and storm conditions, and finally the nature and contribution of mega-rips within these systems. This chapter examines the nature of fair-weather hydrodynamics at the study site and the role of the embayment in nearshore processes. Our knowledge of nearshore and inner-shelf processes and hydrodynamics is presently limited to a few studies in generally low energy environments and identifies the East Australian current, coastal trapped waves, internal and surface waves, tidal currents and wind generated upwelling and downwelling as processes likely to be active during fair-weather conditions. However, the overall contribution of each process to the inner-shelf and nearshore and their activity during storm wave conditions is unknown.

This chapter utilises data collected over 8 deployments between June 1999 and July 2001 in addition to data collected by external agencies to identify the fair-weather hydrodynamics and environmental conditions at MacMasters beach. Specifically, this chapter identifies: 1) the environmental conditions during the study; 2) mean trends for embayment and inner-shelf hydrodynamics; 3) the contribution of each of the above processes to near-bed velocities; and 4) the key processes active at the inner-shelf and within the embayment. Results determined within this chapter will serve as background conditions from which storms depart, allowing a comparison and better understanding of the hydrodynamics during storms.

4.2 Environmental Conditions During the Study
4.2.1 Deepwater and Local Wave Climate
During this study, the Sydney coast was exposed to a modal deepwater wave climate of 1–1.5m from the southeast with a period of 9s (Table 4.1). The deepwater wave climate analysis was based on the hourly significant wave height and period collected by MHL for the duration of the study. During the study waves averaged 1.45m and 8.4s and were received from all directions (N, NE, E, SE, S, SW, W and NW) with 99% arriving from the NE, E, SE and S (13%, 22%, 34% and 30% respectively). This directional constraint was due to the limited fetch between the coast and the wave rider buoy, restricting the maximum wave height from the N, NW, W and SW directions. For seas and swells to be
observed from the N, NW, W and SW they had to be greater than the waves arriving from the NE, E, SE and S directions.

**Table 4.1:** Frequency table of deepwater (14km off Sydney coast) significant wave height and wave direction during the study (July 1999 — July 2001).

<table>
<thead>
<tr>
<th>Hs (m)</th>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.5</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>19</td>
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<td>22</td>
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<td>291</td>
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<td>5</td>
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<td>954</td>
<td>557</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2608</td>
</tr>
<tr>
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<td>1</td>
<td>340</td>
<td>305</td>
<td>561</td>
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<td>0</td>
<td>0</td>
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<td>2-2.5</td>
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<td>135</td>
<td>217</td>
<td>348</td>
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<td>0</td>
<td>0</td>
<td>803</td>
</tr>
<tr>
<td>2.5-3</td>
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<td>116</td>
<td>193</td>
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<td>53</td>
</tr>
<tr>
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<td>10</td>
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<tr>
<td>Total</td>
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<td>892</td>
<td>1555</td>
<td>2360</td>
<td>2086</td>
<td>6</td>
<td>5</td>
<td>17</td>
<td>6927</td>
</tr>
</tbody>
</table>

At the beginning of the study (July 1999) the wave climate was expected to be in a more energetic period of its annual cycle (Trenaman and Short, 1987). Table 4.2 shows the wave height exceedance values for each month of the study period and supports the observation of increased storm frequency during the winter months. Trenaman and Short (1987) observed this seasonality in addition to a second peak in March. Closer inspection of Table 4.2 reveals a less dominant peak in April for the current study. Figure 4.1 shows the wave height exceedance values for the historical and study averages. Average study wave heights were higher than the historical average and, while only recorded from early 1992, suggest that wave energy have been higher in the last few years. Given the study period was of 24 months duration and no sampling preference toward winter months it suggests there may be cyclic processes with a recurrence interval in the order of a decade acting on the wave regime.

A storm swell classification scheme was developed by the Public Works Department (1985) and identifies four levels of waves above a height of 2.5m (Table 4.3). Application of this scheme to the study period shows 64 storms in the two-year period. Of these 64 storms, 38 ‘C’ type, 19 ‘B’ type, 4 ‘A’ type and 3 ‘X’ type storms were recorded. Eighty-
Figure 4.1: Wave height exceedance values for historical data (solid line) and study data (dashed line).
four percent of the storms originated from the two southern directions (SE and S) with the three extreme storms arriving from the E, SE and S directions. Storm waves therefore occurred 9% of the time with extreme storms contributing a total of 0.03% (207hrs measured).

Table 4.2: Monthly wave height exceedence values at MacMasters beach for the period of 1st July 1999 to 1st July 2001. The highlighted values indicate those above the storm threshold used by Public Works Department.

<table>
<thead>
<tr>
<th>HSIG</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
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<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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<td>84</td>
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<td>14</td>
<td>31</td>
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<td>1.2</td>
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<td>5</td>
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<td>0</td>
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<td>0.1</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>6.5</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.3: Storm wave classification system used by Public Works Department (1985), applied to the wave heights during the study (Number of events).

<table>
<thead>
<tr>
<th>Class</th>
<th>Wave Heights (m)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>&gt;6.0</td>
<td>3</td>
</tr>
<tr>
<td>A</td>
<td>5.0–6.0</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>3.5–5.0</td>
<td>19</td>
</tr>
<tr>
<td>C</td>
<td>2.5–3.5</td>
<td>38</td>
</tr>
</tbody>
</table>

Wave statistics were calculated for each burst for all deployments at both the inshore and offshore sites using SonTek ViewHydraPro software (Section 2.5.2). Significant wave heights at both the inshore and offshore sites were consistent with those collected at the deepwater site, however there were occasions when wave heights at the two local sites were significantly less than those at the deepwater site (Figure 4.2). Wave directions at the two local sites showed a distinct narrowing and was most evident at the inner site (Figure 4.2). Narrowing of the wave field resulted from the wave field being refracted towards an orientation more normal to the local contours. This refraction ultimately resulted in a decrease in wave height, as illustrated in Figure 4.3 which demonstrates a trend for
Figure 4.2: Wave height and direction for nearshore (green), inner-shelf (red) and deepwater (blue) instrument sites showing attenuation and direction change.

Figure 4.3: Dependence of wave height attenuation on wave direction, where wave height is expressed as a percentage between deepwater wave height and inner-shelf wave height (attenuation = 100(H_{dwp} - H_{ins})/H_{dwp}).
directions away from normal to the embayment to undergo greater attenuation. The lowest point of the curve represented the lowest attenuation of wave heights and corresponded to waves approaching from 125°, a direction normal to the offshore contours. It is also important to note that, at times, waves from this direction (125°) underwent significant amplification, up to 30%.

4.2.2 Wind Conditions
Analysis of local wind conditions during the study period was based on half-hourly data collected at Norah Head by the Bureau of Meteorology (33°16’53”S 151°34’33”E). The data consisted of wind direction collected in 10° increments and velocity determined to the nearest Knot, which was later converted to ms⁻¹. The wind data were analysed to examine the seasonality, local sea breeze activity and its potential contribution to upwelling and downwelling. Summary statistics of the wind data show southerly winds were the most frequent and strongest (Table 4.4). Southeasterly winds, while much less frequent, were also very strong and exhibited weak seasonality in the summer months. Winds from the northeast and northwest were frequent and moderate in strength with pronounced seasonality (summer and winter respectively). Strong southerly and southeasterly winds are typically associated with east coast cyclones and have a tendency to form in early to mid-winter (Short, 1993).

Table 4.4: Summarised statistics of the primary wind directions.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max (ms⁻¹)</td>
<td>15</td>
<td>16</td>
<td>15</td>
<td>19</td>
<td>23</td>
<td>12</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Mean (ms⁻¹)</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Std (ms⁻¹)</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Seasonal</td>
<td>Weakly</td>
<td>Strongly</td>
<td>Moderately</td>
<td>Weakly</td>
<td>No</td>
<td>Moderately</td>
<td>Moderately</td>
<td>Strongly</td>
</tr>
<tr>
<td>Peak</td>
<td>Summer</td>
<td>Summer</td>
<td>Summer</td>
<td>Summer</td>
<td>N/A</td>
<td>Winter</td>
<td>Winter</td>
<td>Winter</td>
</tr>
</tbody>
</table>

Examination of daily wind activity showed the significance of daily sea-breezes to wind climate (Figure 4.4). Northeasterly winds increased in frequency from morning (9:00 hrs) and peaked in the early evening (18:00 hrs); typical behavior of onshore sea breeze activity. In contrast, winds from the northwest increased in frequency from early evening (18:00 hrs) and peaked in the morning (8:00 hrs); typical behavior of offshore land breeze activity. Winds from the south increased from the morning (9:00 hrs) and reached a peak in the early afternoon (14:00 hrs) and abated by late evening (20:00hrs).
Figure 4.4: Wind frequency for each hour of the day during the study period: a) from the northeast; b) from the northwest; and c) from the south.
Large-scale wind activity has been shown to play a significant role in up- and downwelling driven currents (Middleton et al., 1997; Griffin and Middleton, 1992). For the southeast Australian coastline, northeast through to west winds drive surface waters offshore through Ekman Transport and should result in upwelling events. Conversely, winds from the southwest through to east will create onshore Ekman transport and should result in downwelling. Winds arriving from northeast through to west occurred 60% of the time while winds arriving from southwest to east occurred 40% of the time. Upwelling is likely to be more frequent than downwelling and is associated with daily sea-breeze activity, while downwelling is commonly associated with storms out of the south and southeast. Upwelling events are easily identified by changes in water temperature as cool water is uplifted into a relatively well mixed zone. This, combined with the importance of upwelling for biological productivity, make them well studied events. Conversely, downwelling is difficult to identify as surface water is drawn into water of a similar temperature and identification relies on current directions.

4.3 Embayment and Inner-shelf Hydrodynamics During Fair-Weather Conditions

Fair-weather conditions for the purposes of this study are identified as periods when significant wave height (Hₘ) is less than 2.5m. As shown in section 4.2.1 these conditions occur 78% of the time and it is under these conditions that shoreface is perceived to restore itself to a state somewhat similar prior to a storm.

4.3.1 Near-bed Velocity Statistics

Data collected from the ADVs at the inner-shelf and the nearshore sites during deployments 1, 2, 3, 7 and 8 is shown in Figure 4.5. Included in these plots are the wave heights, local wind velocity and near-bed water temperature for the corresponding periods. Data presented in Figure 4.5 is used to identify the various categories of events (storms, internal waves, upwelling) and will be referred to throughout each of the sub-sections in Section 4.4. The data from these deployments show several episodic events that are explored further in Chapter 5. The averages for all deployments (Table 4.5) showed mean velocities for the nearshore (2.3cms⁻¹) and inner-shelf (2.5cms⁻¹) were directed offshore to the southeast and east, respectively. Mean velocities at the two sites were comparable while the highest maximum velocities occurred in the nearshore. The highest average near-bed velocity of 43cms⁻¹ directed offshore (113°) was recorded in the nearshore during
Figure 4.5: Environmental conditions during deployment 1: a) east and north velocities at the nearshore site; b) east and north velocities at the inner-shelf site; c) deepwater significant wave height; d) wind velocity; and e) near-bed water temperatures. Where red and blue are used to indicate velocities red is $u$ and blue is $v$ and for temperature nearshore and inner-shelf respectively.
Figure 4.5(cont): Environmental conditions during deployment 2: a) east and north velocities at the nearshore site; b) east and north velocities at the inner-shelf site; c) deepwater significant wave height; d) wind velocity; and e) near-bed water temperatures.
Figure 4.5(cont): Environmental conditions during deployment 3: a) east and north velocities at the nearshore site; b) east and north velocities at the inner-shelf site; c) deepwater significant wave height; d) wind velocity; and e) near-bed water temperatures.
Figure 4.5 (cont): Environmental conditions during deployment 7: a) east and north velocities at the nearshore site; b) East and north velocities at the inner-shelf site; c) deepwater significant wave height; d) wind velocity; and e) near-bed water temperatures.
Figure 4.5(cont): Environmental conditions during deployment 8: a) east and north velocities at the nearshore site; b) East and north velocities at the inner-shelf site; c) deepwater significant wave height; d) wind velocity; and e) near-bed water temperatures.
deployment 7 (1st of July 2000) and was concurrent with $H_s$ of 6m from south of southeast. The highest average near-bed velocity at the inner-shelf was 28cms$^{-1}$ directed offshore (120°), occurring during deployment 8 (27th of March 2001) and was concurrent with $H_s$ of 1m from the southeast. Modal statistics of the nearshore were similar to the mean statistics with modal nearshore velocities directed toward offshore (118°) at a magnitude of 0.15cms$^{-1}$, while on the inner-shelf velocities were directed offshore (93°) at a magnitude of 0.85cms$^{-1}$ (Figure 4.6).

4.3.2 Depth-Averaged Velocity Statistics
Depth-averaged ADCP data for deployments 2 north, 3 north, 3 south, 7 north, 8 north, 8 south and 9 south are shown in Figure 4.7. There were three periods where depth-averaged velocities exceeded 40cms$^{-1}$. These periods were treated occurred during storms and are considered in Section 4.4. Deployment 7 was significantly different from the others due to a storm occurring shortly after the beginning of the deployment. The instrument became buried, resulting in half of the velocities recorded coming from storm conditions. As these conditions were representative of the processes active at the field site they were still considered in determining averages, comprising 2048 samples of the total 200,000.

Mean depth-averaged flow for the entire study period showed flow was directed to the southeast (116°) at 1.64cms$^{-1}$, similar to those of the near-bed velocities at the nearshore (Table 4.6). However, categorising the deployments into south and north demonstrated flow at the southern end of the embayment was stronger (2.92 cms$^{-1}$) than at the northern (0.32cms$^{-1}$). The average magnitude of velocities represents the strength of the currents present in the water column as opposed to the residual current, which may be the result of the combination of two currents. Mean velocity magnitudes for the entire study were directed to the southeast at 6.03cms$^{-1}$ with slightly stronger flows at the southern end of the embayment (6.87cms$^{-1}$) than at the northern end (5.16cms$^{-1}$). Modal current directions exhibited two modes at both the southern and northern ends of the embayment (132° and 317°, and 67° and 237° respectively). These directions correspond to offshore and onshore respectively for the southern end of the embayment, and alongshore to the north and south respectively for the northern end of the embayment. It is important to note the relative frequencies of the modes, which were considerably less frequent in the onshore direction.
Figure 4.6: Frequency statistics for nearshore and inner-shelf data: a) nearshore directional; b) nearshore velocity magnitude; c) inner-shelf directional; and d) inner-shelf velocity magnitude.
Figure 4.7: Depth-averaged velocity data: a) deployment 2 north; b) deployment 3 north; c) deployment 3 south; d) deployment 7 north; e) deployment 8 north; f) deployment 8 south; and g) deployment 9 south.
for the southern end, while the two modes of current directions were similar in frequency at the northern end. These differences highlighted the need to treat the southern and northern current data separately.

**Table 4.5:** Near-bed velocity statistics for each deployment.

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Nearshore</th>
<th>Mean (cms⁻¹)</th>
<th>Std (cms⁻¹)</th>
<th>Max (cms⁻¹)</th>
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</thead>
<tbody>
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<td></td>
<td>East</td>
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<tr>
<td></td>
<td>North</td>
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<td>-15</td>
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<tr>
<td></td>
<td>Magnitude</td>
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<td>1.9</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Inner-shelf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deployment</td>
<td>Nearshore</td>
<td>Mean (cms⁻¹)</td>
<td>Std (cms⁻¹)</td>
<td>Max (cms⁻¹)</td>
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</tr>
<tr>
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<td>Deployment</td>
<td>Nearshore</td>
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<td>Std (cms⁻¹)</td>
<td>Max (cms⁻¹)</td>
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<td>Max (cms⁻¹)</td>
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<td>1.7</td>
<td>13</td>
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<td>Nearshore</td>
<td>Mean (cms⁻¹)</td>
<td>Std (cms⁻¹)</td>
<td>Max (cms⁻¹)</td>
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<td>-------------</td>
</tr>
<tr>
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<td>East</td>
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<tr>
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**4.3.3 Velocity Profile Statistics**

Three-dimensional histograms of current direction relative to height above the bed show the presence of two modes in all deployments except deployment 7 for both the northern and southern ends of the embayment (Figure 4.8). Current directions at the southern end of the embayment tended to have two modes, one directed onshore and the second, more dominant mode, directed offshore. Current directions at the northern end of the embayment had one mode directed alongshore to the north, a second one alongshore to the south, and a
Figure 4.8: Contour frequency histogram of velocity profiles at the northern end of the embayment: a) deployment 2; b) deployment 3; and c) deployment 8.
Figure 4.8(cont): Frequency histogram of velocity profiles at the southern end of the embayment: a) deployment 3; b) deployment 8; and c) deployment 9.
third mode was directed offshore. The dominance of the modes varied with depth, the general trend being alongshore north directed flow at the surface, alongshore south flow in the mid to low levels of the water columns, while the third offshore-directed mode was close to the seabed. This third offshore-directed current direction was consistent with the near-bed average velocity measured in the nearshore zone by the ADV.

**Table 4.6:** Depth average velocity statistics for ADCP deployments 1–9.

<table>
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<tr>
<th>Deployment</th>
<th>East (cms(^{-1}))</th>
<th>North (cms(^{-1}))</th>
<th>Magnitude (cms(^{-1}))</th>
<th>Direction</th>
<th>Magnitude (cms(^{-1}))</th>
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<th>Mean</th>
<th>Modal Direction</th>
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<td>214°</td>
<td>4.5</td>
<td>67°</td>
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<td>237°</td>
</tr>
<tr>
<td>D3N</td>
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<td>-0.2</td>
<td>0.3</td>
<td>125°</td>
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<td>D3S</td>
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<td>-1.9</td>
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<td>147°</td>
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</tr>
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<td>104°</td>
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</tr>
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<td>0.4</td>
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<td>52°</td>
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<td>4.5</td>
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<td>8.3</td>
<td>123°</td>
<td>302°</td>
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</tr>
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<td>1.6</td>
<td>116°</td>
<td>6.0</td>
<td>127°</td>
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</tr>
</tbody>
</table>

### 4.4 Identification of Fair-Weather Processes Active at MacMasters

#### 4.4.1 Upwelling and Downwelling

Identification of upwelling and downwelling events was achieved by correlating changes in water temperature with wind activity. Near-bed water temperatures were typically very stable during the winter deployments (deployments 1 and 7), varying up to 1.9°C and 2.6°C respectively. Temperatures during the spring deployment (deployment 2) varied as much as 3.8°C, while the summer and early autumn deployments (deployments 3 and 8) varied by as much as 9°C and 5.7°C respectively (Figure 4.5). Warmer surface waters in the summer months increased the likelihood of temperature stratification. High variations in water temperature near the seabed suggested either warm surface water was being drawn down by downwelling or that warm surface water was being drawn away from the coast and replaced by cool, deeper water.

