CHAPTER 1: INTRODUCTION AND STUDY BACKGROUND

1. General introduction to sandy beach ecosystems

Temperate intertidal sandy beach systems

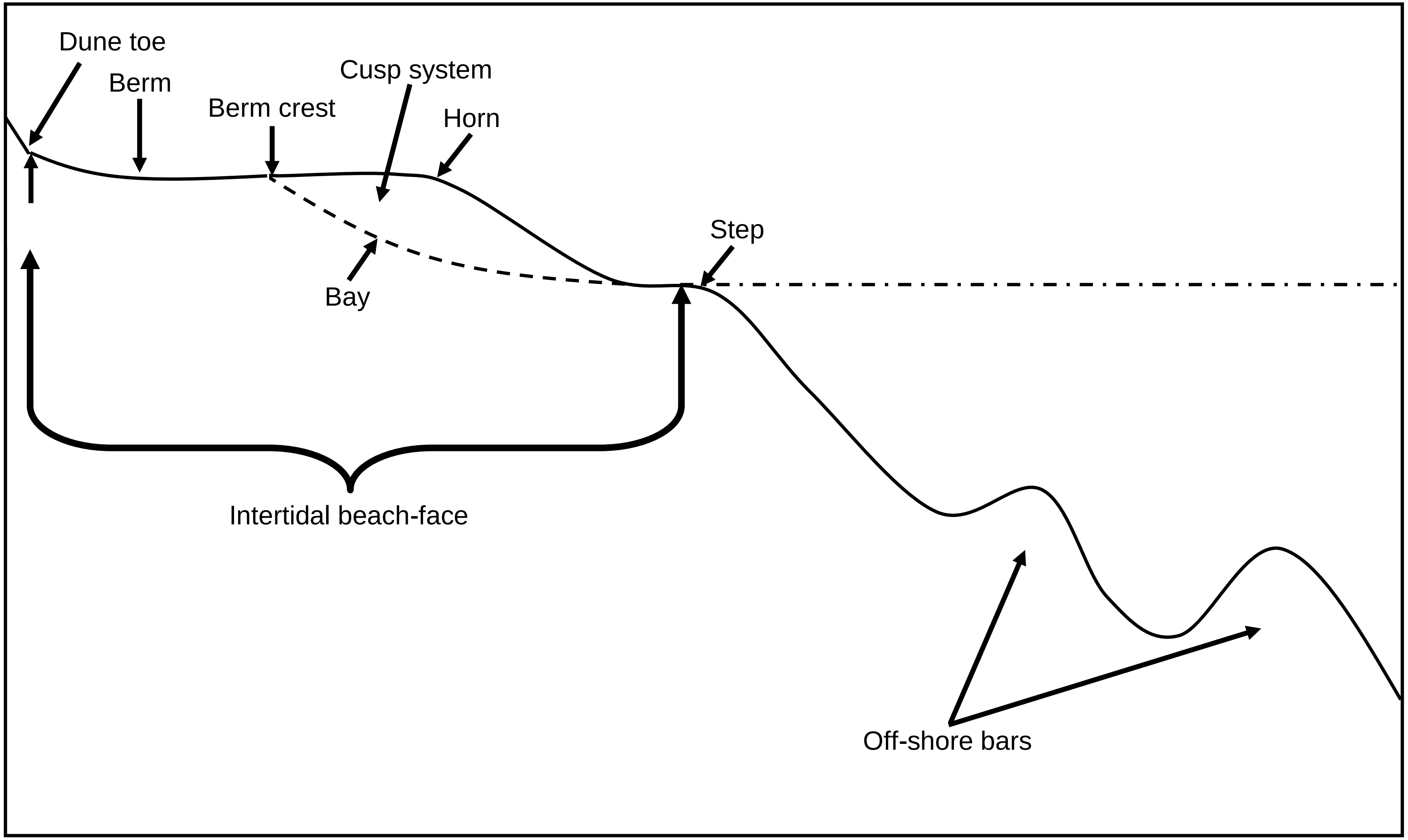
Sandy beaches (hereafter referred to as 'beaches') form one type of 'soft' coastline, characterised by having weakly-consolidated and easily-erodible sediments (Fairbridge 2004). Because of this relative softness or erodability, beaches tend to be highly dynamic, with a physical appearance that is the result of the recent actions of wind, waves and tides on coastal sediment transport (McLachlan & Brown 2006). The dynamic or variable nature of the appearance of the beach-face is the result of changes in the factors that control sediment transport onto and off the intertidal beach, primarily incident wave energy. Such changes can vary in space, time or both. For example, open coastlines, with larger fetches (being the area of ocean upon which climatic forces can act to generate waves) have a higher degree of seasonal variability than protected coastlines with smaller fetches (Aubrey 1983). One of the most obvious changes on temperate beaches are seasonal shifts between a summertime (or 'swell') profile and a wintertime (or 'storm') profile (Komar 1976). A swell profile forms under persistent calm-weather conditions when low incident-wave energy results in sediment deposition onto the intertidal beach and hence accretion, while the storm profile occurs under high-energy wave conditions when sediment is eroded and subsequently deposited as off-shore bars in the surf-zone (Haynes & Boothroyd 1969; Davis & Fox, 1972). While variations in incident wave energy, either temporal or spatial, are often the cause of morphological shifts in beach-face appearance, seasonal shifts in littoral drift direction (movement of sand along a coastline, between beaches) may result in some spatially-close beaches showing contradictory seasonal shifts (i.e. one builds up as the other erodes: Masselink & Pattiaratchi 2001). Temporal variation in beach morphology may occur on time scales other than seasonal cycles. For example, long-term change can occur in response to sea-level and climate change (i.e. on a scale of decades to centuries). On shorter scales, bars migrate on-shore and are then eroded (Masselink *et al.* 2007) and cusps respond to shifts in hydrodynamic conditions (Masselink *et al.* 1997). Extreme short-term variation may be caused by sediment transport associated with tidal influx and efflux of water (i.e. on a scale of minutes to hours; Komar 1976).

