Sediment transport patterns around Port Coogee Marina: Case study of 2009

Thesis

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ABSTRACT

Port Coogee Marina is the hub of Australand's (Australand Holdings Ltd.) development of Coogee Beach in Perth, Western Australia. Construction of the marina occurred between 2006 and 2009 with the outer breakwaters completed by the end of 2006. Prior to construction, the project underwent a significant Public Environmental Review (PER) process that considered its impact on the popular recreational coastline and a sand bypassing program was developed to manage the expected erosion from the southern beach. Annual hydrographic surveys since construction have suggested erosion in excess of the PER estimated values. The years following construction have experienced variable storm activity and a 100-year return period storm was experienced in July 2009.

This study uses numerical modelling to create a bathymetric evolution model using 2009 as a case study. The aim of the study is to model the unique southerly littoral drift direction and consider the impact of storm events on the sediment transport processes to gain further understanding of the impact that the marina has on Owen Anchorage. In addition to this, the impact of Perth's dominant summer sea breeze system is considered and a 6-month sediment budget has been created to enable comparison with previous studies. The presented 6-month sediment budget shows correspondence with the annual hydrographic survey data suggesting that the majority of sediment activity occurs during the summer and winter months.

Results show increased sediment activity with increased storminess. In particular, the erosion from the southern beach is shown to be sensitive to storm activity. During winter, accumulation is experienced on the northern beach and erosion from the southern beach, coinciding with the hydrographic data. During summer, the majority of sediment transport occurs during more intense events or during rapid changes in wind direction. Summer experienced accumulation on both beaches showing a reversal in littoral drift direction along the southern beach during this period. The winter storms dominate the erosion from the southern beach resulting in net annual erosion from this location. The evolution of the beach since the marinas construction shows it has directly affected its adjacent beaches and acts as a barrier to the natural southward sediment migration. This thesis validates this theory but suggests that the above-expected erosion from the southern beach in recent years is a result of higher frequency and intensity storm events rather than as a direct result of the marina's construction.

LETTER OF TRANSMITTAL

7 November 2011

The Dean
Faculty of Engineering, Computing and Mathematics
The University of Western Australia
35 Stirling Hwy
Crawley 6009 WA

Dear Sir,

Please accept this submission to you of my thesis entitled “Sediment transport patterns around Port Coogee Marina: Case study of 2009” as completion of part of my Bachelor of Civil Engineering course requirements.

Yours faithfully,

Matthew Johnson

ACKNOWLEDGEMENTS

- I would like to thank the team at RJ Vincent & Co. for their input in developing this interesting research topic and their understanding and support for the entirety of the year. Thanks to Michael Brunton (Project Manager) for your time, guidance and information regarding the project.

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CHAPTER 1. INTRODUCTION

1.1 Rationale

Port Coogee Marina is part of Australand's $2 billion development located on the Western Australian coast 23km south of Perth's CBD (Australand 2010). The construction of the marina occurred between 2006 and 2009. The development is situated around the approximately 300,000m^2 marina that consists of 2 kilometres of seawalls and breakwaters and two land reclamations (RJ Vincent & Co. 2011). The primary breakwaters were completed by the end of 2006. It is located within the hydro-dynamically complex environment of Owen Anchorage where the coastline experiences a unique net southerly littoral drift. The construction of this shoreline structure results in net sediment accumulation on the northern beach and net erosion from the southern beach adjacent the marina. This is the reverse of what is experienced at more exposed coastlines in the metropolitan area. This thesis has examined this process at different periods of the year.

Prior to construction, the project underwent a significant Public Environmental Review (PER) process. This considered its impact on the popular North Coogee recreational beach and a management program was developed where 15000m^3 is bypassed from the northern beach to the southern beach approximately every 3 years. A study by Hamilton & Hunt (2011) has considered a series of hydrographic surveys recorded since construction that show erosion from the southern beach in excess of the initial estimation. The years following construction have experienced variable storm activity including a 100-year return period storm in July 2009. This study has used 2009 as a case study to examine extreme events and consider their impact on the coastline since construction. Ultimately, this thesis considers if the excessive erosion is a result of storm and storm-like events or as a direct result of the marinas construction.