Theory states the two key wind directions for the generation of upwelling and downwelling currents along this region of the coast are from the northeast through west and southwest through east, respectively (Middleton et al., 1997; Griffin and Middleton, 1992). Section
4.2.2 has shown that high velocity southwesterly wind directions were relatively infrequent, tending to dominate only in the winter months, while northeast winds occurred relatively frequently and tended to dominate the summer months. A noticeable trend for cooler water during periods of north to northeasterly wind directions was observed during deployments 3 and 8. Concurrent with these lower temperatures were high frequency, moderate magnitude, near-bed velocities (~15cms\(^{-1}\)). Conversely, a strong upwelling period during early spring (deployment 2) resulted in the suppression of high frequency, moderate magnitude, near-bed velocities (not associated with waves). One downwelling event associated with a southerly storm punctuated a major upwelling event during deployment 8 (Figure 4.5). Downwelling was defined for this event on the basis that water temperatures during the downwelling event were slightly elevated in comparison to ‘normal’ temperatures, where ‘normal’ was defined as temperatures in the absence of upwelling or downwelling. Downwelling of warmer water suppressed the high frequency, moderate velocities associated with the upwelling event this storm punctuated. In total, positively identified upwelling events contributed to 18% of the deployment time and downwelling events 3% of the deployment time, although this is considered a gross underestimate of downwelling as it was difficult to identify.

4.4.2 Internal Wave Activity
Internal waves are waves that propagate along the interface between two bodies of water with different densities where the difference in density controls the maximum frequency of the internal waves, typically 20mins in the absence of freshwater (Wright, 1995). High frequency variations in near-bed velocities were observed on the inner-shelf site and resulted in moderate to high mean currents during deployments 2, 3 and 8 (Figure 4.5). These velocities persisted for 21% of the study period and resulted in the highest near-bed velocities being measured at the outer site (26cms\(^{-1}\)). The variability of the currents was associated with variability of water temperature and probably represented internal wave activity. Internal wave activity has been observed along the southeast Australian coast in previous studies, which identified a tendency for velocities associated with them to be in the east-west direction (Lawson and Treloar, 1993). Spectral density plots of highpass (<36hrs) water velocity data illustrates this tendency, with the majority of the spectral energy at the inner-shelf being contained in the east component of the velocity (Figure 4.9).
Figure 4.9: Spectral density estimates for velocity data collected during the study period: a) deployment 1; and b) deployment 2.
Figure 4.9(cont): Spectral density estimates for velocity data collected during the study period: c) deployment 3; and d) deployment 7.
Figure 4.9(cont): Spectral density estimates for velocity data collected during the study period e) deployment 8.
The presence of internal waves would imply the water column was stratified, while their absence suggested a homogenous water column. Therefore, the periods of highly stable velocities and water temperatures could have been due to a homogenous water column. When considered in conjunction with the wind-driven currents (Section 4.4.1), upwelling during the summer months would have lowered near-bed temperatures and created a stratification that permitted the propagation of internal waves. Upwelling in the winter months would have homogenised the water column, preventing the passage of internal waves. Internal waves were a dominant hydrodynamic feature in terms of time and of near-bed velocities at the inner-shelf. It is important to note that velocities with similar characteristics were not measured at the nearshore location, which was sufficiently well mixed to prevent stratification, due to the proximity of the nearshore site to the surfzone. It is important to note that these are observations based on a sampling strategy not designed to investigate this phenomenon and a lack of literature on the affect wind-driven currents have on vertical stratification and is hence quite speculative.

4.4.3 Tide Induced Flow

Tides along the NSW coast are semi-diurnal with a strong diurnal inequality (Easton, 1970). Spectral analysis of velocity data revealed a dominant peak at ~ 24 hours and a smaller peak at ~12 hrs in the north directed flow component (Figure 4.9). The 24.4 hr peak may have originated from either diurnal constituents or daily sea breeze activity or both, while the 12.49 hour peak was likely to be associated with the local semi-diurnal tidal constituent. Inspection of the original time series showed no correlation between the timing of wind oscillations and inner-shelf current oscillations, hence wind was not responsible for the generation of the observed current oscillation. It is, therefore, likely that the current oscillations were driven by the tides.

Harmonic analysis was applied to the current and pressure data from deployments 1, 2, 3, 7 and 8. Relative amplitudes were determined by division of the constituents by the $M_2$ (principal lunar semi-diurnal) constituent. Pressure data showed the relative amplitudes of the semi-diurnal and diurnal constituents were similar to those known to exist along the southeast coast of Australia (Table 4.7). Analysis of water velocities after bandpass filtering (less than 30 hours and greater than 10 hours) showed $K_1$ (luni-solar diurnal) was the dominant constituent. This change suggests that propagation of the tidal wave was not directly responsible for velocities at the seabed, although some process was responsible for
filtering of the semi-diurnal constituents or amplification of the diurnal constituents. Velocities associated with the diurnal constituents were in the order of ±3cms⁻¹ in the northerly component of velocity (Figure 4.10), with a near zero mean which indicates they were symmetrical.

Table 4.7: Contribution of diurnal and semi-diurnal tidal constituents to alongshore current velocities on the inner-shelf (v) and water surface elevation (η) during the study period.

<table>
<thead>
<tr>
<th></th>
<th>D1</th>
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<th>D7</th>
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<td>v</td>
<td>η</td>
<td>v</td>
<td>η</td>
<td>v</td>
</tr>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<td>56</td>
<td>98</td>
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</table>

Flow velocities within the embayment demonstrated the same trend for oscillation at diurnal frequencies. Figure 4.11 illustrates the depth profiles taken from the northern nearshore site and southern nearshore site with both sites exhibiting oscillations of 24 hours. The direction of oscillation varies between sites with velocities at the southern end corresponding to onshore-offshore and velocities at the northern site corresponding to northeast-southwest (alongshore). Velocity magnitudes within the embayment were 5cms⁻¹ and 10cms⁻¹ for the northern and southern ends respectively.

4.4.4 Influence of the East Australian Current and Coastal Trapped Waves

Low frequency (>24 hours) contributions to the variation in average velocities on the inner-shelf were assessed by application of a lowpass filter (>30hrs, Appendix A.6). Low frequency near-bed velocities were below 10cms⁻¹ and correlated with the onset of high incident waves and winds (Figure 4.12). Regular low frequency oscillation of the flow was not observed throughout the study, either at the inner-shelf or nearshore sites. All of the larger current events were attributable to high wave or wind activity, with a distinct absence of high velocities (0.5–1.5ms⁻¹) associated with EAC or CTWs as previously observed on the inner-shelf in other studies (Nilsson and Cresswell, 1980; Middleton et al.,
Figure 4.10: Contribution of diurnal tidal constituent to near-bed velocities: a) residual near-bed velocities after bandpass filtering; and b) water surface elevation.
Figure 4.11: Oscillation in velocity and direction corresponding to a 10cms$^{-1}$ current 20-24 hour period, each ensemble represents 2 minutes.
Figure 4.12: Lowpass inner-shelf velocity data of all deployments. East component (dotted line) north component (solid line): a) deployment 1; b) deployment 2; c) deployment 3; d) deployment 7; and e) deployment 8.
1997). This may represent an absence of these processes or, more likely, that the outer-site was not far enough offshore to observe flow associated with these phenomena as they tended to dominant on the mid- and outer-shelf, with the main current off the shelf edge (Nilsson and Cresswell, 1980).

4.4.5 Contribution of Surface Waves to Near-bed Velocities.
Until now only 'steady' (persisting longer than 1 hour) current contributions to the water velocities have been considered, however wave induced oscillatory components contribute significantly to velocities observed at the seabed. Figure 4.13 illustrates the root mean squared wave orbital velocities ($u_{rms}$) at the nearshore and inner-shelf for each of the deployments and illustrates the increased significance of wave induced currents at the nearshore site. Velocities reached a maximum of 105cms$^{-1}$ and 73cms$^{-1}$ at the nearshore and inner-shelf respectively (Table 4.8). Exceedence values of $u_{rms}$ showed that the nearshore site velocities exceeded 20cms$^{-1}$ 45% of the time and at the inner-shelf site exceeded 20cms$^{-1}$ 18% of the time (Figure 4.14).

<table>
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<th>Max (cms$^{-1}$)</th>
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<td>13.8</td>
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4.5 Summary
This chapter has identified the environmental conditions for the study period and the fair-weather hydrodynamic processes active in the field area. Waves approaching the field area underwent a degree of attenuation dependent on the obliquity of the wave approach. Winds out of the northeast to northwest quarter dominated the summer months and drove upwelling in both summer and winter months. Upwelling during summer resulted in stratification and internal wave activity, while upwelling in winter homogenised the water column and suppressed internal wave activity. Internal waves were responsible for the
Figure 4.13: Root mean squared velocities of the near-bed velocity magnitudes for each at each site: a) deployment 1 nearshore; b) deployment 2 nearshore; c) deployment 3 nearshore; d) deployment 7 nearshore; e) deployment 2 nearshore; f) deployment 1 inner-shelf; g) deployment 2 inner-shelf; h) deployment 3 inner-shelf; i) deployment 7 inner-shelf; and j) deployment 8 inner-shelf.
highest time-averaged velocities at the inner-shelf with waves contributing the highest instantaneous velocities. Tidally generated flows on the inner-shelf and within the embayment were weak and exhibited significant amplification of the X1 diurnal component. The nearshore and embayment fair-weather hydrodynamics were dominated by tidal flows with no evidence of IMC flows.

![Graph showing frequency (%)](image)

**Figure 4.14:** Root mean squared velocity exceedance plots for data collected at the nearshore and inner-shelf for all deployments.
highest time-averaged velocities at the inner-shelf with waves contributing the highest instantaneous velocities. Tidally-generated flows on the inner-shelf and within the embayment were weak and exhibited significant amplification of the $K_1$ diurnal constituent. The nearshore and embayment fair-weather hydrodynamics were dominated by tidal flows with no evidence of EAC flows.
Chapter Five

*Embayment and Inner-shelf Storm*

*Hydrodynamics*
5.1 Introduction
While a growing body of literature on storm driven hydrodynamics exists, only a small amount of this research pertains to high energy embayed coastlines. It is suggested that mega-rips play a significant role in the storm driven hydrodynamics of embayed coasts as their formation appears to rely on morphology, with both McKenzie (1958) and Short (1985) identifying mega-rips as forming adjacent to a headland. While Short (1985) attributed their formation to high incident wave energy and embayment topography, it is not understood how the waves and topography control the location of mega-rips. Similarly, there is no data on the flow structure within a mega-rip, nor on how far offshore competent velocities are maintained.

Field data from 20 storm events at MacMasters beach was used to: 1) identify the hydrodynamics of the shoreface during storm events; 2) detail the current velocities associated with mega-rips; 3) determine spatial preferences for mega-rip formation; 4) identify the offshore extent of mega-rips; and 5) identify the activity of mega-rips along the adjacent coastline.

5.2 Embayment and Inner-shelf Hydrodynamics During Storms
5.2.1 Event Classification
The existing storm classification system developed by the Public Works Department (PWD) and introduced in Section 4.2.1 was used to identify and categorise events that occurred during the data collection periods. On this basis, 20 events occurred during data collection. Of the 20 storms, 8 were type C, 10 were type B, 0 were type A and 2 were extreme (X). Wave, wind and current statistics were tabulated for each event (Table 5.1); events hereafter correspond to events within this table.

5.2.2 Impact of Storm Waves on Fair-weather Processes
The inner-shelf and nearshore flows were altered with the onset of incident waves above 2.5m. Flow directions on the inner-shelf responded to changes in incident wave direction suggesting that waves played a significant role in driving near-bed currents on the inner-shelf with the potential to disrupt fair-weather processes. Figure 5.1 illustrates the response of near-bed velocities to the onset of incident waves over 3m accommodated by 12ms⁻¹ winds from the southeast (onshore). Prior to Event 18, upwelling resulted in stratification and internal wave activity dominated the hydrodynamics. The onset of the storm resulted
Figure 5.1: Inner-shelf response to storm waves with the onset of Event 18: a) $u$ (red) and $v$ (blue) velocities blue and red respectively; b) significant wave height; and c) temperature.
in suppression of internal wave activity; this was attributed to the disruption of the thermocline and may have been caused by either the incident surface waves or by a wind-driven current associated with winds from the southeast which accompanied the storm.

Table 5.1: Wave, wind and velocity data from storm events identified during the study period.

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<th>Event/Type</th>
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<th>H (m)</th>
<th>Hm (m)</th>
<th>Dir/Class</th>
<th>V (ms⁻¹)</th>
<th>Vm (ms⁻¹)</th>
<th>Dir</th>
<th>U (cms⁻¹)</th>
<th>Umax (cms⁻¹)</th>
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</table>

Nearshore and embayment hydrodynamics were dominated by tidal flows during fair-weather conditions; when waves exceeded 2.5m the nearshore hydrodynamics were typically overwhelmed by currents and/or mixing associated with the higher waves. Figure 5.2 illustrates the onset of Event 18; the vertical velocity profiles corresponding to this time period show a distinct change in both velocity and direction with waves exceeding 2.5m. Fortuitously, the lowest wave conditions used to identify a storm in the PWD classification scheme (Section 5.2.1) corresponded to this change in embayment circulation and validated its use for this study. Reference to the wave height exceedence values (Figure 3.1) in Section 3.2 identified waves over 2.5m as occurring 11% of the
Figure 5.2: Change in velocity profile due to an increase in incident wave height: a) current magnitude; b) current direction; and c) significant wave height and period.
time, whereas tidal processes were active whenever waves were below 2.5m, hence they were active 89% of the time.

5.2.3 Near-bed Velocity Statistics
The highest near-bed velocities recorded were 43cms⁻¹ for the nearshore and 26cms⁻¹ for the inner-shelf, during Events 13 and 19 respectively (Table 5.1). Nearshore and inner-shelf currents increased with increasing incident wave height, however the changes were not always consistent and waves were often associated with the high winds accompanying the storms.

Inner-shelf maximum current velocities showed a positive correlation with maximum wind velocities and wave heights ($R^2=0.642$ and $R^2=0.654$ respectively), while nearshore velocities showed a slight positive correlation with wind strength and a strong correlation with wave height ($R^2=0.181$ and $R^2=0.619$ respectively). Hence, at the nearshore site a response to storm activity was dependant on wave height, with no discernable trend in velocity direction, while on the inner-shelf a response to both wave height and wind strength was observed. The major changes with the onset of storm waves noted from Table 5.1 were:

1. mean velocity magnitudes for all storms increased at both the nearshore and inner-shelf;
2. current directions at the nearshore showed no discernable trend; and
3. current directions on the inner-shelf changed from offshore (93°) during fair-weather conditions (Section 3.3.2) to alongshore north (35°) during storm events.

To identify a general trend for current directions due to incident wave direction, events were partitioned into two classes: storm waves arriving from south of normal to the embayment; or storm waves arriving from north of normal to the embayment. Waves from south of normal showed a trend for inner-shelf currents to be directed to the northeast, while waves from north of normal showed a trend for inner-shelf currents to be directed to the southeast. It follows that, bottom currents on the inner-shelf during storms are, to some degree, controlled by incident waves.

5.2.4 Velocity Profile Statistics
Events were classified as Class 1 or 2 as in previous sections, however the data were further classified as being from either the northern or southern end of the embayment (Figure 5.3).
Figure 5.3: Data classification scheme showing Class 1 Events where incident waves arrive from a direction clockwise from normal and Class 2 Events where incident waves arrive from a direction counter-clockwise from normal. Under these two Classes data was further identified as coming from either the northern end or southern end of the embayment.
Class 1 north represents data collected when the instrument at the northern end of the embayment was exposed to the wave field: Class 1 south represents data collected when the instrument at the southern end was sheltered from the wave field by the southern headland, Class 2 south represents data collected when the instrument at the southern end of the embayment was exposed to the wave field, and Class 2 north represents the data collected when the instrument at the northern end was sheltered from the wave field by the northern headland.

Mean velocities for each storm event were plotted against direction for each depth bin (Figure 5.4) and for Class 1 south showed similar trends to fair-weather conditions, the dominant flow being directed offshore at the surface and minor onshore directed flow also at the surface (Figure 5.4d–g). However, the dominance of the surface flow in both cases suggested a mechanism other than tidal flow. Minor onshore surface flow may have resulted from wave breaking, while offshore directed surface flow may have represented the formation of a rip current driven by wave setup. Similarly, mean velocities for Class 2 north showed similar trends to the fair-weather hydrodynamics, flow being directed to the northeast and southwest (Figure 5.4h–i). Comparing Class 1 south and Class 2 north showed that under similar incident wave heights, flow was stronger at the southern end of the embayment. Classes 1 north and 2 south exhibited a departure from the typical trend with flow in both cases being directed offshore at significant magnitudes (Figure 5.4a–c and j). These embayment hydrodynamics are investigated further in Section 5.3.3.

5.3 Identification of Storm-Driven Processes
This section examines the major changes in hydrodynamics from fair-weather conditions to storm conditions, including the influence of the embayment on the hydrodynamics during storm events.

5.3.1 Downwelling During Storm Events
Near-bed velocities on the inner-shelf exhibited a variety of responses to changing wave and wind directions. Figure 5.5 illustrates four different storms and the accompanying wind, wave and current velocities. Event 1 experienced 6m waves from the east and strong southeast winds and exhibited elevated northeast directed velocities on the inner-shelf. Event 8 exhibited slightly elevated northeast velocities that coincided with a peak in south-westerly winds ($17\text{ms}^{-1}$), followed by a peak in south-easterly waves (4m). Event 13 exhibited elevated southerly near-bed velocities that corresponded to a peak in south-
Figure 5.4: Mean water velocity plotted against depth and direction for Class 1 N data: a) Event 8; b) Event 11; and c) Event 13.
Figure 5.4(cont): Mean water velocity plotted against depth and direction for Class 1 S data: d) Event 11; e) Event 12; f) Event 19; and g) Event 20.
Figure 5.4(cont): Mean water velocity plotted against depth and direction for Class 2N and S data: h) Event 7 (Class 2 N); i) Event 18 (Class 2 N); and j) Event 18 (Class 2 S).
Figure 5.5: Wind direction (Wdir), wind velocity (W), current velocity (U), current direction (Udir) and wave heights (Hs) for storm Events 1 and 8 during the study period. Current data were taken from the inner-shelf site.
Figure 5.5(cont): Wind direction (Wdir), wind velocity (W), current velocity (U), current direction (Udir) and wave heights (Hs) for storm Events 13 and 18 during the study period. Current data were taken from the inner-shelf site.
westerly winds (15ms$^{-1}$) and southerly waves (6m). The final event, Event 18, exhibited low velocities to the southeast, concurrent with high southerly winds (17ms$^{-1}$) and easterly waves (4m). The impact of winds on inner-shelf currents was not clear as wave heights and wind velocities peaked simultaneously. Although a trend for flow in the presence of winds was apparent during Event 8, when wave heights and wind velocities did not peak simultaneously and near-bed current velocities peaked with wind speeds and not with wave height. This illustrates the complexity of the interactions between wind-driven currents, wave-driven currents and currents associated with other phenomena.