Some terminology and definition of main features of beaches

The beach-face itself forms only part of the total sandy-shore system, with the beach, dunes and near-shore surf and wave shoaling zones all connected via the transport of sediments and also biological material (Masselink & Hughes 2003). The intertidal section of the beach is often defined as the part between the spring low-tide level and some upper physiographic change, such as a cliff or dune (Masselink & Hughes 2003). The swash zone is the section of the beach between the low-tide limit and the highest point reached by the swash (i.e. the swash limit), and is the truly intertidal section of the beach, continuously exposed to alternating wet (i.e. high tide) and dry (i.e. low tide) periods (Masselink & Hughes 2003). The upper section of beach between the high-tide swash limit and cliff/dune base is called the back-beach and is comprised of dry sand that is only wetted by the highest spring tides or storm surges (McLachlan & Jaramillo 1995; Masselink & Hughes 2003). The back-beach is part of the intertidal beach and will be referred to throughout this thesis as part of the ‘high-shore’.

Common features of intertidal sections of open-ocean beach-systems include the berm, cusps, step and attached bars (Figure 1.1). The berm is an accumulation of sediment that forms a near-flat section of the beach, generally occurring in the high-shore zone, with a distinct crest or break in slope at its seaward edge (Masselink & Hughes 2003). Cusps are rhythmic, crescent-shaped shoreline features comprised of linked horns and bays (Fig. 1.1) that are formed by swash action and spaced 5 to 50m apart (Masselink & Hughes 2003; McLachlan & Brown 2006). The step is a subtidal scarp, or sharp drop, that forms at the base of the beach and may be between several centimetres to over 1 metre in height (Masselink & Hughes 2003). Attached bars are accumulations of sand that form off-shore and then move onto the beach during accretion periods (Masselink & Hughes 2003). These features do not occur on all beaches, some are typical of certain morphological states (discussed below) and others are seasonal. The berm, for example, is an accretion feature on a summer ‘swell’ profile beach but is eroded and thus lost during storms/winter.

Figure 1.1 An idealised beach system, including back-beach (referred to as high-shore hereafter), beach-face and near-shore morphological features (vertical scale exaggerated)



Classification of beaches into morphodynamic states

Temperate beaches may be classified into morphodynamical states using the Wright and Short model for wave-dominated, microtidal (i.e. tide range <2m) beach systems (Wright & Short 1983; Short 1999, 2006a), using the dimensionless fall velocity or Dean's parameter (Dean 1973):