To consider these processes a numerical approach was undertaken using the Danish Hydraulic Institute's (DHI) MIKE 21 FM (flexible mesh) suite of modelling tools. This software package has been used extensively throughout the world for a variety of coastal engineering purposes. The results have been used to create sediment budgets, which are compared with those presented in Hamilton & Hunt (2011). This provides insight into the annual trends in sediment transport activity along with the impact of extreme storm events.

1.2 Aim

The aim of this thesis is to characterise the unique sediment transport characteristics around Port Coogee Marina using numerical modelling techniques to determine its impact on the coastline. A case study of 2009 has been used to gain insight into the impact of storm activity on sediment erosion from the southern beach, as above expected erosion has been recorded from this location.

1.3 Objectives

This study can be divided into three primary objectives and these are presented below:

1. Model and analyse the impact of extreme winter storm events on the nearshore processes of Owen Anchorage and consider their impact on the sediment transport processes.
2. Model and analyse the impact of the Perth's dominant summer sea breeze and consider its impact on the sediment transport processes.
3. Create sediment budgets from the above-mentioned simulations to compare with the sediment budget presented in Hamilton & Hunt (2011).

This thesis presents a literature survey to consider previous research, which has been related to this topic and the outcomes have been used to make assumptions for the model setup. An introduction to the modelling software package used is presented with an account of the modelling methods and techniques in Chapter 3. The results of the thesis are analysed and discussed in Chapter 4.

CHAPTER 2. LITERATURE SURVEY

This literature survey discusses the regional setting, bathymetry, sedimentology, physical setting, anthropogenic impacts and meteorology of the study area and considers their influence on sediment transport processes. These oceanographic processes hold the most influence on controlling the nearshore hydrodynamic processes and the morphology of low energy sandy beaches (Hegge, Eliot & Hsu 1996). A concise understanding of these processes is critical when considering the inputs for the model and during the analysis of results.

2.1 Regional Setting

Port Coogee is located on the Western Australian coast located immediately south of Fremantle within the hydro-dynamically complex environment of Owen Anchorage. Owen Anchorage is a depression system that is situated between two carbonate sand banks Parmelia (South) and Success (North) which form the northern boundary of Cockburn Sound. The Sound is a large low energy coastal waterway located on a moderate to high-energy carbonate coast. It forms an elongate waterway approximately 22km long, ranging from 9-15km wide and sits between the mainland and a remnant Pleistocene dune ridge system forming Garden Island, Carnac Island and Rottnest Island (Steedman 1973; Steedman & Craig 1983; Skene *et al.* 2005). The coast receives significant sheltering from the offshore wave climate because of this. The mainland shoreline has a generally western aspect but it varies significantly depending on location due to various bays and differential shoreline alignments. The Swan River is the main fluvial inlet on the metropolitan coast however little sediment is output to the ocean from this inlet (Searle & Semeniuk 1985). The effects of the Swan River have been considered negligible for this study.

The shoreline environment varies considerably. In the past, there has been significant amounts of heavy industry within close proximity to the western mainland coast. Some remnants of this exist today. The South Fremantle Power Station is an example of this. The construction of Port Coogee Marina in 2006 has seen the area recently divided into residential style allotments which given its proximity to the city and the coast is likely to be the trend in the future. Garden Island forms the eastern boundary and is mostly undeveloped excluding the Naval Base at Careening Bay (Skene *et al.* 2005). Anthropogenic impacts on the coastal environment are discussed in section 2.8.