5.3.2 Offshore Flow at the Seabed
During Event 8 a period of strong offshore directed flow at the nearshore site occurred (deployment 2; 562 hours). The individual burst was lowpass filtered with a cut-off period of 20s to remove wave motion (Figure 5.6a). Mid-burst (600s) velocities started to increase, reaching a maximum velocity of 103cms$^{-1}$ directed offshore (south-southeast) (Figure 5.6b). Prior to 600s, velocities were directed alongshore south and onshore (southwest-west). Similar trends were observed during Event 13, hour 56 of deployment 7, with strong offshore flow at the nearshore site. Lowpass filtering of the burst showed elevated velocities (>50cms$^{-1}$) at the beginning of the record which increased to 106cms$^{-1}$ before decreasing to less than 50cms$^{-1}$ halfway through the burst, and increasing above 50cms$^{-1}$ again towards the end of the burst (Figure 5.6c). The modal current direction was again offshore (120°), while the period of low velocities accompanied currents directed to the south (180–210°) (Figure 5.6d). These currents were laterally confined to the headland indicating the presence of a rip (mega-rip) in 10m water depth, making them highly significant due to their magnitude and their offshore direction.

5.3.3 Embayment Hydrodynamics During Storm Events
Of the 20 storm events identified in Section 5.2.1, eight were captured by the ADCPs with only two captured by both the northern and southern ADCPs. Despite this, the events captured gave considerable insight into the hydrodynamics of the embayment under varying storm conditions. Mega-rips in elevated velocities in Classes 1 north and 2 south. Maximum velocities were plotted against direction for each class (Figure 5.7). Events of Classes 1 north and 2 south experienced maximum velocities of 50–120 cms$^{-1}$ in an offshore direction, while events of Classes 1 south and 2 north experienced maximum velocities of 10–38cms$^{-1}$ in an offshore direction.
Figure 5.6: Lowpass velocity magnitudes and current direction at the seabed for the nearshore site: a) velocity deployment 2 burst 562 (during Event 8); b) direction event 8 (deployment 2 burst 562); c) velocity deployment 7 burst 65 (during Event 13); and d) direction Event 13 (deployment 7 burst 65).
Figure 5.7: Maximum water velocity plotted against depth and direction for Class 1 N data: a) Event 8; b) Event 11; and c) Event 13.
Figure 5.7 (cont): Maximum water velocity plotted against depth and direction for Class 1 S data: d) Event 11; e) Event 12; f) Event 19; and g) Event 20.
Figure 5.7(cont): Maximum water velocity plotted against depth and direction for Class 2N and S data: h) Event 7 (Class 2 N); i) Event 18 (Class 2 N); and j) Event 18 (Class 2 S).
All four events had offshore directed flow, interpreted as mega-rips. Velocities in lee of the headland at the southern end of the embayment (24–38 cms⁻¹) were typically higher than those in lee of the headland at the northern end of the embayment (10–20 cms⁻¹). A clear trend for increasing velocity with increasing wave height was observed for each class. Fortuitously, of the two events that were captured by instruments at both the northern and southern ends of the embayment, one was a Class 1 storm and the second was a Class 2 storm. The two storms had elevated velocities at the exposed end of the embayment. Velocities at the northern end were approximately twice that of the southern end when incident waves were from south of normal, while velocities at the southern end were approximately three times that of the northern end when incident waves were from north of normal.

5.4 General Characteristics of Mega-rip Flow

5.4.1 Variation in Mean Flow Between Mega-rip Events

Of the eight events captured by the ADCPs, four were identified as containing mega-rips (Events 8, 11, 13 and 18); three events had incident waves arriving from the south and one had incident waves arriving from the east. A general trend for increasing current strength with increasing wave height was observed. The smallest event (Event 11 with maximum $H_s=3.56m$) was observed at the northern end of the embayment and exhibited weak flows ($\bar{V} \sim 25$ cms⁻¹ and $V_{max}=57$ cms⁻¹) to the south that were confined to the top 2m of the water column. The only event recorded at the southern end of the embayment (maximum $H_s=4.03m$) exhibited moderate flows ($\bar{V} \sim 35–40$ cms⁻¹ and $V_{max}=105$ cms⁻¹) directed offshore (southeast) that spread throughout the water column. Event 8 (maximum $H_s=4.54m$) observed at the northern end of the embayment exhibited moderate flows ($\bar{V} \sim 35–40$ cms⁻¹ and $V_{max}=95$ cms⁻¹) directed offshore (southeast) that spread throughout the water column. The largest of the events (Event 13 with maximum $H_s=6.13m$) observed at the northern end of the embayment had strong flows ($\bar{V} \sim 60$ cms⁻¹ and $V_{max}=130$ cms⁻¹) predominantly offshore (east) throughout the whole water column.

Throughout all events flow was strongest at the surface; the larger the waves the faster the flow and the further the flow velocities extended toward the seabed. Values for the mean velocities were approximately half the observed maximum velocities, suggesting the flow velocities fluctuated significantly.
5.4.2 Response of Mean Mega-rip Flow to Changes in Wave Height
To make a better comparison between wave heights (measured hourly) and depth-averaged velocities (measured every two minutes) a lowpass filter with a frequency cut-off of 80 minutes was applied to the data to remove fluctuations less than one hour. An increase in current velocities with large waves was observed. During Event 11 (maximum Hs=3.56m) high velocities were observed only in the second half of the storm (Figure 5.8b). Wave heights remained below 3.5m for almost the entire event with no velocity response to changes in wave heights (Figure 5.8a and b). Event 18, at the southern end of the embayment, had wave heights up to 3.5m in the initial stages. Later, wave heights exceeded 3.5m reaching a maximum height of 4m (Figure 5.8c). Flow velocities responded to the increase in wave height, mean flow remaining low in the initial stages with the highest velocities being measured at the height of the storm (Figure 5.8d). A rapid change in flow velocities occurred during Event 18 at 30–40hr. No significant change in wave height was noted, however a -5° change in wave direction occurred between 30–40 hours with waves arriving more obliquely and may have resulted in a lateral movement of the rip to the south over the instrument. In the initial stages of Event 8, waves were approximately 3–3.5m with no significant offshore velocities measured. When waves exceeded 3.5m velocities increased, reaching a maximum at the peak of the storm (Figure 5.8c and f). During Event 13, the largest of the events at the northern end of the embayment, wave heights increased rapidly to over 6m and, for the whole period captured, remained above 4.5m (Figure 5.8g). Depth-averaged flow remained above 30cms⁻¹ for the majority of the event (Figure 5.8h). In general, mean flow velocities responded to wave heights greater than 3.5m, with velocities during Event 11 being the exception. It is likely that this observation is a result of the positioning of the instruments as to an actual threshold for mega-rip formation.

5.4.3 Evolution of Mega-rip Velocity Profiles During Storms
A typical trend for growth and decay of the mega-rip over the course of an event was observed. In the early stages of Event 8 offshore flow at the surface (top 2–3m) was observed, while in the lower levels of the water column onshore directed flow was observed (Figure 5.9a). In the middle stages of the event, flow was directed offshore throughout the whole water column with a trend for higher velocities at the surface (Figure 5.9b). In the later stages of the storm flow was directed offshore at the surface with directions rotating counter-clockwise to alongshore (northeast) at the seabed (Figure 5.9c).
Figure 5.8: Wave height and lowpass depth averaged velocity magnitude for storms events identified during the study period: a) wave height Event 8; b) current velocity Event 8; c) wave height Event 18; d) current velocity Event 18; e) wave height Event 11; f) current velocity Event 11; g) wave height Event 13; and h) current velocity Event 13.
Figure 5.9: Velocity profiles from initial middle and final stages of storm events: a) Event 8 initial; b) Event 8 middle; c) Event 8 final; d) Event 18 initial; e) Event 18 middle; and f) Event 18 final. Numbers adjacent to each profile represent the direction of the flow (45°-225° offshore and 225°-45° onshore). Grey shading represents offshore directed flow.
Figure 5.9(cont): Velocity profiles from initial middle and final stages of storm events: g) Event 11 initial; h) Event 11 middle; i) Event 11 middle; j) Event 13 initial; k) Event 13 middle; and l) Event 13 final. Numbers adjacent to each profile represent the direction of the flow (45-225 offshore, grey, and 225-45 onshore).
In the early stages of Event 18 (prior to the 5° change in wave direction), flow was directed alongshore (northeast) indicating the location of the mega-rip was to the north of the instrument site (Figure 5.9d). In the middle stages of the event velocities were directed offshore throughout the water column with a maximum velocity located 2m below the surface (60cms⁻¹) (Figure 5.9e). In the final stages of Event 18 velocities were directed offshore throughout the water column, although significantly lower than in the middle stages of the event (20–30cms⁻¹) (Figure 5.9f).

In the early stages of Event 11 velocities were directed alongshore (northeast) and were depth-uniform (Figure 5.9g). In the middle stages velocities were directed offshore throughout the water column with velocities higher toward the surface (80cms⁻¹) (Figure 5.9h). In the later stages of the event velocities were directed onshore throughout the water column with occasional periods of offshore directed flow at the surface (Figure 5.9i).

In the early stages of Event 13 velocities were directed offshore at the surface (top 5m) and alongshore (northeast) toward the seabed (Figure 5.9j). In the middle stages velocities were directed offshore throughout the water column and slightly elevated at the surface reaching a maximum of 130cms⁻¹ (Figure 5.9k and 1). The later stages of Event 13 were not recorded due to burial of the ADCP by an accumulation of sediment in response to this event (Section 5.3.2).

Two possible explanations exist for these observations an increase in offshore extent of the rip or lateral meandering. Both are likely to occur, however, the former of the two explanations is reinforced in Section 5.5.3. An explanation based on increased offshore extent is now presented.

The trend for surface flows in the early stages of each of these events indicates the average location of the rip-head above the instrument, with the exception of Event 18 where the mega-rip was to the north of the instrument. In the middle stages of each event flows were generally very high (>50cms⁻¹) and directed offshore throughout the whole water column indicating the instrument site was close to or in the rip-neck. Placement of the instrument site within the rip-neck indicated a surfzone width of at least 450m and is corroborated by evidence presented in Section 5.6. The later stages of each event, with the exception of Event 13 for the aforementioned reason, saw a return to the trends observed in the initial stages of the event. The observed increase in mega-rip velocities with wave heights exceeding 3.5m in Section 5.4.2 exhibited a general trend over a storm event for offshore
growth of the mega-rip with increasing wave heights and their subsequent decay with decreasing wave heights. Typically, when waves were 2.5–3.5m the rip-head was located over the instrument; when waves exceeded 3.5m, flow at the instrument site was typical of the rip-neck.

It is important to note that rather than strong, persistent currents being observed during the storm events currents were highly intermittent in strength and direction, which potentially related to changes in the wave field. Highpass data of all events showed contributions of high frequency velocity fluctuations that were equal in magnitude to those of the lowpass data (Figure 5.10). While the lowpass data responded to changes in wave height, the resolution of the wave analysis was insufficient to determine any association with the more frequent pulsing. Pulsing in the flow is further investigated in the following section.

5.5 Dynamics of Mega-rip Pulsing

5.5.1 Vertical Structure of Pulsing During Storm Events

In addition to the evolution of mega-rip velocities over the period of an event, smaller scale (10–20min and 200–400s) pulses in velocity were observed (Figure 5.10). The pulsing observed during each of the storm events often translated to the offshore extension of the mega-rip and is illustrated in a series of profiles, two from each event (Figure 5.11a–g). This figure shows a typical sequence of vertical profiles from the initial stages of Event 11. During the first pulse, flow was slightly elevated at the surface and directed to the south. The remainder of the weakly flowing water column was directed onshore to the northwest (Profile 1a). Surface velocities increased to a maximum of 37cms$^{-1}$ with offshore velocities decreasing to 5m depth, below which flow was weak and onshore (Profile 4a). With time (Profile 9a), flow returned to the previous conditions as seen in Profile 1a. This change correlated to an extension of the rip-head offshore followed by a landward recession. The second pulse captured during the peak of Event 11 (Figure 5.11b) saw depth uniform alongshore (southwest) flow (Profile 1b) change to offshore flow throughout the entire water column, reaching a maximum at the surface (Profile 6b). The change from offshore surface flow to depth-uniform offshore flow indicated a change in the type of flow from that which was characteristic of the rip-head to flow characteristic of the rip-neck and again translated to an increase in the offshore extent of the mega-rip.

Pulsing in the initial stages of Event 18 (Figure 5.11c) was infrequent and irregular, and likely to be the result of flow not being above the instrument (see Section 5.4.2). This
Figure 5.10: Segment of data taken from Event 18 showing pulsing of mega-rip flow at 10-20s and 200-400s periods.
Figure 5.11: Velocity profiles of pulsing: a) pulsing in early stages of Events 8; b) pulsing at the height of Event 8 c) pulsing in the initial stages of Event 18; and d) pulsing at the height of Event 18. Numbers adjacent to each profile represent the direction of the flow (45-225 offshore and 225-45 onshore). Time between profiles is 2 minutes with each profile being average of 120 measurements. Grey shading represents offshore directed flow.
Figure 5.11(cont): Velocity profiles of pulsing: d) type 1 pulsing during Event 11; e) type 2 pulsing during Event 11; f) pulsing in the initial stages of Event 13; and g) pulsing at the height of Event 13. Numbers adjacent to each profile represent the direction of the flow (45-225 offshore and 225-45 onshore). Time between profiles is 2 minutes with each profile being average of 120 measurements.
period consisted of offshore flow (east-northeast) at the surface and onshore flow (northerly) near the seabed (Profile 1c), which progressed to uniformly northeast flow throughout the water column (Profile 6c). These flow directions indicated the location of the rip to be north of the instrument site. After 40 hours, pulsing became frequent and regular due to a change in wave direction (Section 5.4.2). Velocity profiles were depth-uniform offshore (Profile 1d), and velocity increased with time (Profile 4d). It is likely this strengthening of the current translated to an increase in the offshore extent of the rip.

Pulsing in the initial stages of Event 8 was very similar to that observed during Event 11, with offshore directed surface flows to a depth of 2m (Profile 1e). Surface velocities increased to a maximum of 40cms\(^{-1}\) with offshore velocities decreasing to a depth of 2m above the bed. The pulse during the peak of Event 8 started with offshore directed surface flow to a depth of 2m with the remainder of the water column being directed onshore (Profile 1f). Velocities then changed to offshore throughout the entire water column to a maximum of 60cms\(^{-1}\) (Profile 4f). The change from flow typical of the rip-head to flow typical of the rip-neck again translated to an offshore extension of the mega-rip.

Pulsing in the initial stages of Event 13 varied little from that during the mid-stages and consisted of a strengthening in current velocities in the offshore direction (Figure 5.11, Profiles 1g–9g). This lack of variation between the initial and mid-stages of the event was attributed to the rapid increase in wave heights and the resultant rapid establishment of a mega-rip. A second sequence of profiles was observed during this event, where velocities were directed offshore throughout the entire water column (Figure 5.11 profile 1h). The change to stronger offshore flow in the lower levels of the water column continued to Profile 5h, after which the profiles reverted to those seen in Profile 1h (Profile 9h).

The increase in flow velocities at the seabed may have resulted from the instrument being placed in the surfzone. The instrument being placed in the surf zone would experience far more breaking waves than it would outside the surfzone. Under these conditions waves breaking in the mega-rip current could inject onshore directed momentum thus retarding the surface flows. This argument is supported by the absence of this type of profile in the other storm events, where the instruments were placed outside the surf zone.

The general trend observed was pulsing in velocities for all events which translated to an offshore extension of the mega-rip. This indicates the offshore extent of mega-rips was highly dependent on pulsing. It is expected that pulsing was a response to changes in wave
conditions and investigation of a causal relationship follows (Section 5.5.2). Pulsing illustrated at longer periods (200–400s) in Figure 5.10 was only observed in Event 18 and was likely to be a result of forcing conditions unique to that event, whereby wave heights in the later stages of the event were near the 3.5m threshold that placed the rip-neck over the instrument site (Section 5.4.3).

5.5.2 Near-bed Response to Pulsing
A correlation between mega-rip velocity and wave height was identified in Sections 5.4.2 and 5.4.3 respectively. The question arises as to whether pulsing is similarly controlled by changes in wave height, in particular wave groupings. Several bursts containing offshore pulses were identified in Section 5.3.2. The corresponding pressure record from the inner-shelf ADV was used to determine changes in the wave group envelope and identify a relationship with near-bed velocities (Wave groups were determined by taking the absolute value of wave height and plotting the wave peaks). The two pulses identified occurred during Events 8 and 13 and indicated various response times that were likely to be state dependent. In the initial stages of the first burst (occurring during Event 8) wave heights were 1–2m high. In the minutes preceding the pulse three large sets of waves of approximately 3–3.5m were observed (Figure 5.12a) and velocities at the seabed started to increase 200 seconds after the onset of the first wave group. Velocities gradually increased to a maximum occurring 200s after the end of the last wave group. The second burst occurred during Event 13 (Figure 5.12c and d), with wave heights of 1–3m prior to the initial wave group. Four large wave groups were observed with four corresponding peaks in velocity. The edges of each wave group were defined and tabulated with the lows between each peak in velocity (Table 5.2). Onset of the first wave group occurred at 500s with wave heights of 3.5–4m.

Time lag decreased with each successive wave group and may indicate state dependence. For example, prior to the first wave group the mega-rip was situated over the instrument site, where as the onset of the first wave group resulted in offshore extension of the mega-rip. As the waves decreased towards the end of the wave group, the mega-rip started to recede. Before the mega-rip could return to the state prior to the initial wave group the second wave group arrived - this process repeated itself until a sufficiently long period between wave groups allowed the system to return to a state prior to the wave group’s arrival. Extending this idea to the burst during Event 8 where, prior to the wave group,
Figure 5.12: Near-bed velocity increase in response to wave groups: a) wave group envelope at inner-shelf site Event 8 (burst 562 deployment 2); b) near-bed velocities at nearshore site; c) wave group envelope at inner-shelf site Event 13 (burst 59 deployment 7); and d) near-bed velocities at nearshore site.
wave heights relative to the burst from Event 13 were lower and placed the mega-rip closer to the shore. The mega-rip’s proximity to the shore required a longer time-frame to respond to the higher incident waves associated with the wave group, which was indicated by a longer response time (200s) than in the burst from Event 13 (47s).