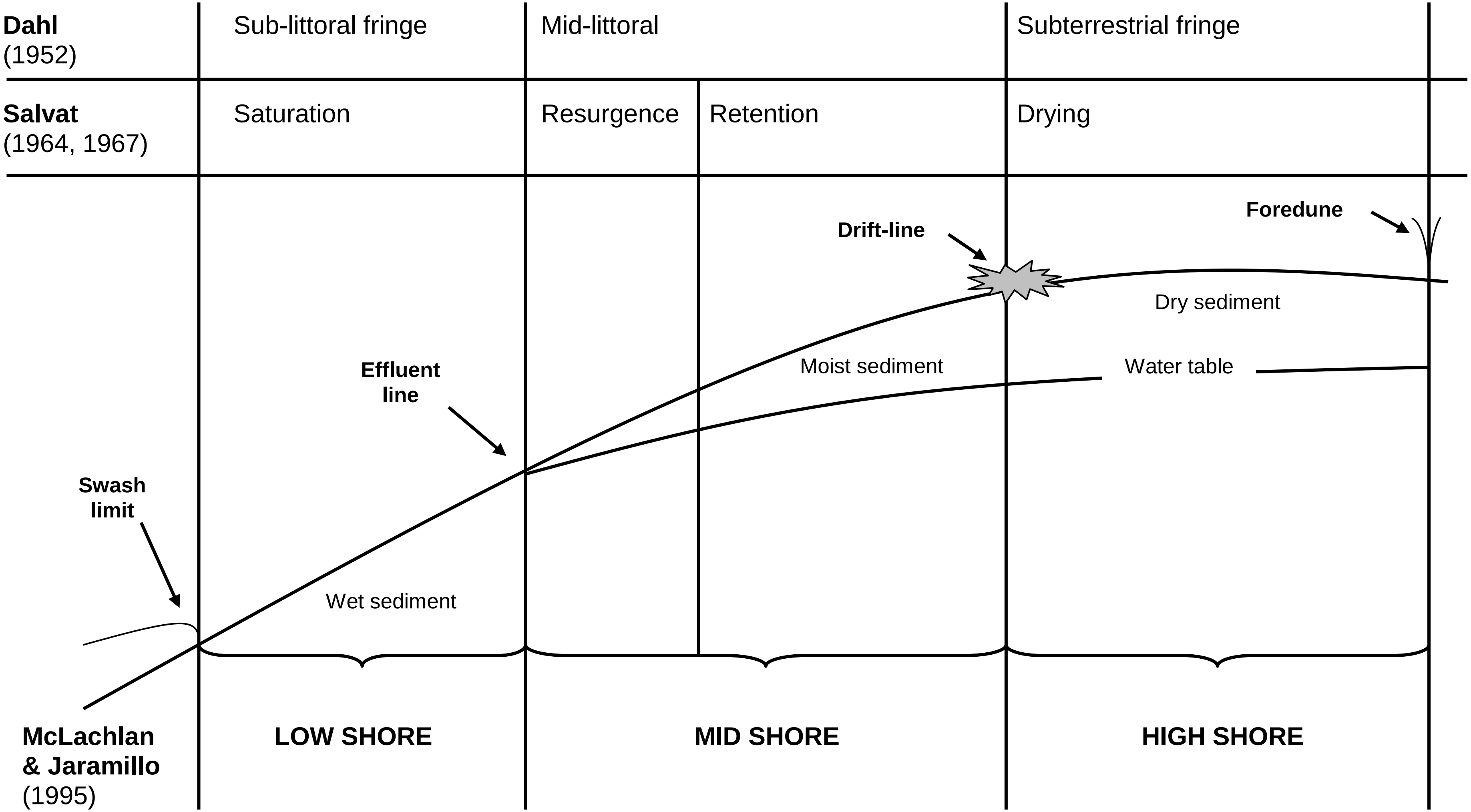
$$\Omega = H_b / W_s T,$$

where H_b equals wave height in metres (m), T equals wave period in seconds (s) and W_s is the sediment grain size defined by fall velocity in $m.s^{-1}$. Microtidal beaches are defined on a spectrum of values for Ω (Short & Wright 1983, 1984; Wright & Short 1984). When sands are coarse and wave energy low, $\Omega < 2$; these beaches are called 'Reflective'. When sands are fine and wave energy is great, $\Omega > 5$; these beaches are called 'Dissipative' (Masselink & Short 1993; Short 1996). Between these extremes, when $2 \geq \Omega \geq 5$, intermediate states occur. In total six microtidal beach states have been identified by this classification scheme, the Reflective and Dissipative extremes and four Intermediate states: Longshore Bar-Trough (LBT: $\Omega = 5$); Rhythmic Bar and Beach (RBB: $\Omega = 4$); Transverse Bar and Beach (TBB: $\Omega = 3$); and Ridge-Runnel or Low Tide Terrace (LTT: $\Omega = 2$) (Wright & Short 1984; Masselink & Short 1993). When relative tidal range (Masselink & Short 1993) and exposure ratings (McLachlan 1980) are also incorporated, it is possible to describe morphodynamic states and exposure levels for all wave-dominated beaches. More recently, Beach Index (McLachlan & Dorvlo 2005) has been developed to similarly describe beaches, including macrotidal sandy beaches, using tide range, beach face slope and sand particle size. BI values of less than 1.5 indicate microtidal reflective beaches while values above 3 indicate macrotidal dissipative beaches (McLachlan & Dorvlo 2005).

Across-beach physical conditions – zonation

Zonation (i.e. across-shore sections of the beach with differing physical [and also biological] characteristics) on the beach-face is also dynamic. This is a result of constant adjustments to swash-zone position which may shift with the tide or in response to changes in weather conditions (McLachlan & Jaramillo 1995). Each zone represents a set of distinct physical conditions (Figure 1.2). McLachlan and Jaramillo (1995) defined the high-shore as the

Figure 1.2 Across-shore physical beach zonation schemes (based on Dahl 1952; Salvat 1964, 1967; McLachlan & Jaramillo 1995).



part of the beach between the recent high tide limit of the swash and the seaward edge of the dunes, and this zone generally contains dry sands (Hesp 1999). The high-shore corresponds to Dahl's (1952) 'subterrestrial fringe' and Salvat's (1964, 1967) 'zone of drying' (Figure 1.2). The mid-shore is defined as the area between the high-tide drift-line (i.e. a high-tide strandline of beach-cast detritus) and water effluent line (where water from the beach-face water table rises to the surface; McLachlan & Jaramillo 1995) and has damp sediments wetted by the most recent high tide. The mid-shore may be absent on very coarse-grained beaches (Jaramillo *et al.* 1993). The mid-shore corresponds to Dahl's (1952) 'midlittoral' but both of Salvat's (1964, 1967) 'zone of retention' and 'zone of resurgence' (Figure 1.2). The low-shore (or sublittoral) zone is characterised by wet sediments and is defined as the area between the effluent line and the swash (McLachlan & Jaramillo 1995). The low-shore corresponds to Dahl's (1952) 'sublittoral fringe' and Salvat's (1964, 1967) 'zone of saturation' (Figure 1.2).

Faunal communities on sandy beaches

Within the 3-dimensional habitat of an intertidal beach, invertebrate organisms may occupy the sand's surface (benthic epifauna), burrow into the sand (benthic infauna), the pore spaces between sand grains (interstitial fauna) or the surface of the grains themselves (epipsammic fauna; Gray & Elliott 2009). Beach fauna may also be divided on the basis of size, although group size-transition points may differ between workers, giving groupings of the macrofauna (metazoans trapped on a 500-1000μm sieve), meiofauna (metazoans passing through a 500-1000μm sieve) and the microfauna (single-celled protozoa; Fenchel 1978). On intertidal beaches macrofauna tend to be dominant in terms of biomass but the microfauna are numerically dominant and more speciose, with meiofauna in-between (Fenchel 1978).

Macrofauna

It is theorised (and widely accepted) that beach macrofaunal populations and communities are regulated by physical processes, with biological regulating mechanisms, such as predation and competition, being of minimal influence, except in cases of relatively-rare benign dissipative states or undisturbed beaches (Defeo & McLachlan 2005; McLachlan & Dorvlo 2005, 2007). Consistent patterns of community abundance, diversity and biomass have been observed between described beach morphodynamical states (based on increasing harshness of the swash conditions from Dissipative to Reflective beaches) and latitudinal gradients (summarised by Defeo & McLachlan 2005; McLachlan & Dorvlo 2005). For microtidal, temperate beaches, abundance and species richness both show a general linear increase at the community level from Reflective to Dissipative beaches, while biomass shows a non-linear but positive relationship with morphodynamic classification (Defeo & McLachlan 2005; McLachlan & Dorvlo 2005; McLachlan & Brown 2006; and references therein). Seasonality in abundance has been observed at the population level (Leber 1982; Haynes & Quinn 1995) but not for total abundance or species richness at the community level (Veloso & Cardoso 2001). However, all of these studies only covered a short time period, with a limited number of seasons being sampled. Zonation patterns of beach macrofauna, based on variable environmental properties, are highly dynamic (Defeo & McLachlan 2005) and so may not be detected by snapshot studies due to the highly dynamic nature of the overall beach environment (Brazeiro & Defeo 1996). Zonation and/or the distribution of representative fauna has been shown to be inconsistent in space and/or time (e.g. Leber 1982; McLachlan 1990; Defeo *et al.* 1992; Haynes & Quinn 1995; James & Fairweather 1996; Defeo & Rueda 2002).

The drift-line

The drift-line is the collection of wrack (i.e. beach-cast, detached macrophytes algae and seagrass), carrion and other detritus (Colombini & Chelazzi 2003) that occurs on most temperate Australian beaches (Kirkman & Kendrick 1997). Where wrack occurs it offers a source of organic matter (detritus) in a habitat that is typically devoid of large primary producers. Wrack provides both food and habitat for intertidal and supralittoral invertebrates on temperate Australian beaches (Ince *et al.* 2007). Wrack occurring on beaches has been shown to enhance the abundance of both terrestrial (Polis & Hurd 1995) and beach invertebrates (McLachlan 1985; Ince *et al.* 2007). Energy and nutrients from decomposed wrack material may be utilised by a food chain up to birds and fish in near-shore marine and terrestrial communities (Kirkman & Kendrick 1997). The occurrence, composition and amount of drift material are often highly dynamic in space and time, and the drift-line is considered to be an ephemeral resource on most beaches (Colombini & Chelazzi 2003). The drift-line may form in any zone of the beach, but typically occurs at the highest point reached by the previous high tide (Fig. 1.1), sometimes with material from previous high-tide deposits found above this point. Where it occurs, the drift-line offers a peak concentration of fauna on the intertidal beach-face, sometimes containing 25% or more of the total macrofaunal populations of a beach (Dugan *et al.* 2003; McLachlan & Brown 2006). Once deposited, wrack material is colonised, utilised and eventually decomposed by beach macroinvertebrates, meiofauna, bacteria and some shorebirds (Inglis 1989; Colombini & Chelazzi 2003; Olabarria *et al.* 2007). The drift-line may also play a role in stabilising the shore-line via providing suitable habitat for colonising plants (i.e. relatively moist and organic-rich conditions on the high-shore) as well as the entrapment and eventually build-up of wind-blown sand, sometimes resulting in the formation of foredunes and dunes (Colombini & Chelazzi 2003). Where beaches are cleaned to remove drift-line material, decreased benefit from wrack decomposition processes is observed (Malm *et al.* 2004).

Meiofauna and the interstitial environment

The water-filled interstitial spaces in beach sands comprise both laminar water streams in the capillary space and surrounding stationary fluid in the cavity space (Webb 1991). Water circulation throughout the sediment is by capillary action, through the interstitial pores of differing diameters, with the widest point in the tube determining the height up the pore through which the water is drawn (Webb 1991). Input of water into the intertidal beach is by capillary action up from the water table to the overlying sediments, and by percolation from the surface of rain, spray, swash or the incoming tide (Komar 1976, Webb 1991). Via percolation, beaches are able to filter large volumes of seawater, thus oxygenating the sediment and providing organic matter to the interstitial ecosystem. Studies by McLachlan and others in the 1980s showed that the volume of seawater that could be filtered increased from fine-grained Dissipative beaches (0.1-7$m^3m^{-1}d^{-1}$; McLachlan 1989) to coarse-grained Reflective ones (10-91 $m^3m^{-1}d^{-1}$; McLachlan *et al.*1985), with Intermediate beaches in-between (3-15 $m^3m^{-1}d^{-1}$; McLachlan 1979). Flushing rates of interstitial water also differed between beach-types, with percolated water having higher residence time in Dissipative beaches (10-400 days) than Intermediate (15-30 hours) or Reflective ones (1-5 hours; McLachlan 1989). Because of the high productivity of Dissipative surf-zones, and the high rate of water filtration on Reflective beaches, both Dissipative and Reflective beaches would be expected to have diverse and abundant interstitial fauna, with diminished richness on Intermediate beaches (McLachlan 1989). However, studies have shown that there is a tendency for a decrease in meiofaunal diversity and density (per m^2) as beach morphotype tends towards the Dissipative extreme (Rodriguez *et al.* 2001; Gheskiere *et al.* 2005; Di Domenico *et al.* 2009) and as exposure rating decreases from exposed to more sheltered conditions (Rodriguez *et al.* 2003). This trend is opposite to that observed for the macrofauna, and is likely due to a response of the meiofauna to more favourable interstitial conditions towards the Reflective extreme of morphotypes.

Meiofaunal organisms inhabit the interstitial environment. These organisms are small defined as those metazoan organisms that can pass through a sieve (typically 0.5 or 1mm mesh) designed to retain the macrofauna (Mare 1942) but are trapped on a smaller (typically 53μm) sieve that separates the meio- and microfauna. Because of this classification, some protozoans (specifically larger ciliates and foraminiferans) may be included in sampling for meiofauna (Fenchel 1978). Meiofauna are distinct from the macrofauna in terms of their size range, energy sources and nutrient exchange pathways (Somerfield *et al.* 2005; McLachlan & Brown 2006). The vertical distribution of meiofauna in the sediment is determined by the degree of drainage (in turn determined by grain size, compaction and exposure) and oxygenation of the sediment, with the oxygen content of the sand being a key limiting factor for the distribution of meiofauna (McLachlan & Brown 2006). These organisms rely on interstitial water flows for oxygen and as a source of dissolved and particulate organic matter, upon which they may feed (McLachlan & Brown 2006). The composition of meiofaunal communities in sandy habitats depends on the size of the interstices, which in turn is determined by the mean grain size (Fenchel 1978). Distribution of meiofauna across the beach-face (i.e. zonation) is complicated, being determined by various combinations of salinity, temperature, grain-size, water and oxygen content (Fenchel 1978). The richest meiofauna on the intertidal beach is found in the moist sand area above the effluent line (Fenchel 1978; McLachlan 1980; Armonies & Reise 2000), in other words, the mid-shore zone.

2. Vehicle impacts on beaches: an overview

Sandy beaches are popular and highly-valued recreational and tourist destinations, and are culturally important locations in Australia (James 2000). It is widely recognised that beaches as functional habitats are under significant threat worldwide from degradation via human use, poor coastal management regimes, increasing coastal development and the effects of climate change and sea level rise (James 2000; Brown & McLachlan 2002; Scapini 2003; Schlacher *et al.* 2006, 2007a, 2008a Defeo *et al.* 2009). There is increasing pressure on these environments from recreational uses, yet the level of impact of many activities has yet to be quantified (Brown & McLachlan 2002). Off-road vehicle (ORV) use on beaches has been identified as one activity that causes negative impacts to beach ecosystems (Brown & McLachlan 2002).