**Table 5.2:** Time lag between onset of near-bed velocities at incident wave groups within Event 13 (burst 59 deployment 7), where Ts, Tm and Tf are the start middle and finish respectively of the wave groups and velocity pulses.

<table>
<thead>
<tr>
<th>Wave groups</th>
<th>Velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ts (s)</td>
</tr>
<tr>
<td>Peak 1</td>
<td>500</td>
</tr>
<tr>
<td>Peak 2</td>
<td>574</td>
</tr>
<tr>
<td>Peak 3</td>
<td>693</td>
</tr>
<tr>
<td>Peak 4</td>
<td>842</td>
</tr>
</tbody>
</table>

**5.5.3 Surface Flow During Pulsing**

A mega-rip pulse was recorded on video during deployment 7, from which individual images were extracted and used to determine the size and velocity of rip-head propagation (Figure 5.13 and Table 5.3). The mega-rip can be observed in the right of the first frame (indicated by the black lines) with a concentrated jet of water in the centre of the rip-neck and a poorly formed rip-head. Frame B places the seaward edge of the rip-head 23m further seaward with a concentrated jet of water feeding the current. The rip continued to grow until Frame F, where the rip-head was 654m offshore. An absence of the jet feeding the current was evident in Frame G when the rip-head began to dissipate. As the flow dissipated it continued to advect offshore in the last 2 frames, the extent of which was not known. Waves in the first frame and several frames prior were approximately 4m and abated to 2–2.5m by the fifth frame. Dissipation of the rip occurred shortly after the waves abated, supporting the relationship between rip pulses and wave grouping. These frames also validate the assertion of changes in flow regime measured by the instruments, where waves below 3.5m placed the rip-head shoreward of the instrument site and waves over 3.5m placed the rip-head seaward of the instrument site. Unfortunately the absence of concurrent velocity measurements prevented a comparison between la grangian and eulerian velocities.
Figure 5.13: Surface expression of mega-rip pulsing during Event 13 blue dot indicates location of instrument during study.
Figure 5.13 (cont): Surface expression of mega-rip pulsing during Event 13 blue dot indicates location of instrument during study.
Table 5.3: Distance of rip offshore and propagation velocity during pulsing event observed on 1\textsuperscript{st} of July 2000 (Deployment 7 Event 13).

<table>
<thead>
<tr>
<th>Distance offshore (m)</th>
<th>Velocity (m s\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame1</td>
<td>523</td>
</tr>
<tr>
<td>Frame2</td>
<td>546</td>
</tr>
<tr>
<td>Frame3</td>
<td>582</td>
</tr>
<tr>
<td>Frame4</td>
<td>615</td>
</tr>
<tr>
<td>Frame5</td>
<td>633</td>
</tr>
<tr>
<td>Frame6</td>
<td>654</td>
</tr>
<tr>
<td>Frame7</td>
<td>out of frame</td>
</tr>
<tr>
<td>Frame8</td>
<td>out of frame</td>
</tr>
</tbody>
</table>

5.6 Spatial Extent of Mega-rips

Spatial characteristics were determined using photographs collected during the study period. Several of the events presented in this section occurred outside of the five deployments identified in Section 3.3.1 and are classified alphabetically.

5.6.1 Event 1: 13\textsuperscript{th}–17\textsuperscript{th} of July 1999.

Several photographs and observations were made during this event on two days; 14\textsuperscript{th} and 15\textsuperscript{th} of July 1999. This event occurred in association with waves from the east with $H_{max} = 6$ m, where $H_s$ exceeded 2.5 m for 92 hours. At the time the observations were made for each day wave heights were ~ 4.5 m, the peak of the storm having occurred at night between these two days. A mega-rip was observed at the southern end of the embayment (Figure 5.14a) with the head of the rip adjacent to the southern headland and extending approximately 700 m offshore. Plumes associated with the rip were identified 900 m from the shore introducing the possibility that advection carried water and sediment much further seaward. A second rip was identified at the northern end of the embayment that extended approximately 250 m offshore (Figure 5.14b). This event occurred during deployment 1 when only near-bed velocities at the northern end of the embayment were measured.

5.6.2 Event A: 30\textsuperscript{th} of May–3\textsuperscript{rd} of June 2000

This event occurred during deployment 6 with $H_{max} = 5$ m from the south where $H_s$ exceeded 2.5 m for 92 hours. Photographs and observations were made on the 2\textsuperscript{nd} of June 2000 when wave heights were 4–4.5 m. A mega-rip was observed at the northern end of the embayment (Figure 5.15) with the rip-head situated 200 m south of the northern headland, extending approximately 560 m offshore. At other times during the event the rip-head was
Figure 5.14: Rip currents observed during a storm on the 14th and 15th of June 1999: a) mega-rip at the southern end of the embayment; and b) small rip observed at the northern end of the embayment.
Figure 5.15: Photograph of mega-rip at the northern end of the embayment taken on the 15th of July 1999.

Figure 5.16: Photograph of mega-rip at the northern end of the embayment taken on the 2nd of June 2000.
not as pronounced. As this event occurred during deployment 6 no hydrodynamic data were collected due to instrument failure.

5.6.3 Event 13: 30th June–3rd of July 2000
Photographs and video footage were collected during this event on the 1st of July 2000. This event occurred in association with waves from the south with a $H_{\text{max}}=6\text{m}$ where $H_s$ exceeded 2.5m for 84 hours and resulted in a mega-rip at the northern end of the embayment (Figure 5.16). The head of the rip was observed 480m offshore (Figure 5.16), while at other times was observed 600m offshore (Figure 5.13). Photographs and video footage were taken when $H_s=4.5\text{m}$ after burial of the instrumentation, therefore no data concurrent with the observed rips was available.

5.6.4 Event B: 6th–9th of July 2001
Event B occurred after deployments concurrent with a storm from the east when $H_{\text{max}}=3\text{m}$, where $H_s$ exceeded 2.5m for ~70 hours. Waves during this event were very clean (near monochromatic wave field) and had a period of 13–15 s resulting in a mega-rip at the southern end of the embayment (Figure 5.17). The head of the rip was adjacent to the headland and extended 650m offshore. This event occurred outside the measurement period, hence no hydrodynamic data were available.

5.6.5 Event C: 27th–30th of July 2001
Event C also occurred after the deployments were completed and was concurrent with waves from the southeast where $H_{\text{max}}=7\text{m}$, where $H_s$ exceeded 2.5m and persisted for ~ 72 hours. No wave data were collected after the 29th of June due to instrument failure. This event resulted in a mega-rip at the northern end of the embayment (Figure 5.18a). The head of the rip was 250m south of the headland and extended ~ 600m offshore. A small rip was observed at the southern end of the embayment extending ~ 150m offshore (Figure 5.18b). This event occurred outside the measurement period, hence no hydrodynamic data were available.

5.6.6 Summary of Observations at MacMasters Beach
A pattern in incident wave direction and location of the dominant current was evident, whereby mega-rips formed adjacent to the headland exposed to the incident wave field (Figure 5.19). Observations during the storms placed an alongshore current parallel to the shore feeding the mega-rip (Figure 5.20). A secondary current was observed adjacent to
Figure 5.17: Mega-rip observed at the southern end of the embayment during a storm on the 7th of June 2001.
Figure 5.18: Rip currents observed during a storm on the 29th of July 2001: a) mega-rip at the northern end of the embayment; and b) small rip at the southern end of the embayment.
Figure 5.19: Schematic representation of mega-rips relative to incident wave field observed at MacMasters beach during the study period. Letters indicate storms captured on film or video only while numbers correspond to those captured on instrument.
Figure 5.20: Photos taken during a storm on the 10th of November 1999 showing: a) the direction of the longshore current; and b) the mega-rip the longshore current fed into.
the sheltered headland when incident waves exceeded 4m and corresponded to offshore surface flow identified in the data (Section 5.4.3). Placement of the major rip current supported the oblique wave-driven alongshore current mechanism, while the presence of a smaller current under extreme conditions at the opposing end of the embayment suggests the wave setup-driven current mechanism also played a significant role in nearshore hydrodynamics. Typically, the largest storms resulted in currents being observed further offshore and mega-rips at the southern end of the embayment were observed further seaward than at the northern end.

### 5.6.7 Observations of Mega-rip Phenomena Outside of the Study Area

Mega-rip and surfzone characteristics were identified for several embayments along the southeast coast of Australia from photographs for events occurring on the 31st of December 1984 and 3rd of September 1985 (pers. comm. P. Cowell, Table 5.4; The method used to determine the offshore extent of the mega-rips involved scaling relative to the adjacent headland and hence precision of the measurements is limited). A trend for the offshore extent of mega-rips being 1.5 times the surfzone width was observed for this data and was compared to the MacMasters beach dataset collected over a variety of storm conditions (Table 5.5 and Figure 5.21) — a similar trend was identified in data from the study area. A large degree of fluctuation around the mean was expected due to the high temporal variability in the offshore extent of mega-rips, inherent from previously noted wave height variations.

### Table 5.4: Mega-rip, embayment and wave characteristics for embayed beaches in the Sydney region during storms on the 31st of December 1984 and the 3rd of September 1985.

<table>
<thead>
<tr>
<th>Location</th>
<th>Cordline length (Cl)</th>
<th>Seaward Limit RI</th>
<th>Surfzone Width (Szw)</th>
<th>RI/Szw</th>
<th>Local Wave Dir</th>
<th>Embayment Orientation</th>
<th>Rip Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoca</td>
<td>1250</td>
<td>600</td>
<td>400</td>
<td>1.5</td>
<td>E</td>
<td>117</td>
<td>South</td>
</tr>
<tr>
<td>MacMasters</td>
<td>1250</td>
<td>450</td>
<td>250</td>
<td>1.8</td>
<td>E</td>
<td>124</td>
<td>South</td>
</tr>
<tr>
<td>Palm</td>
<td>1900</td>
<td>450</td>
<td>300</td>
<td>1.5</td>
<td>E</td>
<td>104</td>
<td>Centre</td>
</tr>
<tr>
<td>Avalon</td>
<td>750</td>
<td>650</td>
<td>400</td>
<td>1.6</td>
<td>E</td>
<td>119</td>
<td>South</td>
</tr>
<tr>
<td>Bilgola</td>
<td>625</td>
<td>500</td>
<td>300</td>
<td>1.7</td>
<td>E</td>
<td>133</td>
<td>South</td>
</tr>
<tr>
<td>Newport</td>
<td>1000</td>
<td>300</td>
<td>275</td>
<td>1.1</td>
<td>E</td>
<td>101</td>
<td>Centre</td>
</tr>
<tr>
<td>Palm</td>
<td>1900</td>
<td>700</td>
<td>400</td>
<td>1.8</td>
<td>SE</td>
<td>104</td>
<td>North</td>
</tr>
<tr>
<td>Whale</td>
<td>650</td>
<td>400</td>
<td>300</td>
<td>1.3</td>
<td>SE</td>
<td>102</td>
<td>North</td>
</tr>
<tr>
<td>Curl curl</td>
<td>1000</td>
<td>450</td>
<td>350</td>
<td>1.3</td>
<td>SE</td>
<td>83</td>
<td>Centre</td>
</tr>
<tr>
<td>Queens</td>
<td>475</td>
<td>500</td>
<td>300</td>
<td>1.7</td>
<td>SE</td>
<td>139</td>
<td>South</td>
</tr>
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**Table 5.4:**

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std</th>
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<tr>
<td>1.52</td>
<td>0.23</td>
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</table>
Postglacial shoreface sediments were dependent on the local wave direction and orientation of the embayments and the incident wave direction. As observed for the study area, waves obliquely incident from the south resulted in mega-rip formation at the northern end of embayments, while waves obliquely incident from the north resulted in a mega-rip forming at the southern end of the embayments. Several occurrences of mega-rips in the study area of longer embayments have been noted (Elliot, 1999: p229 Fig 9.8) and likely the result of waves arriving normal to the shoreline of the beach (Table 5.4).

Table 5.4: Mega-rip, embayment and wave characteristics for MacMasters beach during the study period.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Surface Water</th>
<th>Mean</th>
<th>Local Wave</th>
<th>Embayment</th>
<th>Rip</th>
</tr>
</thead>
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<tr>
<td>1.20</td>
<td>1.75</td>
<td>1.25</td>
<td>1.50</td>
<td>1.95</td>
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<td>1.25</td>
<td>1.50</td>
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<td>1.75</td>
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<tr>
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<td>1.35</td>
<td>1.25</td>
<td>1.50</td>
<td>1.95</td>
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<td>1.35</td>
<td>1.25</td>
<td>1.50</td>
<td>1.95</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Figure 5.21: Change in offshore extent of mega-rip relative to surfzone width X, MacMasters data + data external to field area. Solid line indicates line of best fit and dashed lines indicate upper and lower limits ($R^2=0.5953$). Upper and lower limits were determined taking 2 standard deviations above and below the line of best fit.
Positioning of the mega-rip within embayments was dependent on the local wave direction and orientation of the embayment to the incident wave direction. As observed for the study area, waves obliquely incident from the south resulted in mega-rip formation at the northern end of embayments, while waves obliquely incident from the north resulted in a mega-rip forming at the southern end of the embayments. Several occurrences of mega-rips in the centre of longer embayments have been noted (Short, 1999: p239 Fig 9.8) and likely the result of waves arriving normal to the chordline of the beach (Table 5.4).

Table 5.5: Mega-rip, embayment and wave characteristics for MacMasters beach during the study period.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Seaward Limit Ri</th>
<th>Surfzone Width (Szw)</th>
<th>RI/Szw</th>
<th>Local Wave Dir</th>
<th>Embayment Orientation</th>
<th>Rip Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/07/1999</td>
<td>695</td>
<td>475</td>
<td>1.5</td>
<td>E</td>
<td>124</td>
<td>South</td>
</tr>
<tr>
<td>14/07/1999</td>
<td>700</td>
<td>565</td>
<td>1.2</td>
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<td>124</td>
<td>South</td>
</tr>
<tr>
<td>2/06/2000</td>
<td>510</td>
<td>260</td>
<td>1.9</td>
<td>SE</td>
<td>124</td>
<td>North</td>
</tr>
<tr>
<td>2/06/2000</td>
<td>565</td>
<td>420</td>
<td>1.3</td>
<td>SE</td>
<td>124</td>
<td>North</td>
</tr>
<tr>
<td>1/07/2000</td>
<td>465</td>
<td>370</td>
<td>1.3</td>
<td>SE</td>
<td>124</td>
<td>North</td>
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<tr>
<td>7/06/2001</td>
<td>650</td>
<td>350</td>
<td>1.8</td>
<td>E</td>
<td>124</td>
<td>South</td>
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<td>29/07/2001</td>
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<td>North</td>
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<tr>
<td>29/07/2001</td>
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<td>370</td>
<td>1.7</td>
<td>SE</td>
<td>124</td>
<td>North</td>
</tr>
<tr>
<td>29/07/2001</td>
<td>740</td>
<td>485</td>
<td>1.5</td>
<td>SE</td>
<td>124</td>
<td>North</td>
</tr>
</tbody>
</table>

| mean   | 1.58 |
| Std    | 0.27 |

5.7 Summary

Data from 20 storm events was used to show an alteration of embayment hydrodynamics from weak tidally dominated flow to strong, offshore directed flow at one end of the embayment when $H_s$ exceeded 2.5m — these conditions were identified as mega-rips. Concurrent with this change in the nearshore, velocities associated with internal wave activity on the inner-shelf were suppressed due to disruption of the thermocline. In addition, directions of mean currents on the inner-shelf changed in response to both wind and waves, however a consistent pattern in the contribution of each to the observed changes was not discernable.

Mega-rip velocities and their offshore extent increased with increasing wave heights and a threshold for mega-rip flow changing from surface-dominated flow to depth uniform flow in 10m water depth was identified at $H_s=3.5$m. Velocities associated with mega-rips reached a maximum of 130cms$^{-1}$ near the surface and 100cms$^{-1}$ at the seabed. The offshore extent of mega-rips increased with wave height with waves above 3.5m resulting in the rip-
head being seaward of the instrument site (480m from the shoreline). Pulsing in mega-rip velocities was observed at 10–20 min intervals and a potential causal relationship with wave grouping was established, with changes in response time implying state dependence of the system. The maximum offshore extent of mega-rip flow observed at MacMasters beach was ~900m and occurred at the southern end of the embayment. The location of mega-rips at MacMasters beach was dependent on the incident wave direction; waves south of the normal resulted in mega-rips adjacent to the northern headland, and waves from north of normal resulted in mega-rips at the southern end of the embayment. This observation indicates a strong likelihood that mega-rips formed as a result of an alongshore current driven by oblique waves, with wave setup playing a role in the generation of a secondary current at the opposite end of the embayment. Lateral positioning of mega-rips at the southern end of the embayment was sensitive to incident wave direction. Mega-rips were identified in areas outside the field area, which displayed the tendency to form adjacent to the exposed headland and the centre of longer embayments. Their offshore extent was typically 1.5 times the surfzone width, a similar relationship to that of MacMasters beach.
Chapter Six

Sediment Transport in Response to

Mega-rips
6.1 Introduction
Preceding chapters have identified mega-rips as a significant hydrodynamic phenomenon in the study area under storm wave conditions and have highlighted the presence of high velocity offshore-directed currents adjacent to headlands. Typically, currents at the nearshore site \((h=10\text{m})\) were constrained to the surface, however during extreme storms high velocities were observed in the lower levels of the water column. Pulsing in the currents varied over 10–20min periods in response to wave grouping, the increase in velocity corresponding to growth in the offshore extent of the mega-rip. Identification of the seaward extent of mega-rips as far offshore as 900m at the field site implies sediments were transported at least that distance. The quantities involved remain unresolved, as does the ability of calm wave conditions to return these sediments to the nearshore.

Sediment characteristics and their distribution within the embayment were determined using samples collected from the field area. These samples were used to ground truth the seabed mapped from sidescan data collected on the 2nd of September 1999. The sidescan data in conjunction with detailed bathymetry was used to identify existing nearshore and inner-shelf morphology. Assessment of morphological change in response to mega-rips was limited to one case where bathymetry data were collected shortly after a storm event. This chapter identifies: the nearshore and inner-shelf morphology and its response to a mega-rip event; the offshore limits of sediment transport by mega-rips; and the potential for the return of sediments delivered offshore by mega-rips.