Vehicle tyres rut the beach-face as they pass through the soft sands, leaving tracks that have been measured at up to 28cm deep (mean 5.8±4.7cm; Schlacher & Thompson 2008). Rutting of the beach-face by vehicles can be extensive; Schlacher and Morrison (2008) observed up to 15% of the area of a beach on North Stradbroke Island, Queensland, Australia, being rutted after only 10 vehicle passes and 85% being rutted after 100 vehicle passes. This rutting of beach-face sediments can lead to significant down-slope displacement and potential erosion as sediments are moved into the swash zone (Anders & Leatherman 1987). It was estimated via extrapolation from data collected as part of a displacement experiment on a beach used by vehicles on Fire Island, New York, US, that up to 119,300$m^3.y^{-1}$ of sediment could potentially be moved towards the swash zone and lost via rutting and displacement of sand by vehicles. Most of the sediment displaced towards the swash zone on beaches comes from the steeper, dry sands of the foreshore or high-shore, rather than the area of the beach frequently wetted by the tides (Anders & Leatherman 1987; Schlacher & Thompson 2008). At least half of the volume of sediment displaced by vehicles during the peak usage season on two beaches on North Stradbroke Island, Queensland, originated from the high-shore zone, even though this zone of the beach was quite narrow (Schlacher & Thompson 2008). It was estimated that, for the Fire Island beach, this could be reduced by over 90% by restricting driving activities to more resilient sections of the beach (Anders & Leatherman 1987).

Sediment compaction of beach sands is altered by vehicle tyres. Increased sediment compaction is observed at depth (depth = 35cm) while surface sediments are loosened by the actions of vehicle tyres (Anders & Leatherman 1987). Compaction effects have been shown to differ among zones on the beach, depending on sediment moisture content. Schlacher *et al.* (2008b) found that compaction of dry beach sands (moisture content <18%) decreased following 75 experimental vehicle passes on a beach on North Stradbroke Island, Queensland, while compaction of sediments on this beach increased in the lower intertidal (moisture content >18%). These authors also found that sediment compaction was reduced on the beach in areas where vehicles turned, regardless of traffic intensity or sediment moisture content (Schlacher *et al.* 2008b).

Vehicle impacts on beach wrack accumulations and processes were investigated as part of a larger project looking at the impacts of vehicles on Cape Cod National Seashore (summarised by Leatherman & Godfrey 1979). When vehicle tyres pass over wrack deposits on the intertidal beach they break-up and desiccate these accumulations, reducing habitat and food quality for organisms that utilise this resource (Leatherman & Godfrey 1979; Zaremba *et al.* 1979; Godfrey & Godfrey 1981). Careful measurements of wrack material decomposition rates by bacteria revealed that decomposition rate was lower in the experimental plot exposed to 10 and 100 vehicle passes than the un-impacted control plots (Zaremba *et al.* 1979). The impacts of vehicles on the wrack-associated macrofauna are unknown, but there is potential for both direct impacts (e.g. crushing) and indirect impacts (e.g. habitat degradation or loss) on this group of organisms. Wrack-associated macrofaunal abundance and species richness have been shown to be related to wrack patch-size, with smaller wrack patches having lower abundance and species richness than medium or large patches on the same beach (Olabarria *et al.* 2007). If vehicles do break-up wrack patches, effectively reducing the size of individual clumps of wrack, macrofaunal abundance and species richness may be affected.

Much of the work on vehicle impacts on beach macrofauna has focused upon determining impacts on species by applying vehicle traffic to experimental plots containing organisms and then measuring levels of damage to individuals (Wolcott & Wolcott 1984; van der Merwe & van der Merwe 1991; Schlacher *et al.* 2008b) or measuring sub-lethal effects (e.g. burrowing rates; Sheppard *et al.* 2009). Other studies have looked at vehicle effects on macrofauna via population studies of single or multiple species, exclusively burrowing crabs (Steiner & Leatherman 1981; Wolcott & Wolcott 1984; Moss & McPhee 2006; Foster-Smith *et al.* 2007; Schlacher *et al.* 2007b). To have an actual impact upon beach macroinvertebrates, vehicles must not only directly damage or kill individuals of a species, but also use the same area of the beach-face that they inhabits (Schlacher & Thompson 2007).

Damage or death to individuals or effects on populations are difficult to predict because there is a large degree of inter- and intra-species variability in direct susceptibility to crushing by vehicles when either buried or at the surface (e.g. see Wolcott & Wolcott 1984; van der Merwe & van der Merwe 1991). However, within closely-related groups, such as between congeners, impacts may be more predictable. For example, the susceptibility of surf cockles of the genus *Donax* to vehicular traffic appears to increase with increased exposure to traffic; *D. variabilis* in the USA were undamaged by 1 vehicle pass when buried (Wolcott & Wolcott 1984); minimal damage (3-7% of individuals) to buried cockles was observed for two South African species, *D. sordidus* and *D. serra*, after 50 vehicle passes (van der Merwe & van der Merwe 1991); and for the Australian species, *D. deltoides*, over 50% of buried individuals were killed after 75 vehicle passes (Schlacher *et al.* 2008b). On the other hand, ghost crab species of the genus *Ocypode* differ in their susceptibility to vehicle traffic when buried in their burrows during the day; of 15 individuals of the American species, *O. quadrata*, only two were injured and none killed by a single vehicle pass when sheltered in artificial burrows 5cm deep in soft sand (Wolcott & Wolcott 1984) but only 10 vehicle passes were required to crush all individuals of the Australian species, *O. cordimanus* and *O. ceratophthalma*, also sheltered in artificial burrows 5cm deep (Schlacher *et al.* 2007b). All species of ghost crabs studied appear to be highly susceptible to crushing by vehicles when foraging on the beach surface at night (Wolcott & Wolcott 1984; Schlacher *et al.* 2007b).

Body size of individuals may appear to be a factor for some species (van der Merwe & van der Merwe 1991). For ghost crabs, larger individuals may occupy deeper burrows, and thus be ‘safer’ from vehicles because mortality declines with increased depth of burial (Schlacher *et al.* 2007b). At the population level, ghost crabs appear to be vulnerable to vehicle impacts. Burrow counts may be used as a proxy to determine the abundance of crab species in salt marsh habitats (Mazumder & Saintilan 2003); however, such counts may be artificially reduced on beaches in areas of high pedestrian activity, via the collapse of burrow entrances but without mortality to the crabs (Lucrezi *et al.* 2009). The same bias is possible for burrow counts on beaches exposed to vehicle activity. Reduced burrow counts have been reported for crab species in areas open to vehicles relative to closed areas (Moss & McPhee 2006), or high versus moderate or low intensity usage on North Stradbroke Island, Queensland (Schlacher *et al.* 2007b), and in areas of high vehicle usage on Cable Beach, Broome, Western Australia (Foster-Smith *et al.* 2007).