6.2 Sediment Characteristics Within the Embayment
Sediment grain size analysis was conducted on 32 samples to determine the characteristics of the sediment. The bulk of samples displayed very similar cumulative distributions with a median grain size of 1.5–2 phi (Figure 6.1). Ten samples had a median grain size of 0.5–1.0 phi, of these, 5 samples showed skewness toward coarser grainsizes. Figure 6.2 illustrates the location of the samples within the embayment. Splitting the samples into median grainsizes of 0.5–1 phi and 1.5–2 phi plotted the coarser sediments as being offshore of the 30m contour. These samples were identified as inner-shelf sands with the exception of two samples that were situated in the nearshore region. These samples were relatively close to a deeply incised channel adjacent to the headland and may have indicated a channel lag type deposit due to higher mean currents. Sediment samples falling into the median grain size of
Figure 6.1: Cumulative histograms of sediment grain size analysis for sediment samples collected within MacMasters Beach embayment. Locations of sediment samples are shown in Figure 6.2.
Figure 6.2: Location of sediment samples collected within the field area (AGD 66 co-ordinate system).
1.5–2 phi were well sorted and typical of the nearshore sands along the Sydney coast identified by Roy and Stephens (1981).

A sediment composition analysis was also conducted on a sample from the nearshore region. Calcium carbonate contributed to 31% of the total mass of the sediment, the remainder being composed of quartzose grains with trace amounts of heavy mineral sands. The calcium carbonate fraction had a modal grain size of 1.75 phi, while the quartz fraction had a modal grain size of 2 phi. The disparity in grain size between the two major fractions is likely to be the result of differing physical properties. Calcium carbonate having a lower specific gravity and platy grains while quartz has higher specific gravity and rounded grains.

6.3 Embayment Bathymetry Response to a Storm Event

6.3.1 Embayment Bathymetry Prior to A Major Storm Event

Hydrographic, surfzone and shoreface surveys were combined, gridded and plotted to determine the morphology of the MacMasters beach embayment (Figure 6.3). Several major features were identified from the bathymetry: the offshore extent of the sub-aqueous headland; a major break in the slope angle at 1400m; the presence of an offshore bar with intersecting rip channels; and depressions adjacent to the headlands seaward of the 22m contour. Five cross-shore and two alongshore transects were extracted from the data (Figure 6.4). Cross-shore profiles A₁–A₁' and E₁–E₁', taken offshore of the headlands, showed a relatively steep slope punctuated by shallow gradient platforms, the profiles changing to 0.01 seaward of ~1400m. Cross-shore profiles B₁–B₁', C₁–C₁', and D₁–D₁', taken offshore of the embayment, showed the presence of a bar between ~150m and 250m offshore and a shallow gradient of 0.01 seaward of 1650m. Profiles B₁–B₁', and D₁–D₁' were adjacent to the headlands and showed a lower bed elevation (depressions) than the central profile (C₁–C₁') seaward of 1000m and corresponded to the observed depressions in Figure 6.5.

Two alongshore transects were taken to illustrate the bar crest morphology and the two depressions adjacent to the headlands, transects F₁–F₁' and G₁–G₁' respectively. Transect F₁–F₁' showed two rip channels dissecting the bar ~ 1.5m deeper than the adjacent bar. Spacing between the two channels was approximately 600m and, given wave heights on the day were 1.2m, suggested the morphology may have been antecedent to those conditions. Transect G₁–G₁' showed the presence of two depressions that were 50cm lower
Figure 6.3: Embayment bathymetry of the field area showing typical nearshore morphology prior to a storm event.
Figure 6.4: Location of profiles and transects within the field area.
Figure 6.5: Profile and transects of the field area prior to a major storm event, showing major morphological features. Colour of profiles and transects correspond to those depicted in Figure 6.4.
than the centre of the embayment. At the terminus of these depressions, where the cross-shore profiles $B_1-B'_1$ and $D_1-D'_1$ shallowed to form the inner-shelf ~ 1600m offshore, there was a change in the relief that may have represented sand accumulation.

### 6.3.2 Embayment Bathymetry After a Major Storm Event

A hydrographic survey was collected as soon as practicable (11th of September 2001) after a major storm event that occurred in early July 2001 and was used to determine beach morphology after a storm (Figure 6.6). Amongst the major changes to embayment morphology were a flattening of the nearshore profile and a large deposit of sediment at the northern end of the embayment. The three embayment profiles collected prior to the storm were compared to those after the storm (Figure 6.6). Profiles $B_1-B'_1$ and $B_2-B'_2$ showed the removal of the bar between 150m and 200m and the presence of a large accumulation of sediment between 300m and 500m offshore. Profiles $C_1-C'_1$ and $C_2-C'_2$ showed little change, while profiles $D_1-D'_1$ and $D_2-D'_2$ showed an infilling of the trough and removal of the bar, resulting in a flattening of the profile.

To highlight changes in the bathymetry a residual surface was created by subtraction of the pre-storm bathymetry from the post-storm bathymetry (Figure 6.7). Figure 6.7 shows a general flattening of the nearshore profile, with the nearshore trough being in-filled and the nearshore bar being planed off. Deposition of a large sand body approximately 1m thick occurred at the northern end of the embayment. Landward of this sand body a negative change in the seabed was the result of bar removal. Discontinuity of the sand body across the embayment and its coincidence with the position of the rip-head indicated it corresponded to a rip-head bar. Formation of the proximal rip-head bar represented a volumetric deposition of 56,000m$^3$ (78.5cm change over 72,000m$^2$) and was verified by burial of the instruments located at the northern end of the embayment. Changes to the inner-shelf profile were highly variable due to the wave conditions during the initial hydrographic survey. However, a trend for deposition at the northern end, as far offshore as the inner-shelf instrument site, was apparent (Figure 6.7). Volumetric analysis of this area showed an accumulation of ~5,500m$^3$ (4.5cm change over 120,000m$^2$). The seaward extent of the accumulation coincided with the inner-shelf instrument site approximately 1km offshore, which recorded a 5cm bed level increase relative to the instrument.
Figure 6.6: Profiles taken before and after a storm, showing morphological response to a storm event on the 29th of July 2001. Colour of profiles correspond to the profiles in Figure 6.4.
Figure 6.6 (Cont): Transects taken before and after a storm, showing morphological response to a storm event on the 29th of July 2001.
Figure 6.7: Change in bathymetry after a storm event on the 1st of July 2000. Blue indicates negative change (erosion), light blue 2 standard deviations below the mean (erosion within error), white 1 standard deviation about mean (no change within error), light red 2 standard deviations above the mean (deposition within error) and red positive change above 2 standard deviations (deposition).
6.4 Seabed Mapping

Sidescan data collected on the 11th of September 1999 was plotted as an image (Figure 6.8) from which units of similar texture were identified. A total of three units were identified within the image that were ground truthed using sediments from Section 6.2.1 (Figure 6.9). The three units comprised rocky reef, nearshore sands and inner-shelf sands. Rocky reef composed much of the seafloor adjacent to and offshore of the headlands with very few outcrops. The contact between nearshore and inner-shelf sediments on previous maps is shore parallel, however in this study an irregular contact was observed with two lobes of nearshore sediment extending seaward adjacent to the headlands. Between the two lobes was an area of discontinuous texture, where ripples were observed on the light and dark patches, with ripples spaced further apart in the dark section. Ripple spacing increases with grainsize and thus the darker patches corresponded to coarser sediments. As these patches were parallel and aligned to the dominant southeast wave direction they may have indicated the presence of larger bedforms. Without coring the sediments a definitive relationship between the contact (coarse on fine, fine on coarse) can not be established, although it is foreseeable that this pattern of textures may be interpreted as finer nearshore sediments laying between the crests of larger bedforms. It follows that the finer sediments were likely to be derived from the nearshore having been re-worked in the swales of the larger bedforms.

The extension of the shore normal lobes adjacent to the headlands coincided with the depressions observed in the hydrographic survey (Section 6.3.1) and suggested an active pathway for sediments from the nearshore. That these depressions were adjacent to the headlands, strongly suggests mega-rips were involved in their formation. The lack of a discrete channel implied that active erosion of the bed by high velocity currents was unlikely, however wave stirring and advection by residual currents was possible.

6.5 Sediment Suspension

6.5.1 Sediment Suspension Criteria

The contribution of oscillatory and steady currents to the suspension of sediments was assessed by determining the total skin friction Shields parameter (\(\theta_f\)). The Shields parameter under combined wave and current conditions is dependent on the bed shear stress as given by Shields (1936):
Figure 6.8: Sidescan image of MacMasters beach, collected on the 11th of September 1999 by Department of Land and Water Conservation.
**Figure 6.9:** Sediment type distribution at MacMasters beach after interpretation and ground truthing of sidescan image.
\[ \theta_r = \frac{\tau_o}{\rho(s-1)gD} \] ..................................E6.1

where \( \rho \) is the water density, \( s \) is the immersion density, \( g \) is the acceleration due to gravity and \( D \) is the modal grainsize diameter. Contributions of time-averaged shear velocities under combined oscillatory and steady currents to the total bed shear stress are defined by Beach and Sternberg (1992) as:

\[ \tau_o = \rho(u^2_{oc} + u^2_w) \] ..................................E6.2

where

\[ u^2_{oc} = \frac{1}{8} f_c \bar{u}^2 \] ..................................E6.3

and

\[ u^2_w = 0.25 f_w u^2_m \] ..................................E6.4


The time averaged shear velocities are dependant on the velocity of the flow defined by the mean current velocity \( \bar{u} \) and the maximum orbital velocity \( u_m = 2.8u_o \) and on the friction felt by the flow from the seabed for currents and waves defined by Van Rijn (1990) and Swart (1974) respectively:

\[ f_c = 0.24 \log^2 \left( \frac{12h}{k_s} \right) \] ..................................E6.5

\[ f_w = \exp \left[ 5.123 \left( \frac{k_s}{a_s} \right)^{0.194} - 5.977 \right] \] ...E6.6

where \( h \) is the water depth, \( k_s \) is the grain roughness defined by \( k_s = 2.5D \), and \( a_s \) is the maximum wave orbital semi-excursions determined using \( a_s = u_o T / \pi \).

Contributions of the oscillatory component were often an order of magnitude larger than that of the steady current component at both the nearshore and inner-shelf sites (Figure 6.10). Most of the time (79%), \( \theta_w \) was greater than the critical value of 0.05 at the nearshore site, while the critical Shields parameter at the inner-shelf site was exceeded 48% of the time (Figure 6.10). Contributions from the steady current component never
Figure 6.10: Scatter plot of contribution of waves and currents to the Shields parameter showing a weak trend for the inner-shelf site.

Figure 6.11: Scatter plot of contribution waves and currents to the Shields parameter showing a weak trend for the nearshore site.
exceeded the critical Shields parameter at either the nearshore or inner-shelf site. Inner-shelf steady current Shields parameter showed no correlation with the wave-induced Shields parameter, indicating that surface waves contributed little to driving currents on the inner-shelf (Figure 6.11). However, a trend for an increasing current Shields parameter with increasing wave-induced Shields parameter indicated that waves contributed to the generation of currents in the nearshore region. This analysis does not take the direction of steady currents into account, hence a direct relationship with mass transport is not inferred.

The largest contribution to steady current velocities on the inner-shelf under fair-weather conditions was made by internal waves. The potential presence of internal waves was identified in Chapter 4. It was further suggested that surface wave re-suspension of sediments and internal waves were mutually exclusive due to disruption of the thermocline by surface waves greater than 2.5m. However, the potential exists that on their own or in combination with surface waves under 2.5m, internal waves were capable of entraining sediment. A segment of data where internal wave activity was greatest was taken from deployment 8 (450–900hrs) and steady current-induced and wave-induced Shields parameters were determined. Figure 6.12 illustrates the steady current, wave-induced and combined Shields parameters for the above period of high internal wave activity and indicated internal waves were never solely responsible for exceeding the critical shields parameter and thus suspending sediment on their own. During this period wave-only contributions exceeded the threshold for entrainment 6.9% of the time, while combined wave and steady current contributions exceeded the entrainment threshold 7.6% of the time. A cluster of data points with high θc and low θw was observed in Figure 6.10 and corresponded to the values occurring during this time due to internal wave activity. The containment of this cluster to lower θw values supported the observation of internal wave disruption and mutual exclusion of large incident waves.

6.5.2 Sediment Suspension Response to Mega-rip Pulses
Maximum sustained near-bed velocities were measured up to 90cms⁻¹. These velocities were associated with pulses and were sustained for durations of approximately 5 minutes. Under these conditions the skin friction Shields parameter, due to a steady current, reached a value of 0.25, sufficient for active erosion of the seabed by the flow. Hind casting the critical Shields parameter to yield the mean current for the critical entrainment velocity
given - 41 cm$^3$. From two of the near-bed bursts containing a pulse, mean velocities were 29 cm$^3$ and 31 cm$^3$, for bursts 362 of deployment 2 and burst 59 of deployment 2 respectively, the threshold velocity of 41 cm$^3$ was exceeded 21% and 31% of the time respectively. This clearly demonstrated inadequacy of mean currents to represent near-bottom flow due to the presence of pulsing.

Figure 6.12: Scatter plot of potential contribution to Shields parameter by internal waves at the inner-shelf. The straight line representing a linearly combined Shields parameter of 0.05.
gives ~ 41 cms\(^{-1}\). From two of the near-bed bursts containing a pulse, mean velocities were 29 cms\(^{-1}\) and 32 cms\(^{-1}\), for bursts 562 of deployment 2 and burst 59 of deployment 7 respectively; the threshold velocity of 41 cms\(^{-1}\) was exceeded 21% and 31% of the time respectively. This clearly demonstrated inadequacy of mean currents to represent mega-rip flow due to the presence of pulsing.

An advective or erosional activity regime was defined for mega-rip flow during three events where advection was defined by \(\theta_w > 0.05\) and \(\theta_c < 0.05\) and erosional was defined by \(\theta_w > 0.05\) and \(\theta_c > 0.05\). Specifically, these criteria were applied to the lowpassed current velocities from the nearshore site during Events 8, 11 and 13. Individual measurements within a burst were tagged as either being above the threshold or below, those above being counted to determine a percentage contribution to the total number of data points. Applying the above analysis technique to Event 11 indicated that steady current (hourly average) exceeded the threshold to entrain sediment. Only two bursts at the peak of Event 8 contained values exceeding the threshold, with up to 25% of values within one burst exceeding the threshold. Sixteen of the 81 hours during Event 13 contained values that exceeded \(\theta_c = 0.05\), with up to 50% of values within a burst exceeding the threshold. The times when the critical steady current Shields parameter was exceeded correlated with significant wave heights above 4.3m (Figure 6.13). It follows that active erosion by mega-rip currents at the nearshore site (11m water depth) typically occurred when significant wave heights exceeded 4.3m. Wave heights of 2.5–4.3m resulted in currents that were capable of advecting sediment as \(\theta_w\) always exceeded 0.05.

6.5.3 Visual Observations of Sediment Suspension Events
Extensive plumes of sediment were observed during several events (Figure 6.14). These plumes were most evident under good light conditions, which was rare due to the high winds and overcast weather associated with many of the storms. The offshore extent of the plumes varied between storms and a few were observed to extend over 1km offshore. Plumes of this nature have previously been observed along the coast and were attributed to a downwelling front (pers. Comm. D. Hanslow). However, several of these plumes were clearly associated with mega-rips indicating that advection of water and sediment associated with the rips was responsible for transport of sediment to the inner-shelf further seaward than the proximal mega-rip deposition identified in Section 6.3.2. In addition,
Figure 6.13: Percentage of points within the burst having mean currents that exceeded the critical entrainment value with corresponding wave heights included for reference: a) Event 13; and b) Event 8.
Figure 6.14: Plumes of sediment associated with storm waves observed at MacMasters beach.
Figure 6.14(cont): Plumes of sediment associated with storm waves observed at MacMasters beach.
these types of flows may be responsible for the formation of the depressions observed in the above section (Section 6.4). It is envisaged that in the presence of a current wave stirring would be adequate to suspended sediments for transport by the current and as the currents have a preference to form adjacent to the headland it follows that channels may be formed adjacent to them.

6.6 Sediment Transport Within the Study Area

Sediment transport for the water column is reliant on knowledge of the velocity profile and suspended sediment concentration profiles. Given that sediment concentration is known at two heights above the bed and the relationship determined by Nielsen (1979):

\[ c = c_0 \exp\left(-\frac{w_z z}{\varepsilon_s}\right) \] ..........................E6.8

the concentration profile for \( z \) above the seabed can be determined for a reference concentration \( c_0 \), and assessed using the second known concentration where \( w_z \) is the sediment fall velocity and \( \varepsilon_s \) the sediment diffusivity constant. In the case of water velocity profiles a method such as that employed by Wright et al. (1997) used the known velocity to determine the mean current friction velocity:

\[ \frac{u_c(z)}{u_c} = \frac{1}{k} \ln \frac{z}{z_0} \] ..........................E6.9

This method requires a robust knowledge of velocity at several other locations within the water column to ensure uniform direction of flow and correspondence to the modeled velocity profile. Given the highly complex interaction of currents in the nearshore and inner-shelf due to upwelling and downwelling currents, internal waves, surface waves and tidal flows it was inappropriate to attempt to define a velocity profile for the study site. Therefore, sediment transport was limited to a sediment flux at only one point above the bed at the nearshore and inner-shelf sites.

6.6.1 Transport Trends During and After Storm Events in the Nearshore

Two storm events occurred when all four OBS were working and unaffected by fouling (Event 1, and 13). Event 1 constituted a storm of maximum \( H_s = 6m \) from the east, during which, offshore sediment transport reached a maximum of 1500gm\(^{-2}\)s\(^{-1}\) 10cm above the bed (Figure 6.15). However, the bulk of sediment transport was in the north-south direction with transport being directed north in the early stages and south in the later stages.
Figure 6.15: Sediment transport direction and rate at the nearshore site for: a) Event 1; and b) Event 13.
Conditions after the storm were not able to be observed due to burial of the OBS. Event 1 resulted in a mega-rip at the southern end of the embayment and transport of sediment toward the southern end of the embayment. Event 13 constituted a storm from south of southeast with maximum $H_s=6$ m. Sediment transport in the nearshore during Event 13 was directed offshore (east-south) at up to $1800 \text{gm}^{-2}\text{s}^{-1}\text{mcm}^{1}$ above the bed (Figure 6.15), with the bulk of sediment transport alongshore to the north in an offshore direction. Following the storm, low rates of transport were observed in an onshore direction. Event 13 resulted in a mega-rip at the northern end of the embayment and peak sediment transport was directed offshore. In the days following this event sediment transport was directed onshore and indicated the initiation of post-storm recovery.