As yet, only one study has looked at effects of vehicles on beach macrofauna at the community level (Schlacher *et al.* 2008c). Macrofaunal assemblages were negatively affected by vehicles on beaches in South-East Queensland, Australia (Schlacher *et al.* 2008c). Beaches open to vehicles had fewer species, reduced densities and different community composition and structure relative to closed beaches (Schlacher *et al.* 2008c). Effects were greatest where vehicle traffic was concentrated in the mid- and high-shore and when the beaches were most intensively used by vehicles, during the summer months (Schlacher *et al.* 2008c).

3. Background to the local situation

In South Australia (SA), vehicles are permitted to drive on most beaches outside metropolitan areas. Many users drive onto the beach to launch and retrieve boats, leaving vehicles parked on the beach while out on the water. Others drive along the beach to locate good fishing spots or to travel between small coastal towns. Along the metropolitan coastline of Adelaide, vehicles may access the beach at certain locations to launch boats but may not drive along the beach outside of designated areas. However, in southern metropolitan Adelaide, there are three beaches upon which vehicles are permitted to drive and park along at least part of their length: Moana; Silver Sands and Sellicks Beaches (the latter two in Aldinga Bay, Figure 1.3). Unlike the (mostly) 4WD users on more remote SA beaches, people driving on the southern metropolitan beaches often use the family sedan, and drive on the beach to park for the day and set-up tents to recreate (pers. obs.; Figure 1.4a). Also, rather than traversing the difficult, soft high-shore sands (as is common on more remote beaches), most users on these southern metropolitan beaches drive and park on the firmer low- and mid-shore sands (pers. obs.). The other major difference in vehicular usage between the remote and "open" southern metropolitan beaches is the density of vehicles on the beaches; many hundreds of vehicles may be parked on each open beach in metropolitan areas on a hot summer's day (Fig. 1.4a).

The presence of vehicles on these beaches is a contentious issue among residents and visitors to the area. Community focal groups involving key stakeholders revealed divided opinions on the topic. Many users believe that it is their right to drive on these beaches, citing reasons such as family tradition and accessibility while others perceive a danger to beach goers, especially young children, or potential damage to the environment (especially birds) and want vehicles banned from beaches (Anon. 2008). However, a social survey using both a random telephone survey (targeting ratepayers) and on-the-beach survey (targeting users) techniques of residents and users of Aldinga Beach revealed majority support for vehicle restrictions (45-64%) and seasonal and permanent beach closures (43-56); however, most people still wanted to access the beach (50-75%; Anon. 2008). These findings indicated that the apparent strongly-divided community opinion on this topic was being driven by a vocal minority (Anon. 2008).

Following two years of community debate over the issue, the local managers, the City of Onkaparinga (COO), proposed a seasonal closure of Aldinga Beach between the Aldinga and Silver Sands ramps (1.8 km section)

Figure 1.3 Map of study region showing study sites. Circles denote Closed beaches/sections, squares denote Open sections and the triangle denotes the Seasonal Closure section at Aldinga. Sites with * denote beaches used for Open v. Closed between-beach comparisons. Moana and Aldinga Bays each contain 3 sections based on vehicle access, as indicated by the solid lines. Inset map shows location of study region (black box) in relation to the Adelaide CBD. A satellite image of the study area is presented in Appendix 1.1.