6.6.2 Trends during and After Storm Events on the Inner-shelf
Sediment transport on the inner-shelf during Event 1 was directed between north and east up to $112 \text{gm}^{-2}\text{s}^{-1}\text{mcm}^{1}$ above the bed (Figure 6.16). The bulk of sediment transport was to the north in both onshore and offshore directions, the peak in transport being onshore. Sediment transport on the inner-shelf during Event 13 was directed between northeast and east up to $46 \text{gm}^{-2}\text{s}^{-1}\text{mcm}^{1}$ above the bed (Figure 6.16), indicating the bulk of sediment transport was in an offshore direction to the north. Transport directions for these two storms were similar in that the primary direction of transport was to the north, however they differed in that Event 1 exhibited onshore-directed transport while Event 13 exhibited offshore-directed transport.

6.6.3 Qualitative Suspended Sediment Concentrations
Data collected by the ADCPs included echo intensity for each depth bin. Echo intensity was a measure of the amount of signal returning to the instrument from reflected particles and therefore, gave a qualitative indication of suspended sediment concentrations. A noticeable relationship between high echo intensities and offshore directed mega-rip currents was apparent during storm events (Figure 6.17). In order to clarify this relationship a background level was required, to identify variations. A reference profile ($R_p$) was established using the data for the whole deployment period, excluding storms, and was applied using Equations 6.10 and 6.11.

$$R_p = \bar{E}_t + 1.5 \times E_o \quad \text{E6.10}$$
Figure 6.16: Sediment transport direction and rate at the inner-shelf site for: a) Event 1; and b) Event 13.
Figure 6.17: Data output by ADCP during Event 7 showing: a) velocity; b) direction; and c) echo intensity.
\[ E_N = \frac{E_p}{R_p} \]  

This normalized echo intensity, \( E_N \), was used for qualitative assessment of suspended sediments during storm events, where values above 1 indicated an increase above the background level. Results of this analysis established a trend for echo intensities to be 1.5 times greater than the reference level during storm events (Figure 6.18). In the presence of mega-rips echo intensities were up to 2.5 times greater than the reference level measured during fair-weather conditions and two times greater than the echo intensities at the opposite end of the embayment during an event (Figure 6.19). It was also evident that concentrations in general were elevated toward the surface and may have been the result of increased air bubbles in the upper levels of the water column.

### 6.7 Summary

Sediments distributed on the inner-shelf showed a well demarcated boundary between the nearshore and inner-shelf sands as depicted by Roy and Stephens (1981). However, the nature of the boundary clearly indicated the presence of processes active in moving sediments at these waters depths. Nearshore sediments were found beyond the boundary, laying in the swales of larger bedforms and in depressions adjacent to the headlands. The discernable seaward extent of sediment transport due to mega-rips was identified by a change in profile at depths of 25m. The bulk of sediment suspension was the result of wave stirring with burst-averaged velocities indicating current re-suspension was absent. However, inspection of velocities within the bursts indicated pulsing within the mega-rips resulted in sediment re-suspension. Transport within the nearshore, resulting from a mega-rip event equated to 57,000m³ of sediment or an elevation change of 75cm in water depths of up to 15m. Sediment plumes observed in association with mega-rips indicated sediment was transported further seaward than indicated by bathymetric change.
Figure 6.18: Quasi-suspended sediment concentration as an elevation above background for data collected in the presence of mega-rips.
Figure 6.19: Quasi-suspended sediment concentration as an elevation above the background for data collected at the opposite end of the embayment to mega-rips.
Chapter Seven

Shoreface Morphodynamics and Hydrodynamics Associated with Mega-rips
7.1 Introduction
The primary aim of this thesis was to investigate the hydrodynamic coupling between the nearshore and inner-shelf of the Sydney region, with a specific focus on role of mega-rips. The first results chapter (Chapter 4) assessed the contribution of various oceanographic processes to the hydrodynamic coupling during fair-weather conditions. Chapter 5 identified storm-weather processes active on both the upper and lower shoreface and examined how they differed from and interacted with the fair-weather processes. In addition, Chapter 5 identified mega-rips and their contribution to the hydrodynamics of an embayed beach. The final results chapter (Chapter 6) identified the significance of these storm- and fair-weather processes in transporting sediments across the shoreface, with an emphasis on the mega-rip phenomenon.

This chapter examines the various processes that were active on the inner-shelf under both fair-weather and storm conditions and makes comparisons to previous studies. In particular, a synthesis of mega-rips is presented and the implications of various aspects of mega-rips are discussed, including: the implications of vertical flow structure on hydrodynamic modelling; the implications of mega-rip spatial characteristics on sediment modelling; the implications for the coast of the Sydney region; and the implications for embayed coasts in general.

7.2 Fair-weather Processes Active on the Inner-shelf
As stated previously, a general lack of data on inner-shelf hydrodynamic processes, particularly in reference to the lower shoreface, was apparent for the Sydney region. This study has identified the presence of several oceanographic processes active on the lower shoreface for the Sydney region, including surface waves, internal waves and tide-generated currents. How these processes interact and affect the oceanography off the coast of Sydney is important when predicting coastal behaviour.

7.2.1 Mean currents on the inner-shelf
Mean currents represent the net effect of all oceanographic processes and frequently represent the general direction of sediment transport. For the data collected during this study mean currents on the inner-shelf were directed to the northeast parallel to the shoreline at 0–2 cms\(^{-1}\). This observation corresponds to a previous study by Wright et al. (1980) conducted at Palm beach, 30km to the south of Macmasters Beach, in similar water
depths (25m). In this earlier study no one mechanism was attributed to driving these currents, the authors favouring a combination (net result) of processes.

In contrast, data collected in deeper water (65m) during the study of Middleton et al. (1996) indicated a dominant southerly flow (2cms\(^{-1}\)). The residual flow observed in that study was largely attributed to the EAC. The opposing direction of the flow between this study and that of Middleton et al. (1996) may be explained by a decreased exposure to the EAC as the measurement location in this study was much closer to the shore. This explanation is supported by the notable absence of EAC related flow as noted in Section 4.4.4. This decreased exposure to the EAC allowed other hydrodynamic processes to dominate namely wind-, wave- and tidally-driven currents.

7.2.2 Tidal Flows on the Inner-Shelf
The relative contributions of each phenomenon varied considerably, with diurnal tidal constituents dominating and being active 100% of the recorded time period. Their contribution to near-bed velocities was relatively small (±3cms\(^{-1}\)), and varied periodically with the diurnal (K\(_1\)) tidal constituent. At these velocities, the tides were only capable of transporting sediment when other processes were actively re-suspending sediments (surface and internal waves). Tidal flow associated with the nearby Hawkesbury River estuary oscillates at semi-diurnal frequencies, is restricted to the estuary mouth and has a dominant east-west component (Wright et al., 1980).

The dominance of the K\(_1\) constituent observed in this study was not present in the study of Wright et al. (1980), suggesting that flow associated with the Hawkesbury River estuary was not responsible for the significant K\(_1\) constituent. A similar dominance of diurnal constituents was observed by Lawson and Treloar (1992) during a sand-mining proposal; tidal analysis (similar to the analysis in this study) failed to identify these constituents. Visual observation of the data, as no soft copy of the data were obtainable, showed velocities associated with the diurnal constituents were on the order of ±20cms\(^{-1}\). Research conducted by Freeland (1988) identified coastal trapped waves at diurnal frequencies, propagating along the coast, however no generating mechanism was established. A later study by Gibbs and Middleton (1997) identified large diurnal constituents in current meter records and suggested that wind forcing and CTW may have been contaminating the record. The role of tidal forcing in the diurnal constituent (K\(_1\)) can not be dismissed from the present study due to the strong correlation between neap-spring tidal range fluctuations.
in the bandpass filtered current record and water surface elevation records as shown in Figure 4.12. The source of these currents needs to be identified and their possible link to CTWs investigated. These aspects are beyond the scope of this study and are suggested for further research.

7.2.3 Internal waves on The Inner-Shelf
Internal waves were poorly resolved due to oscillations lying between the two sampling regimes (0.5s for 1024s and 1hr), however their potential contribution to near-bed velocities was significant for both time (21%) and magnitude (±20cms⁻¹). Internal waves contributed the highest velocities (26cms⁻¹) and were reliant on stratification in the water column for their formation. Typically, during the summer months when temperature differences were greatest, internal waves were active — a finding supported by previous studies along the southeast coast of Australia (Lawson and Treloar, 1992; Middleton et al., 1996). Velocities associated with internal wave activity during both the earlier studies were lower than those measured in this study; ±10cms⁻¹, ±10cms⁻¹ and ±20cms⁻¹ respectively. The difference in water depths between the three sites (43m, 52m and 23m respectively) adequately explain this variation in near-bed velocities, where near-bed orbital velocities increase with decreasing water depth for a propagating wave. The generally accepted generating mechanism for the internal waves is the propagation of the tidal wave across the shelf break and as such they are commonly referred to as internal tides Gibbs and Middleton, 1997). The direction of propagation for these waves is predominantly in the east-west direction, as was observed in this study, which supports the notion of their formation by this mechanism. In addition to a dependence on the seasonal water temperatures, a strong dependence with regional wind climate for internal wave propagation was also identified and is further discussed in Section 7.2.4.

Wave-generated mixing strongly affected the propagation of internal waves, whereby waves higher than 2.5m resulted in disruption of the thermocline and an absence of internal waves, thus making high waves and internal waves mutually exclusive on the inner-shelf. However, a narrow window existed whereby the combined contribution of internal waves and surface waves were responsible for the re-suspension of sediment. These occasions were restricted to moderate wave heights (1.5–2.5m) during the summer months when stratification was greatest and internal wave activity was high; this occurred less than 1% of the time.
7.2.4 Upwelling and Downwelling on the Inner-Shelf
Velocities of upwelling-generated currents were very weak and below the limit of detection, however upwelling exerted significant control on temperature stratification. In the summer months, winds from the northwest to northeast resulted in upwelling which uplifted cool water to the lower water levels and produced a density contrast with the warmer surface waters, along which internal waves could propagate. The reverse was true in the winter months, with low internal wave activity present. The onset of upwelling removed the weak stratification, stopping the internal wave activity.

Two mechanisms driving upwelling along the coast of the Sydney region have been identified (Roughan and Middleton, 2002). These include wind-driven currents and separation of the East Australian current. While winds were directly responsible for the majority of upwelling events, several events during the study period occurred in the absence of the requisite winds and may have been the result of eddies shed from the EAC, or separation of the EAC from the coast as observed by Roughan and Middleton (2002).

Downwelling was difficult to identify as flow associated with these events was below the detectable limit of the sensors and resulted in no significant change in temperature to the usually well-mixed waters present on the shoreface. As such, they were rarely observed (3%; this value is considered an underestimate). Downwelling was most strongly associated with storm events and high winds. The current response on the inner-shelf was suppression of internal wave activity and very weak offshore directed flow (±2cms\(^{-1}\)). This was not consistent with currents during storms, which reached velocities as high as 15cms\(^{-1}\). The exact mechanism for downwelling remains unresolved as no apparent consistency between wind direction and current direction was observed in association with downwelling. Further study using wind-driven current models may provide insight into the driving force and was beyond the scope of this study.

7.2.5 Surface Wave Induced Near-bed Velocities and Sediment Re-suspension on the Lower Shoreface
The largest contribution to near-bed velocities was surface wave induced wave orbital velocities which were the primary means of sediment re-suspension. Sediments were considered to be in suspension when \( u_{rms} \) exceeded 20cms\(^{-1}\), which occurred 14% of the time on the inner-shelf and typically when waves exceeded 2.0m. In the context of fair-weather conditions, sediments were relatively immobile, however a major contribution to
the bulk sediment transport was likely the result of combined surface waves and oscillating flow at diurnal frequencies. This flow was persistent throughout all wave conditions, with a weak net northerly component. The highest transport rates were associated with combined surface and internal wave activity that was shown to re-suspend sediments for a narrow window of wave heights (2.0–2.5m).

7.3 Fair-weather processes active on the upper shoreface and within the embayment

7.3.1 Tidal Flows within the Embayment
Under fair-weather conditions the primary contribution to mean near-bed velocities was oscillatory tidal currents, oscillating between onshore-offshore at the southern end and alongshore northeast-southwest at the northern end of the embayment. Near-bed velocities obtained from the ADVs at first appeared to contradict this observation, however modal current directions from the current profilers adjacent to the near-bed sensor illustrated a distinct variation between upper-mid levels and the lower levels of the water column, highlighting the importance of profile measurements. Typically, tidal flows were restricted to the diurnal constituent (K₁) and were only absent when wave heights exceeded 2.5m, which occurred 10% of the time during the study. Tidal velocities were up to ±15cms⁻¹ and, on their own, were unable to re-suspend sediments. However, wave stirring of the sediments and their subsequent transport by tidal flows was envisaged for wave heights greater than 0.5m and less than 2.5m. The similarity between the major tidal components within the embayment and on the inner-shelf suggested the same mechanism was responsible for generating the tidal currents, and that inner-shelf processes were influencing embayment circulation.

7.3.2 Internal Wave Activity Within the Embayment
A distinct absence of internal wave activity was noted within the embayment. This was a direct result of mixing associated with wave activity and the dependence of internal waves on stratification. Internal waves are dependent on density stratification which, for the field area, was associated with variations in water temperature. Wave shoaling and eventual breaking increases the mixing throughout the water column and removes stratification. With no contrast in density, internal waves are unable to propagate which results in their absence.
7.3.3 Wave-Induced Currents and Sediment Re-suspension on the Upper Shoreface
Mean currents on the upper shoreface showed a weak positive correlation with increasing wave orbital velocities particularly at lower wave heights. This observation indicates mean currents were frequently wave-generated, however these currents were unable to re-suspend sediments on their own. The largest instantaneous near-bed velocities were the result of wave-induced orbital velocities. Root mean square velocities exceeded the critical vortex entrainment velocity of \(20 \text{cms}^{-1}\) 45% of the time, indicating that sediments on the upper shoreface were highly mobile. The combination of mean currents and wave orbital velocities transports sediment and given that the mean currents were often generated by wave action the direction of transport was likely to be in the direction of wave propagation. Therefore, under fair-weather conditions, onshore-directed transport was likely on the upper-shoreface.

7.4 Storm-Weather processes

7.4.1 Storm Processes Active on the Inner-Shelf
During storms currents on the inner-shelf were typically to the north with a minor offshore component indicating currents and sediment were being transported alongshore. An exception was storm Event 18 which came from the east and resulted in velocities again to the north, however with a minor onshore component. The generating mechanism for these currents was attributed to a combination of wind-driven downwelling and wave-generated currents as no one process was isolated due to winds accompanying the high waves and peaking at the same time as the waves within a storm. A better indication of the primary contributor to inner-shelf currents may be obtained from current profile data on the inner-shelf and by modelling wind-driven currents - suggestions for further research. In addition to the two processes above, tidal flows were potentially involved in the transport of sediments under storm conditions as tidal flows on the inner-shelf appeared to be unaffected by even the largest wave event recorded during the study. However, the observation of disrupted/overwhelmed tidal flow on the upper shoreface under high wave conditions (Section 7.4.2) suggests that under wave heights higher than those recorded in this study may result in a disruption of tidal flow, especially in light of the similarity in the signature of the tidal flow (pronounced K\(_1\) constituent).
7.4.2 Storm processes active within the embayment
Unlike the lower shoreface, tidal flow on the upper shoreface was impacted by increased wave heights. The onset of waves over 2.5m resulted in the disruption of the tidal flows previously identified under fair-weather conditions and was concurrent with a distinct change in circulation within the embayment (Section 7.3.1). This change in circulation was noted above the threshold wave height of 2.5m whereby a single large rip cell (mega-rip) dominated the entire embayment. Mega-rips are discussed further in Section 7.5.

7.4.3 Importance of Wave Height Decay at the end of Storms
Wave heights during the largest storm showed a typical rapid rise and slow decay, with the largest rates of sediment transport occurring when wave heights were greatest. At this time the direction of sediment transport on the inner-shelf was offshore. As the storm decreased in intensity and the wave heights decayed in the later stages of the storm, transport directions changed to onshore. This change in direction occurred when wave heights reached 4.3m. As wave heights continued to decay sediment transport rates decreased until wave heights fell below that required to re-suspend sediments. These observations suggest that the period after the peak of the storm may often play a significant role in returning sediments to the upper shoreface.

Consider a profile in equilibrium that experiences a storm; the response of the profile is to flatten and for sediment to be transported from the upper shoreface to the lower shoreface. A time lag is associated with the time it takes to move sediment, thus while the bulk of sediment transport occurs at the peak of the storm, sediment is still transported offshore to flatten the profile after the peak of the storm. At some instant in time the profile is in equilibrium, with the falling wave heights and the trend of sediment transport changes from offshore to onshore initiating a period of recovery. Recovery continues until wave heights fall below that which is required to re-suspend sediments. Several factors become important in determining the recoverability of a profile from a storm event. The key aspects of the wave height profile are:

1. The peak wave heights reached and for how long they are sustained; and
2. How rapidly wave height decays after the peak of the storm.

This first aspect is, in essence, an indicator of how far from equilibrium the peak storm profile is from the modal profile (Figure 7.1), while the duration of peak wave heights indicates how close the system is likely to reach the equilibrium storm profile (Figure 7.1).
This aspect also determines how soon the system can attain recovery of the profile; the longer the duration of the peak of the storm the closer the profile is to reaching equilibrium for the peak storm conditions. The second aspect determines how long the system has to recover from the perturbation before waves fall below the threshold required to transport sediments. A slow reduction in wave heights will allow a greater period for the recovery of the profile.

7.4.1.2. Influence of Storm Recovery

When a storm occurs, sediments on the lower shoreface are unconsolidated and readily mobilised by energy from breaking waves. Giant motions of surf zone sediment are often associated with storm waves, resulting in onshore transport (Event 13), suggesting that sediments on the lower shoreface period were sufficiently mobile to prevent full recovery of the pre-storm profile during the storm. Given the onshore velocities were the result of wave induced transport, this indicated severe storm conditions as a contributing factor to the direction of sediment transport. Under this scenario, extratropical storms are an important consideration in the prediction of profile response to the storm. It also highlights the importance of subsequent lower energy storms in aiding the recovery of the shoreface.