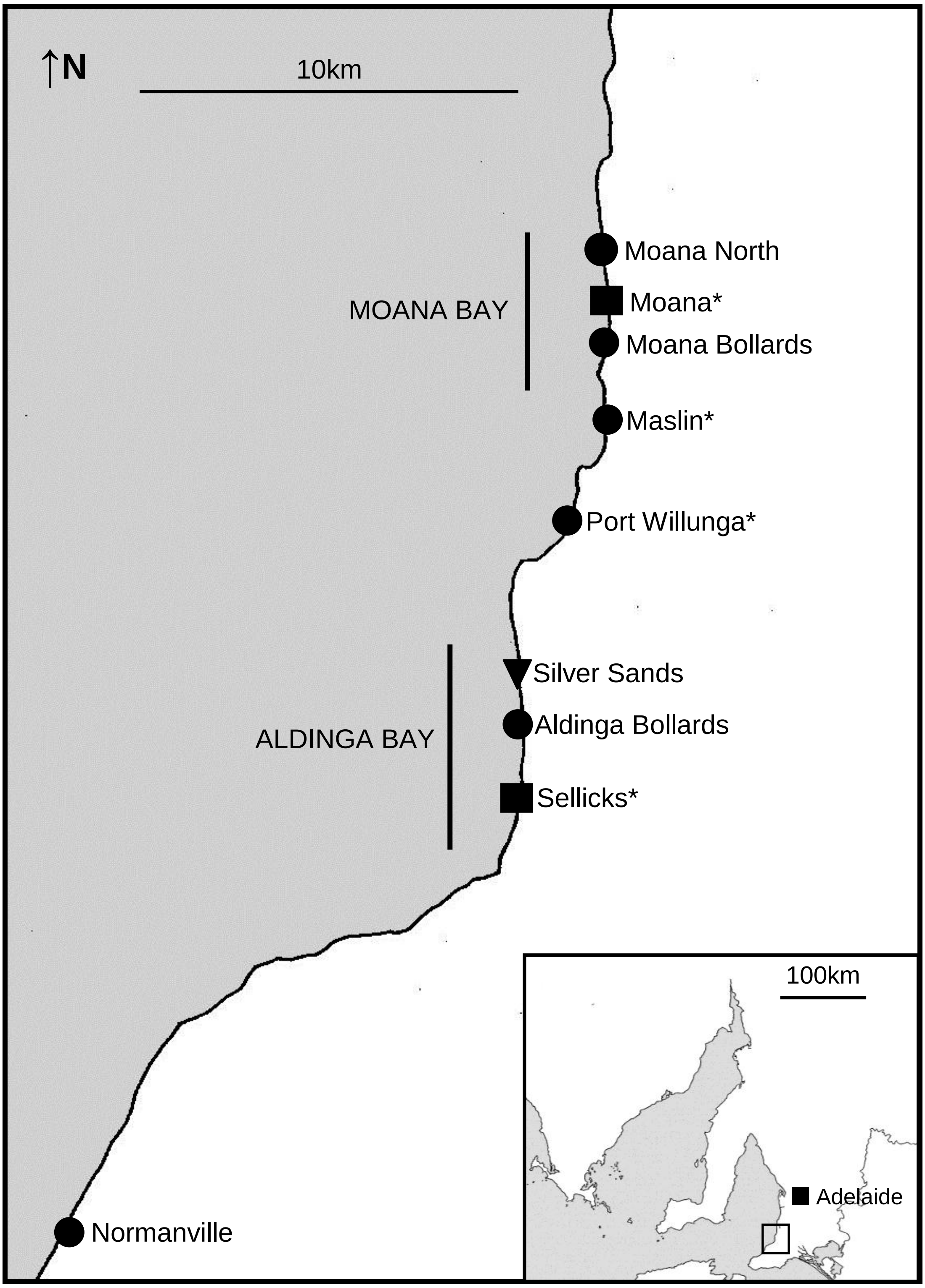


Figure 1.4a: Vehicle traffic on one of the beaches open to vehicle use, Moana Beach, on the Australia Day public holiday, 26th Jan. 2009.
(Note the open section with cars is distinct from the adjacent vehicle-free sections of Moana Bollards [back-ground] & Moana North [fore-ground])

Figure 1.4b: Bollards at Aldinga

during the winter months (May – September), and a permanent closure of a 140m long section of Silver Sands Beach, preventing through access from Silver Sands to Sellicks Beach. This was done via temporary structures between December 2004 and January 2005, followed by the erection of permanent wooden bollards in February 2005 (Figure 1.4b). Another beach, Moana, also contains an open section (850m long), a closed section (to the north; 1km long) and a southern closed section (600m long), access to which is also blocked by wooden bollards (Figure 1.4a).

The measures put in place by the COO provided a unique opportunity to study experimentally the impacts of vehicles on the ecology of these beaches. By having both beach sections that were open and closed to vehicles at Aldinga, a second open beach at Moana and some beaches that are completely inaccessible to vehicles within the same region, it has been possible to compare various components of beach ecology, both within and between beaches, to investigate vehicle impacts. Additionally, the second open beach in the region, Moana, also has closure sections within the same Bay (Figure 1.3), thus allowing for a second set of within-beach comparisons making it possible to separate natural spatial variation from vehicle effects on sections with differing vehicle access. The closures at Moana Bay have also been established for a longer time period (at least 15 years) than at Aldinga Bay (approx. 5 years), making it possible to look at the effectiveness of closures on open beaches for different periods of installation.

4. General methods

Study sites & region

The beaches used as the main study sites are located along the coast of Gulf St. Vincent, between 30 and 50km south of Adelaide, South Australia (Figure 1.3). The various sites differ in length and surroundings, and of course exposure to vehicle access (see Chapter 2 and Appendix 1.2). In total there are 9 study sites; three in Moana Bay (Moana North, Moana and Moana Bollards), Maslin Beach, Port Willunga Beach, three in Aldinga Bay (Silver Sands, Aldinga Bollards and Sellicks Beaches) and Normanville (Figure 1.3 and Appendix 1.3). All beaches, except Normanville, are within the COO area (Figure 1.3).

All study sites are Intermediate sandy beaches of the Low-Tide Terrace (LTT) morphotype described by Short and Wright (1983; 1984) and were so classified by Short (2006b). LTT beaches are exposed to moderately-low wave energy and are characterised as having a high-tide Reflective (steep high-shore) and low-tide Dissipative (flat low-shore) profile (Short 1999). These beaches are reasonably distinctive, with coarse sediment (often including gravel or cobbles) typically forming a high-shore Reflective beach and fine sands in a low-tide Dissipative zone (Short 1999).

Study design

Six of the nine study sites were visited over three years from July 2005 to March 2008 (i.e. 9 sampling occasions in total) for sampling of biotic and abiotic variables. The remaining three sites were incorporated after the initiation of the sampling program; Normanville, as a control site outside the City of Onkaparinga, in February 2006, and Moana North and Moana Bollards were included in July 2006 as additional closure sites, thus allowing for a second set of within-beach comparisons. Beaches were intensively sampled three times during each year. Sampling visits were timed around the peak vehicle usage period on the open beaches (i.e. the six-week South Australian summer school holidays, from mid Dec. to late Jan.). One visit was made before (Nov./early Dec.) and one after (Feb./early Mar.) this peak time, and one additional visit during the austral mid-winter, in the time when storm profiles are displayed on these beaches (July), to incorporate expected seasonal variation. During each visit to the study sites, three transects were haphazardly established at least 100m apart, where possible. A tape measure was run out across the width of the beach from the toe of the dune (or other suitable high-shore starting point if dunes are absent) down to the upper limit of the swash; the same transect locations were not sampled each visit. The beach was then divided visually into three zones based on the moisture of the sediments according to the zonation scheme proposed by McLachlan and Jaramillo (1995; see Figure 1.1): high-shore – dry, unconsolidated sand above the drift-line and berm (if present); mid-shore – damp sand; and low-shore – wet sand. Due to the nature of LTT beaches (with the mid- and low-shore technically comprising one low-tide terrace) differentiating the mid- and low-shore can be difficult. In cases where this distinction was not immediately clear, every effort was made to carefully and consistently differentiate a slightly drier mid-shore from a wet low-shore. The study designs for the seasonal sampling programme and a number of the targeted experiments allow for both within- and between-beach statistical comparisons (see later chapters for further details).