7.5.1. Wave-Generated Rip Currents

Two popular theories propose the generation of rip currents. One is wave setup associated with the generation of longshore currents driven by wave breaking. Another is due to depth contour changes between energy dissipation near the bar and over the rip channel. The latter being lower. This difference in water surface driven the circulation, in the rip current scenario with waves normal to the shoreline, waves reflect along the headlands forming energy while also driving incident wave energy associated to the headlands as shown in Figure 7.2a. An asymmetry develops near the wave setup with flow setup being higher at the shoreline.

Figure 7.1: Schematic diagram of storm profiles and wave heights throughout Event 13, showing: the equilibrium profile prior to the storm, A at time T_1; the storm profile as predicted by maximum wave height, C at time T_3; and the actual storm profile during the storm, B at time T_4.
This aspect also determines how soon the system can initiate recovery of the profile; the longer the duration of the peak of the storm the closer the profile is to reaching equilibrium for the peak storm conditions. The second aspect determines how long the system has to recover from the perturbation before waves fall below the threshold required to transport sediment. A slow reduction in wave heights will allow a greater period for the recovery of the profile.

7.4.4 Importance of Storm Recurrence
While the most severe storm (Event 13) observed during the study resulted in offshore sediment transport on the lower shoreface, the next storm to significantly mobilise sediments on the lower shoreface resulted in onshore transport (Event 18), suggesting that sediments in the intervening period were sufficiently immobile to prevent full recovery of the profile some six months later. Given the onshore velocities were the result of wave processes, this indicated antecedence conditions as a contributing factor to the direction of sediment transport. Under this assumption, antecedent storms are an important consideration in the prediction of profile response to any given storm. It also highlights the importance of subsequent lower energy storms in aiding the recovery of the lower shoreface profile, particularly when the intervening fair-weather periods are insufficient to mobilise sediments on the lower shoreface. To better assess these hypotheses a study with more intensive seabed mapping and surveying of profiles is required.

7.5 Mega-rip synthesis
7.5.1 Mechanism responsible for mega-rip formation
Two possible mechanisms exist for the generation of mega-rips: a wave setup-generated current and alongshore currents driven by waves breaking oblique to depth contours (Komar, 1978). Considering wave setup, for normal bar and rip morphology an imbalance exists between energy dissipation over the bar and over the rip channel, the latter being lower. This difference in water surface drives the circulation. In the mega-rip scenario with waves normal to the embayment, waves refract onto headlands focusing energy while also diverging incident wave energy adjacent to the headlands as shown in Figure 7.2a. An alongshore disparity now exists in wave setup with wave setup being higher at the centre of the embayment, resulting in flow away from the centre. When waves are oblique to the embayment a shadow zone is created by diffraction in lee of the headland and setup would
Figure 7.2: Theoretical position of rip when considering: a) wave setup and waves approaching normal to the embayment; and b) wave setup and waves approaching oblique to the embayment.
thus be less in lee of the headland, such that the formation of a rip on the lee side of the headland is predicted (Figure 7.2b).

Considering alongshore currents driven by waves oblique to contours, on an arcuate embayment, normally incident waves generate alongshore currents that converge toward the centre of the embayment (Figure 7.3a). This requires an assumption that the shape of the embayment is not in equilibrium with the given wave field, which was somewhat validated for MacMasters beach by the occurrence of these events during storm events when waves were typically not from the modal direction. Convergence of the two currents resulted in deflection and formation of an offshore directed flow. When waves arrive oblique to the embayment an alongshore current is generated that is impeded by the presence of a headland. This impedance results in deflection of the flow and formation of a rip adjacent to the headland on the exposed side (Figure 7.3b).

Observations made during this study indicated the presence of mega-rips adjacent to the exposed headland and smaller rips occasionally adjacent to the headlands on the lee side (Figure 7.4). The dominant mega-rip forms in a location that supports the alongshore current drive by oblique waves, while the smaller rip at the opposite end of the embayment supports the wave setup model. It is most likely that both mechanisms contribute to the circulation within the embayment, with alongshore currents dominating. This relationship can be investigated further with wave height modelling, which is presented in the following section (Section 7.5.2).

7.5.2 Wave Refraction and Diffraction Within the MacMasters Embayment.
A previous study conducted by Henderson (1983) applied a wave refraction and diffraction model (REF/DIF) to the MacMasters beach embayment. Conclusions made during that study were focussed on identification of storm cut and not the generation of currents, however the results are adequate for discussion in this study.

A nearshore wave coefficient was determined at 6 locations along the MacMasters beach embayment (Figure 7.5). At each of these locations a coefficient for wave height was determined for deep water waves arriving from ENE through to S at 22.5 intervals for a wave with 10s period. Waves approaching normal to the embayment (from the SE) resulted in higher wave coefficients toward the centre of the embayment (Figure 7.6), currents driven by wave set up would thus flow away from the centre of the
Figure 7.3: Theoretical position of rip when considering: a) obliquely incident wave driven current with waves approaching normal to the embayment; and b) obliquely incident wave driven current with waves approaching oblique to the embayment.
Figure 7.4: Generalised pattern of mega-rip under obliquely incident waves when considering currents driven by wave setup and obliquely incident waves.
Figure 7.5: Location of points at which wave height co-efficient were determined.
Figure 7.6: Wave height co-efficients along the shoreline for waves arriving from the SE with a wave period of 10s.
7.5.3 Wave Height Thresholds and Circulation

Embankment breaching by the progradation formation is critical to preserving the presence, size, and location of the embayment at MacMurray Beach. Spatial changes of wave height can cause erosion and damage. The direction relative to the embayment was stabilized at location 7, and a significant erosion occurred when wave heights extended beyond 1.5m (Section 7.4).

A wave height of 2.5-3.0m resulted in destruction of the tip-head over the instrument stations, which were placed near the embayment and on the lower portion of the profile. Wave heights of 1.5-2.0m were observed near the wave, with a wave spectrum angle of 80°-90° and reached the instrument close to or in the water. The peak of the wave height co-efficient was high in the instrument profile, which shows the occurrence of wave height co-efficient in the wave profile. The wave height co-efficient was high in the instrument profile, with a wave spectrum angle of 4.5° and reached the instrument close to or in the water. The peak of the wave height co-efficient was high in the instrument profile, with a wave spectrum angle of 4.5° and reached the instrument close to or in the water.

Figure 7.7: Wave height co-efficient for directions ENE, E, ESE, SE, SSE and S for a 10s period wave at the 6 points along the shoreline.
embayment. Plotting all the data as a surface (Figure 7.7) shows the reduction in wave height resulting from diffraction of the wave field around the headland leading to higher wave setup at the exposed end of the embayment which could drive a current alongshore away from the exposed headland. This, however, opposes the observations made during this study suggesting that wave setup played a lesser role in the generation of mega-rip currents.

7.5.3 Wave Height Thresholds and Circulation

Establishing thresholds for mega-rip formation is critical to predicting the presence, size and location of the phenomenon at MacMasters Beach. Spatial control of mega-rip formation by wave direction relative to the embayment was identified in Section 7.5.1. Disruption of nearshore circulation occurred when wave heights exceeded ~2.5m (Section 3.5.3). Wave heights of 2.5–3.5m resulted in incursions of the rip-head over the instrument site and generally resulted in the mega-rip being placed landward of the instrument site (450m). These incursions were typified by offshore-directed surface 2min time averaged velocities ~ 20–40cms\(^{-1}\). When wave heights exceeded 3.5m, flow at the nearshore site was still directed offshore, however, velocities toward the lower levels of the profile changed from onshore to offshore, while velocities at the surface were measured at 40–60cms\(^{-1}\). For wave heights greater than 4.5m, velocities at the surface averaged 60cms\(^{-1}\) and reached velocities of 130cms\(^{-1}\), while at the seabed velocities averaged 30–40cms\(^{-1}\) and reached velocities of 90cms\(^{-1}\). These high velocities indicated the instrument was close to or in the rip-neck, suggesting the surfzone was over 450m wide.

Overprinted on the average trends was pulsing, which was possibly related to wave grouping in the incident wave field. Pulsing resulted in intensification of the flow, with a seaward extension and growth of the mega-rip (Section 4.4.3). These pulses in rip velocity were responsible for the highest velocities observed at the surface and at the seabed. The peak magnitude of these velocities was equal to the instantaneous wave induced orbital velocities (u_\text{rms}). This signifies the importance of instantaneous recordings of velocities, as opposed to averages, as the average velocity of the offshore mega-rip flow was below the theoretical to erode sediment from the seabed. However, there were periods when velocities were fast enough to erode the seabed. It was noted during this study that sampling periods of hourly averages was not high enough to resolve the pulsing, although two minute averages of the ADCP’s was high enough to resolve the pulsing.
7.5.4 Evolution of Mega-rips During a Storm Event

A distinct pattern for rip growth and decay was apparent throughout all storm events captured on the ADCP’s. Once wave heights reached the threshold to establish mega-rip circulation the observed response to increasing wave heights was offshore growth, the peak in wave heights typically corresponding to the peak in offshore extent. Conversely, as wave heights decreased mega-rips receded until wave heights fell below the threshold required for their formation. Once established mega-rips were prevented from alongshore growth by the presence of the headlands that play an integral role in mega-rip formation.

A positive relationship between observed surfzone width and mega-rip offshore extent was identified, where mega-rips were typically 1.5 times further offshore the width of the surfzone. The offshore extent of the surfzone is defined by the point of breaking with the breaking wave height occurring in a water depth that is defined by:

\[ h_b = H_b / \gamma \ldots \text{E.7.1} \]

where a value of 0.78 is prescribed for \( \gamma \) by solitary wave theory (McGowan, 1894). A surfzone width can be determined by simple trigonometry whereby:

\[ X_s = \frac{H_b}{\gamma} \sin \beta \ldots \text{E7.2} \]

applying the correction factor of 1.5 to obtain a relationship for the offshore extent of mega-rips as determined in Section 5.6.6 yields:

\[ O_e = 1.5 \frac{H_b}{\gamma} \sin \beta \ldots \text{7.3} \]

Application of Equation 7.3 to determine the offshore extent of the mega-rips to the limited observations made during this study period showed the use of \( H_b \) tended to underestimate the offshore extent of mega-rips. Given the sensitivity of the mega-rip growth and hence offshore extent to wave grouping is a possible source for the underestimation. The random nature of wave heights has been noted as affecting \( \gamma \) and hence the validity of using a solitary wave breaker criterion on natural beaches is questionable. The use of \( H_{rms} \) has been adopted to give a new criteria which is the random wave equivalent, \( \langle \gamma \rangle \) (Masselink and Hegge, 1995). As values for \( H_{rms} \) were not known for the observations this can’t be pursued.
Table 5.1: Comparison of the observed offshore mega-rip extent ($O_{\text{obs}}$) with values calculated using $y=0.78$ and $H_b$ ($O_{cb}$) and $H_{\text{max}}$ ($O_{cmax}$).

<table>
<thead>
<tr>
<th>$H_b$ (m)</th>
<th>$H_{\text{max}}$ (m)</th>
<th>$O_{cb}$ (m)</th>
<th>$O_{cmax}$ (m)</th>
<th>$O_{\text{obs}}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>6</td>
<td>504</td>
<td>672</td>
<td>700</td>
</tr>
<tr>
<td>4.3</td>
<td>5</td>
<td>482</td>
<td>560</td>
<td>560</td>
</tr>
<tr>
<td>4.5</td>
<td>6</td>
<td>504</td>
<td>672</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>336</td>
<td>785</td>
<td>600</td>
</tr>
</tbody>
</table>

Pulsing formed an integral part of mega-rip flow and was persistent throughout all storms. Pulsing has been previously identified in rip studies and attributed to tidal modulation (Brander, 1999) and infra-gravity standing waves (MacMahan et al., 2004). However, in this study no relationship was established between tidal modulation and rip current strength and hence it is likely that pulsing was generated by either wave group forcing or infra-gravity standing waves. A potential cause for pulsing was wave grouping were large sets of waves resulted in growth of the mega-rip and a subsequent rise in rip velocities due to closer proximity to the rip-neck. A time lag between the wave groups and the peak in velocities was identified and a degree of state dependence was noted. However, it could not be said definitively whether wave grouping was responsible.

7.5.5 Zones of erosion and deposition associated with mega-rips

The most important consideration of mega-rips is their ability to transport sediments within and out of the embayment. A dominant zone of deposition was identified as the proximal rip-head bar and was associated with the rip-head. During the largest storm an accumulation of 56,000m$^3$ sediments was associated with this feature. These sediments were deposited in the 10–17m depth range and corresponded to a bed elevation change of 75cm. These sediments were deposited as a result of flow deceleration in the rip-head and indicate the dominant position of the rip-head. A distal rip-head bar was also identified and resulted in the accumulation of 5,500 m$^3$ in the 17–25m depth range and corresponded to a change in bed elevation of 4cm. These sediments were may be associated with the rip-head at its greatest offshore extent at the height of the storm or the advection of the rip-head under its own momentum.

The source of sediments that formed the proximal and distal rip-head bars was the beachface and upper shoreface. Sediments derived from the beachface were attributed to typical storm processes of swash runup and elevated water table and were consistent with observations made during Event 13 (Figure 7.8). A large alongshore channel was apparent in the bathymetric data that fed into the proximal rip-head bar and was concurrent with the
Figure 7.8: Example of swash processes responsible for removing sediment from the beachface during Event 13.
location of the alongshore current feeding the mega-rip. Velocities in feeder channels were likely to have been comparable to those observed in the rip-neck (Brander, 1999) and thus, on their own, were capable of scouring a channel. This action combined with advection of sediments suspended by breaking waves contributed to the supply of sediments.

Extensive sediment plumes observed during the study indicate that sediments were being carried much further offshore than indicated by the bathymetric surveys. The grainsize of the sediment contained within these plumes is unknown, however, taking into account the hydrodynamic properties measured during the study it is likely that these plumes represent wash-load and not the modal grainsize. At times these plumes were over 1.5km offshore with corresponding water depths of 35–40m. The seaward edge of these plumes was distinct, forming a front that extended further seaward adjacent to the headlands. Identifying the processes involved in generating the plumes was not possible, however, it is speculated that plumes consisted of fine sediments suspended by mixing within the surfzone. It was possible the distinct nature of the plume front was produced by a balance in onshore directed surface water by downwelling and the offshore-directed diffusion associated with surfzone mixing. The extension of the front further seaward adjacent to the headlands was likely to be produced by the breaking of waves on the headlands and the resultant mixing. However, several cases were observed where flow associated with mega-rips was responsible for the generation of sediment plumes (Figure 6.8).

7.5.6 Theoretical Shoreline Response to Sediment Erosion
It is pertinent to consider the implications of several factors addressed thus far. Firstly, sediments in the distal rip-head bar were taken as far offshore as the outer site (lower shoreface) and totalled 6,000m³, while sediments in the proximal rip-head bar were taken as far offshore as the nearshore site and totalled 60,000m³. Secondly, a significant proportion of the profile recovery occurred in the latter stages of a storm event. Thirdly, data used to determine bed level changes were collected well after the storm event and the major recovery period. Finally, sediments on the lower shoreface have been identified as being relatively immobile during fair-weather conditions. These factors strongly suggest that sediments delivered offshore by mega-rips will have a long return period.

Considering a simplified case where the measured across-shore profile conforms to the equilibrium profile for the entire width of the embayment prior to the storm (Figure 7.9),
Figure 7.9: Schematic diagram of calculated shoreline change after removal of sediments contained in the proximal and distal rip-head bar (66,000m$^3$=15cm change in shoreline) and the distal rip-head bar only (6,000m$^3$=1.5cm change in shoreline).
removing the volume of sediment contained in both the distal rip-head bar (6,000 m$^3$) and the proximal rip-head bar (60,000 m$^3$) results in a new profile. This new profile has regressed 15 cm from its previous position and is likely to have a relatively short residence time as 90% of the sediments are in an area of high mobility. However, 10% of the sediment was contained in the distal rip-head bar and contributed 1.5 cm of shoreline regression. Given the location of these sediments they were more likely to have a much longer residence time. Therefore, over the short-term (immediately after the storm) a significant regression of the shoreline is likely, which gradually recovers over the medium term (up to 12 months after the storm), with full recovery in the long-term (several years).

A notable caveat exists in this simplified case: the recurrence of storms, in particular severe storms. The more frequent the severe storms the more likely that losses of sediments to the lower shoreface will have permanence and more profound implications for the shoreline.

7.5.7 Lateral Sediment Transport Response
Following on from the above section the bulk of the sediment located in the proximal rip-head bar is likely to return to the beach face. This raises the question of how the sediment is redistributed along the beach face, given that sediments were removed from the whole beach face and placed at the northern end of the embayment in a water depth of ~10 m. It has been shown for embayed beaches that the beach planform attempts to achieve an equilibrium defined by the refraction pattern of waves entering the embayment (Davies, 1958). Irregularities in the shoreline are removed by currents generated as a result of waves arriving obliquely to the morphology. This coupled with onshore migration of the sediment body as is typified by onshore bar migration under decreased energy conditions is expected to occur. It is speculated that for the case of MacMasters Beach that the modal wave climate from the SE and the presence of the proximal rip head bar would likely migrate onshore and extend to the S until the shoreface reaches equilibrium.

7.5.8 A Definition for Mega-rips – Topographically arrested rips versus Mega-rips.
There are two paths that can be taken in defining mega-rips: 1) a definition which is independent of scale and would result in topographically controlled rips in small embayments under modal wave conditions being called mega-rips; or 2) a definition which is dependent on scale that takes into consideration the size of the embayment relative to the hydrodynamics, and is the one preferred by the Author. The most important aspect of
defining a mega-rip, applies to both definitions, and is the rip spacing versus embayment length. The distinction between the two definitions comes by identifying the rip spacing under modal wave conditions, which in order for the second definition to hold must be less than one, indicating multiple rips occupy the embayment under modal wave conditions. Observational evidence made by Martens et al. (1993) suggests that small embayments (ones that have one rip occupying the whole embayment under modal wave conditions) may become morphologically insignificant under storm conditions, with the hydrodynamics being so over-sized that a mega-rip was controlled by morphology on a much larger scale. (Figure 7.10). In order to fully validate the use of the definition further study is required into rip spacing under various wave conditions on embayments of varying size.

7.6 Importance of Mega-rips to Coastal Morphodynamics

7.6.1 Impact of Mega-rips on Embayed Coasts

Mega-rips have the potential to influence coastal morphodynamics in several ways. Firstly, being a storm related phenomenon they transform nearshore morphology rapidly in accordance with their hydrodynamic features, namely the longshore feeder and rip-neck current. Secondly, they deliver large quantities of sediment to the outer surfzone and lesser quantities further offshore onto the lower shoreface.