Thesis structure and outline

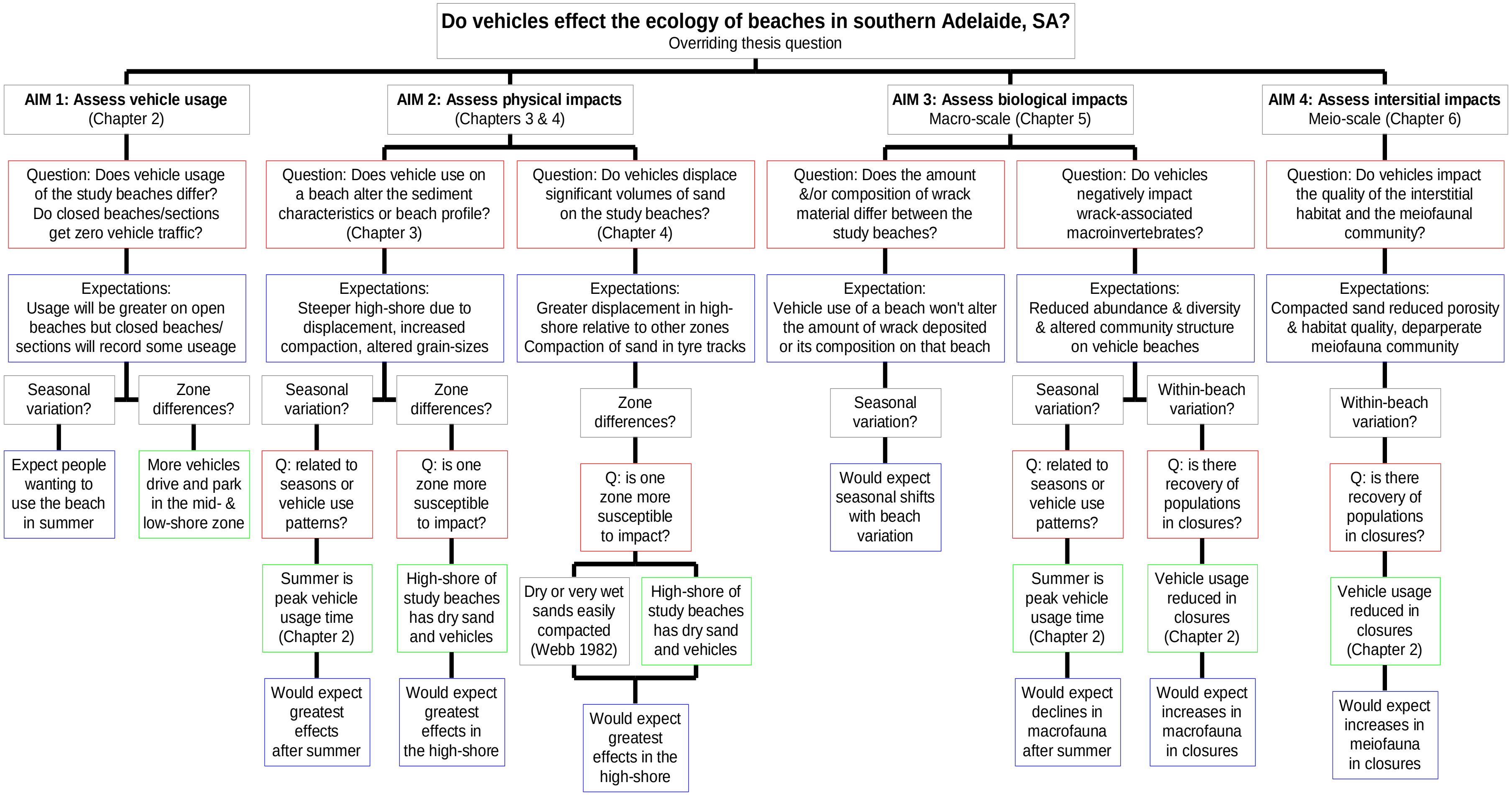
This thesis is written in a traditional style, with 8 parts covering a general introduction (this chapter), 5 data chapters, a synthesis of findings in a general discussion (Chapter 7) and appendices. Chapter 2 details vehicle usage on the study beaches, assessed via monthly surveys conducted over 18 months during this PhD research. Chapter 4 moves onto an investigation of the volume of sand that could potentially be mobilised by vehicles on these beaches via displacement by tyres (*sensu* Anders & Leatherman 1987). Chapters 3 and 5 investigate vehicle impacts on abiotic and biotic components, respectively, of the study beaches, by making comparisons among and within beaches, across seasons and, where appropriate, different physical zones on the beach-face. Chapter 6 then looks at the impact of vehicles on the interstitial environment and the meiofaunal organisms that inhabit it.

5. Aims of this study and associated research questions

The overriding aim of this research (Figure 1.5) was to assess the potential ecological impacts of vehicles on the beaches of southern metropolitan Adelaide, with respect to both biotic and abiotic components. Due to the unique situation (i.e. vehicle use) and patterns of vehicle usage on the study beaches, it was difficult to determine which aspects, if any, of vehicle impact reported in the literature would be most prominent locally, so I decided to assess potential impacts in a broad sense. Specifically, I aimed to;

1. Determine the level of vehicle usage on the study beaches, in order to place the other findings of this research in context and allow comparison and application of the study findings to other locations and situations of vehicle use on beaches (Chapter 2);
2. Determine the impact of vehicle usage on the physical (abiotic) characteristics of the study beaches, by assessing sediment

Figure 1.5 Study aims, research questions (red boxes), preliminary observations and results (green boxes) and expectations (blue boxes)



characteristics (grain-size distributions, organic matter and moisture content), compaction, sand displacement and potential erosion via mobilisation by vehicle tyres, and the profile of the intertidal beach-face (Chapters 3 & 4);

3. Determine the impact of vehicle usage on the macrobiotic component of the study beaches, specifically the wrack and wrack-associated macroinvertebrates. These were targeted because of the prominent nature of the drift-line feature on the study beaches and its ecological significance (e.g. previous work in this lab by McKechnie 2003; McKechnie & Fairweather 2003; Duong 2008). The amount and composition of wrack material, and the abundance, diversity and composition of the wrack-associated macroinvertebrate community were assessed (Chapter 5); and
4. Determine if the meiofaunal community can be used as a tool to assess the impacts (if any) of vehicles on the interstitial environment, via an assessment of the characteristics of the beach-face habitat (sediment characteristics, moisture content, percolation rate and compaction) and the abundance, diversity and composition of the associated meiofaunal community (Chapter 6).

Each aim has associated research questions and expectations (Figure 1.5) based on predictions from the literature on sandy beaches and vehicle impacts. Where appropriate, seasonal and zonal effects have been investigated, and these will be described and then discussed in detail within the relevant thesis chapter.

6. Significance of this work

Much of the information available comes from international studies in habitats that do not necessarily match our southern temperate beaches. Effects found in this investigation will aid in the management of this activity on local beaches (Anon. 2008), and will also contribute significantly to our limited understanding of the ecological effects of vehicles on beaches at a broader scale. The findings of this study will be applicable to other coastlines where vehicles are permitted access to the beach, aiding coastal management and local policy decision-making.