The first possible impact of sediment delivered to the lower shoreface is minor and sees their return to the upper shoreface over a longer time period (as discussed in Section 7.5.6). A second possible impact is that the sediments remain in these water depths, unable to return and thus form inner-shelf sand bodies as have been recorded in the Sydney region (Field and Roy, 1984). A third possibility is that these sediments are transported alongshore by currents and thus take part in processes such as headland sand bypassing.

It is an important consideration that this phenomenon requires an embayed morphology or structure analogous to the headlands. Thus, mega-rips have the potential to influence coasts that have human-made structures such as groins or seawalls.

Embayments of the Sydney region are traditionally seen as closed sedimentological systems with the headlands acting as barriers, preventing coastal sediments from being transported north by littoral drift (Davies, 1974). However, the very barriers that form the embayment may now provide an additional means for the offshore transport of upper shoreface sediments to the lower shoreface where a weak northerly-directed current exists.
It is therefore possible that sediments, whilst generally impermeable, are not entirely prevented from accumulating offshore. The importance of seaward transported sediments is a function of the offshore depth of the headlands that define the embayment and the varying tide exist on the lower shoreface.

The sediment delivered to the lower shoreface by mega-tips if unreported alongshore may be transported further as a plume or coarsely gravelly. The way in which these sediments are transported depends on the rate of supply versus the rate of movement of such mega-tips may play a role in the phenomena of sand by-passing as observed along the NSW coast.

The boundary of a wave trough is viewed as being logarithmic, and any length of a wave may be considered as an element in wave theory. The wave motion is described by the solution of a one-dimensional wave equation.

The diagrams show a portion of land behind outlines of the embayment and in a new location the wave, formations, sand by-passing, etc., are described by Mathay (1945).

7.7 Implications on Coastal Morphology

The boundary of the embayment is viewed as being logarithmic, and any length of a wave may be considered as an element in wave theory. The wave motion is described by the solution of a one-dimensional wave equation.

At this stage, the processes responsible for generating the non-linearities present are not known, although it is speculated that they may result from turbulence. The phenomenon of plunging waves is

Figure 7.10: Mega-rip position in a composite embayment (reproduced from Martens et al., 1993)
It is therefore possible that sediments, whilst severely impeded, are not entirely prevented from northward transport. The impedance of northerly transported sediment is a function of the offshore extent of the headlands that define the embayment and the currents that exist on the lower shoreface.

The sediments delivered to the lower shoreface by mega-rips if transported alongshore may be transported either as a pulse or released gradually. The way in which, these sediment are transported depends on the rate of supply versus the rate of removal. As such mega-rips may play a role in the phenomena of sand by-passing, as observed along the NSW coast. Given the onshore nature of fair-weather transport on the lower shoreface losses of sediments from an embayment are in likely to be balanced by the same processes acting in down-drift embayments.

7.6.2 Response Sea Level Variations
In the case of the Sydney region under lower sea-level scenarios, the impact of mega-rips would be largely reduced as much of the embayment morphology does not extend to the mid- and outer-shelf (Chapman et al., 1984) where the shoreline has been located during lowstands in sea-level (Roy and Thom, 1981). Under higher sea-levels, their activity is unlikely to change as much of the embayment morphology persists at higher elevations. Transgression of the shoreline with the presence of headlands introduces the possibility that mega-rips may play a role in the formation of sand bodies offshore of the headlands and is a process consistent with the perceived sand body formations noted by Field and Roy (1984).

7.7 Implications of Mega-rips on Coastal Modelling
7.7.1 Boundary Layer Models
The boundary layer profile for currents is viewed as being logarithmic and as such any departure from the logarithmic profile will result in errors in flow circulation. Observations of a non-logarithmic profile for significant periods of time during this study imply significant errors may occur when attempting to accurately model flow associated with mega-rips. At this stage the processes responsible for generating the non-logarithmic profiles are not known, although it is speculated that they may result from turbulence associated with plunging waves. If these processes are responsible it is likely that the change in profile may be accounted for by a turbulent injection term that is applied in the presence of plunging waves (Figure 7.11). The classification of plunging waves is
Figure 7.11: Possible mechanism responsible for observed shape of boundary layer profile.
dependant on wave steepness which, in turn is a function of seabed slope, wave height and period and current velocity. Inherent in this observation is the need for the model to be truly 3 dimensional and indicates that for embayed beaches simple 2 dimensional models of water circulation are inadequate.

7.7.2 Sediment Transport models
In a similar context to the modelling of boundary layers in Section 7.7.1, sediment concentration profile can be defined by equations such as:

\[ \bar{c}(z) = c_o \exp(-z/l) \] E7.3

formulated by Nielsen et al. (1982), where sediment concentration decreases exponentially away from the bed. Qualitative data collected by the ADCPs (echo intensity) in the rip showed distinctly higher concentrations in the upper levels. These values were associated with higher amounts of reflectors in the water column and thus may be attributed to water bubbles, sediment or organic matter. Nonetheless, it suggests further study is required with an additional degree of complexity when attempting to model sediment transport in association with mega-rips.
Chapter Eight

Conclusions and Suggestions for Further Work
8.1 General Conclusions

This study has achieved the aims and objectives as stated in Chapter 1

1) Identification of the key hydrodynamic processes active in the field area during fair-weather conditions:

- Wave agitation across the shoreface was the most significant process in terms of instantaneous velocities.
- Mean flows associated with tides were active across the entire shoreface, with a dominant $K_1$ tidal constituent.
- Internal waves were only observed on the lower shoreface, their absence on the upper shoreface being attributed to a higher degree of mixing associated with the surfzone.

2) Identification of the key hydrodynamic processes active in the field area during storm events:

- Tidal flow on the upper shoreface was disrupted when waves exceeded 3m.
- Similarly, internal waves on the lower shoreface were disrupted by waves exceeding 2.5m.
- By far the dominant processes within the embayment were mega-rips occupying the entire embayment.

3) Identification of the processes that generate mega-rips in the embayment:

- Evidence presented in this thesis strongly suggests the primary mechanism involved in forming mega-rips is oblique wave incidence, which generates an alongshore current that is deflected offshore by a headland.
- To a lesser extent wave setup played a role in generating a second smaller rip at the opposite end of the embayment to the primary current.

4) Assessment of the potential for mega-rips to transport sediment:

- Mega-rips played a significant role in transporting sediment offshore. During one event ~60,000m$^3$ of sediment were delivered as far as 900m offshore by a mega-rip.
- Extensive plumes of sediment were also observed more than 1km offshore and were associated with mega-rips.
5) Documentation of the hydrodynamic characteristics of mega-rips:

- The fastest current measured within a mega-rip was 130 cms\(^{-1}\) occurring at the surface in 15m of water. During the same event at the same water depth the fastest current measured at the seabed was 90 cms\(^{-1}\).

- Velocities within a mega-rip increased with larger wave groups, the increase occurring in conjunction with a growth in the offshore extent of the mega-rip.

- The offshore extent of mega-rips was typically 1.5 times the width of the surfzone, and was observed to extend over 900m from the shore.

8.2 Suggestions for further work

Additional research is required on aspects of mega-rips and fair-weather processes. These include:

- The role embayment shape plays on mega-rip characteristics.

- The coupling between wave groups and pulsing in the rip channel flow.

- The velocity and spatial aspects of the feeder system.

- The role mega-rips play in headland sand bypassing.

- The dominance of the K\(_1\) tidal constituent in the current velocities measured on the inner-shelf and its possible link to “short period” coastal trapped waves.

- The contribution of wind-driven currents to downwelling and the velocities on the inner-shelf associated with it.

- Consolidate sediment transport paths with tracer experiments.

8.3 Final Comments

In conclusion, the original and demanding research project presented in this thesis has provided considerable insight into the phenomenon of mega-rips. In addition, this study has shown the fair-weather processes active on inner-shelf of the Sydney region and their transformation by storm events.
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Appendix A

Appendix A1

function data_out=fir(lowpass(data_in, Fsample, Fcutoff, N))
% Fsample is the sample frequency, Fcutoff is the frequency cutoff and N is the order of the
% filter
% Note the filter order will determine how sharp the frequency cutoff is, the length of the data
% series will be shortened by half the order number and offset by half the order number.
if (nargin<=4)
    error('Requires 4 input arguments (input data, sample frequency, cutoff frequency, filter order)');
end
Fc=Fcutoff/(0.5*Fsample);
dlen=length(data_in);
B=fir1(N,Fc,kaiser(N+1,0));
int1=filter(B,1,data_in);
data_out=int1(N/2+1:dlen);
end

Appendix A2

% INVPEPSR - Computes inverse perspective transform for plane rectification.
% Function calculates the 3x3 homogeneous inverse transformation matrix
% describing the perspective transformation of a planar surface in an
% image. This can then be passed to imTrans to perform a rectification of
% the surface. Four or more known image points are required.
% Usage: [T, err] = invpersp(refpts, pts)
% Arguments:
%   refpts - Array of reference points [x1 x2 ... xn
%            y1 y2 ... yn] (n>=4)
%   pts - Array of image points [x1 x2 ... xn
%            y1 y2 ... yn]
% Returns:
%   T - The 3x3 homogeneous transformation matrix
%   err - Consistency errors (only meaningful for n > 4 points)
% See also: imTrans.
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% July 2001
function [T, err] = invpersp(refpts, pts)
[refrows, refnpts] = size(refpts);
[rows, npts] = size(pts);
if rows ~= 2 | refrows ~= 2
    error('Data points must be in the form of a 2xN array');
end
if npts ~= refnpts
    error('Data arrays must be of same size');
end
if npts < 4
    error('Need at least 4 data points');
end
end
x = pts(1,:); y = pts(2,:);  % Extract data in a convenient form
xref = refpts(1,:); yref = refpts(2,:);
% Set up equations to be solved
M = zeros(2*npts, 8);           % Allocate memory
XY = zeros(2*npts,1);
for n = 1:npts
    M(2*n-1,:) = [x(n) y(n) 1 0 0 0 -x(n)*xref(n) -y(n)*xref(n)];
    M(2*n,:)  = [ 0 0 0 x(n) y(n) 1 -x(n)*yref(n) -y(n)*yref(n)];
    XY(2*n-1) = xref(n);
    XY(2*n)    = yref(n);
end
A = MXY;
A(9) = 1;
T = reshape(A,3,3);
err = [ ];
if npts > 4
    % Apply transformation to image points and compare against
    % reference points to check consistency.
    newxy = T*[x;y;ones(1,npts)];
    newxy(1,:) = newxy(1,:)/newxy(3,:);
    newxy(2,:) = newxy(2,:)/newxy(3,:);
    dxdysqrd = (newxy(1:2,:)-refpts).^2;
    err = sqrt(dxdysqrd(1,:)+dxdysqrd(2,:));
end

Appendix A3
% IMTRANS - Homogeneous transformation of an image.
% Applies a geometric transform to an image.
% [newim, newT] = imTrans(im, T, region, sze);
% Arguments:
% im       - The image to be transformed.
% T        - The 3x3 homogeneous transformation matrix.
% region   - An optional 4 element vector specifying
%            [minrow maxrow mincol maxcol] to transform.
%            This defaults to the whole image if you omit it
%            or specify it as an empty array [].
% sze       - An optional desired size of the transformed image
%            (this is the maximum No of rows or columns).
%            This defaults to the maximum of the rows and columns
%            of the original image.
% Returns:
% newim    - The transformed image.
% newT     - The transformation matrix that relates transformed
%            image coordinates to the reference coordinates for use in a
%            function such as DIGIPLANE.
% The region argument is used when one is inverting a perspective
% transformation of a plane and the vanishing line of the plane lies
% within the image. Attempts to transform any part of the vanishing line will
% position you at infinity. Accordingly one should specify a region that
% excludes any part of the vanishing line.
% The sze parameter is optionally used to control the size of the
% output image. When inverting a perspective or affine transformation
% the scale parameter is unknown/arbitrary, and without specifying
% it explicitly the transformed image can end up being very small
% or very large.
% Problems: If your transformed image ends up as being two small bits of
% image separated by a large black area then the chances are that you have
% included the vanishing line of the plane within the specified region to
% transform. If your image degenerates to a very thin triangular shape
% part of your region is probably very close to the vanishing line of the
% plane.
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% April 2000 - original version.
% July 2001 - transformation of region boundaries corrected.
function [newim, newT] = imTrans(im, T, region, sze);
    if isa(im,'uint8')
        im = double(im); % Make sure image is double
    end

    % Set up default region and transformed image size values
    [rows cols depth] = size(im);
    if nargin == 2
        region = [1 rows 1 cols];
        sze = max([rows cols]);
    elseif nargin == 3
        sze = max([rows cols]);
    end

    if isempty(region)
        region = [1 rows 1 cols];
    end

    threeD = (ndims(im)==3); % A colour image
    if threeD % Transform red, green, blue components separately
        im = im/255;
        [r, newT] = transformImage(im(:,:,1), T, region, sze);
        [g, newT] = transformImage(im(:,:,2), T, region, sze);
        [b, newT] = transformImage(im(:,:,3), T, region, sze);
        newim = repmat(uint8(0),[size(r),3]);
        newim(:,:,1) = uint8(round(r*255));
        newim(:,:,2) = uint8(round(g*255));
        newim(:,:,3) = uint8(round(b*255));
    else % Assume the image is greyscale
        [newim, newT] = transformImage(im, T, region, sze);
    end

%----------------------------------------------------------------------------
% The internal function that does all the work
function [newim, newT] = transformImage(im, T, region, sze);
    [rows, cols] = size(im);
    if 0 % Determine default parameters if needed
        region = [1 rows 1 cols];
    end
sze = max(rows,cols);
elseif nargin == 3
    sze = max(rows,cols);
elseif nargin == 4
    error('Incorrect arguments to imtrans');
end

% Cut the image down to the specified region
if nargin == 3 | nargin == 4
    im = im(region(1):region(2), region(3):region(4));
    [rows, cols] = size(im);
end

% Find where corners go - this sets the bounds on the final image
B = bounds(T,region);
ncols = B(4) - B(3);
nrows = B(2) - B(1);

% Determine any rescaling needed
s = sze/max(nrows,ncols);
S = [s 0 0 0; 0 s 0 0; 0 0 1];
T = S*T;
Tinv = inv(T);

% Recalculate the bounds of the new (scaled) image to be generated
B = bounds(T,region);
ncols = B(4) - B(3);
nrows = B(2) - B(1);

% Construct a transformation matrix that relates transformed image
% coordinates to the reference coordinates for use in a function such as
% DIGIPLANE. This transformation is just an inverse of a scaling and
% origin shift.
newT = inv(S - [0 0 B(3); 0 0 B(1); 0 0 0]);

% Set things up for the image transformation.
newim = zeros(nrows,ncols);
[xi,yi] = meshgrid(1:ncols,1:nrows); % All possible xy coords in the
image.

% Transform these xy coords to determine where to interpolate values
% from. Note we have to work relative to x=B(3) and y=B(1).
svx = homoTrans(Tinv, [xi(:);'+B(3); yi(:);'+B(1); ones(1,ncols*nrows)]);
sxy = reshape(svx(1,:),nrows,ncols);
yi = reshape(svx(2,:),nrows,ncols);
[x,y] = meshgrid(1:cols,1:rows);
x = x+region(3)-1; % Offset x and y relative to region origin.
y = y+region(1)-1;
newim = interp2(x,y,double(im),xi,yi); % Interpolate values from source
image.

% Plot bounding region

P = [region(3) region(4) region(4) region(3)
     region(1) region(1) region(2) region(2)
     1 1 1 1 ];
B = round(homoTrans(T,P));
% Bx = B(1,:);
% By = B(2,:);
% Bx = Bx-min(Bx): Bx(5)=Bx(1);
% By = By-min(By): By(5)=By(1);
% show(newim,2), axis xy
% line(Bx,By,'Color',[1 0 0],'LineWidth',2);
% end plot bounding region

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% Internal function to find where the corners of a region, R
% defined by [minrow maxrow mincol maxcol] are transformed to
% by transform T and returns the bounds, B in the form
% [minrow maxrow mincol maxcol]
function B = bounds(T, R)
P = [R(3) R(4) R(4) R(3)] % homogeneous coords of region corners
    R(1) R(1) R(2) R(2)
    1 1 1 1 ];
PT = round(homoTrans(T,P));
B = [min(PT(2,:)) max(PT(2,:)) min(PT(1,:)) max(PT(1,:))];
% minrow    maxrow    mincol    maxcol

Appendix A4

% DIGIPLANE - Digitise and transform points within a planar region in an
% image.  This function allows you to digitise points within a planar region of
% an
% image for which an inverse perspective transformation has been
% determined using, say, INVPERSP. The digitised points are then
% transformed into coordinates defined in terms of the reference frame.
% Usage: pts = digiplane(im, T, xyij)
% Arguments:  im    - Image.
%             T    - Inverse perspective transform.
%             xyij - An optional string 'xy' or 'ij' indicating what
%                     coordinate system should be used when displaying
%                     the image.
%                     xy - cartesian system with origin at bottom-left.
%                     ij  - 'matrix' system with origin at top-left.
%                 An image which has been rectified, say using
%                 imTrans, may want 'xy' set.
%          Usage: pts = digiplane(im, T, xyij)
% Returns:  pts    - Nx2 array of transformed (x,y) coordinates.
% See also:  invpersp, imTrans
% Examples of use:
% Assuming you have an image 'im' for which you have a set of image
% points 'impts' and a corresponding set of reference points
% 'refpts'.
% T = invpersp(refpts, impts); % Compute perspective transformation.
% p = digiplane(im,T); % Digitise points in original image.
% % or work with the rectified image
% [newim, newT] = imTrans(im,T); % Rectify image using T from above
% p = digiplane(newim,newT); % Digitise points in rectified
% image.
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% August 2001
function pts = digiplane(im, T, xyij)
    if nargin < 3
        xyij = 'ij';
    end
    pts = [];
    figure(1), clf, imshow(im), axis(xyij), hold on
    fprintf('Digitise points in the image with the left mouse button\n');
    fprintf('Click any other button to exit\n');
    [x,y,but] = ginput(1);
    while but == 1

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p = T*[x;y;1];        % Transform point.
xp = p(1)/p(3);
yp = p(2)/p(3);
pts = [pts; xp yp];  % Mark coordinates on image.
plot(x,y,'r+');      % Mark coordinates on image.
text(x+3,y-3,sprintf('[%.1f, %.1f]',xp,yp), 'Color',[0 0 1],...
   'FontSize',6);
[x,y, butt] = ginput(1); % Get next point.
end