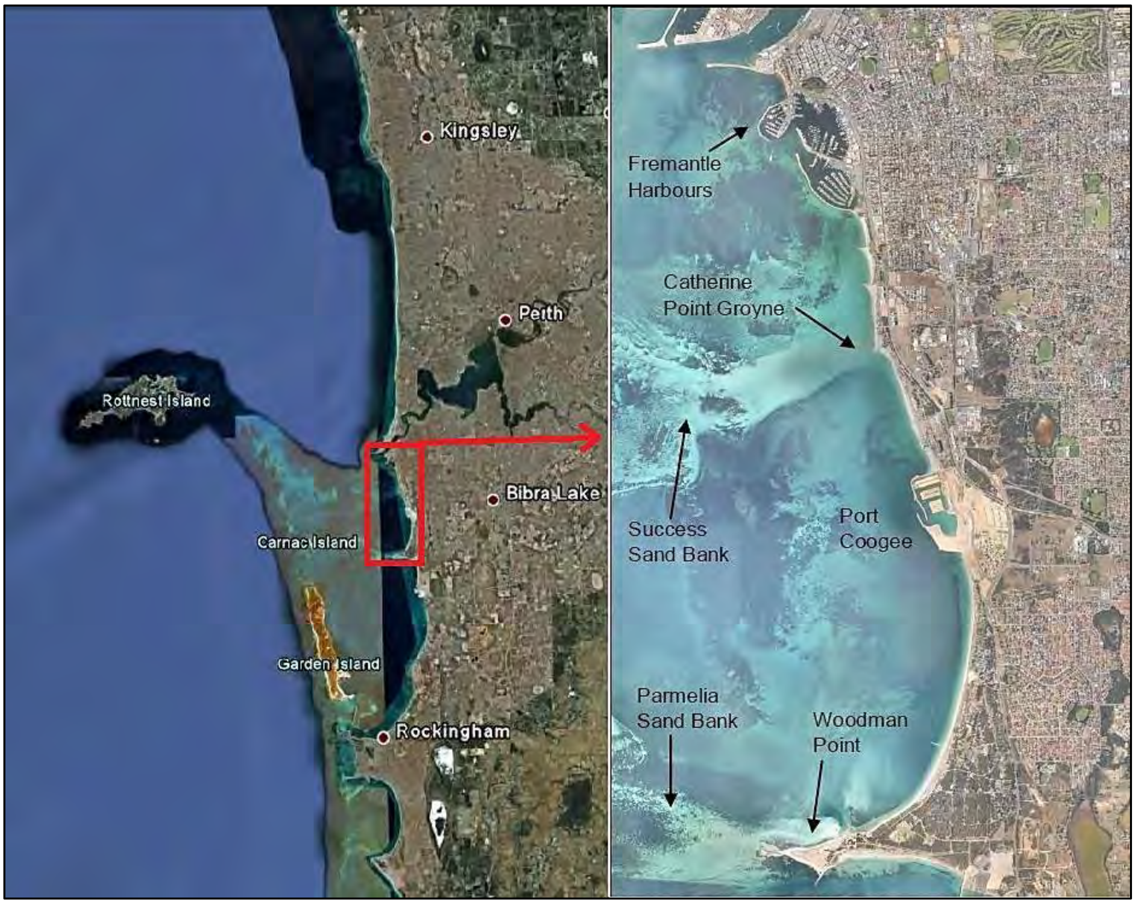

Figure 1: Regional setting of Port Coogee Marina with respect to Perth, Western Australia. (Adapted from Hamilton & Hunt (2011))

2.2 Sediments

Knowledge of the local sediment parameters is critical for coastal engineering calculations particularly when considering the effects of longshore sediment transport (Stul 2005). The potential longshore sediment transport rate of a coastal system requires the porosity and mean grain size of the local sediments (USACE 1984). In design or modelling projects, incorrect sediment assumptions or poor analysis can have detrimental effects on the final design.

Skene *et al.* (2005) conducted a study undertaken as a part of the Coastal CRC Project at Geoscience Australia where the geomorphology of the seabed, the spatial distribution of sediment types and the geomorphic evolution of Cockburn Sound was analysed. This data was collected via sixty-three sediment grab samples and twelve 3-6m vibrocores. Four distinct sediment types were identified based on the sedimentological analysis conducted on the surface sediment samples and they are listed below. (Figure 2)

- *Nearshore Quartz Sand (Gravelly/Shelly mix carbonate/quartz sand).* Consists of fine to coarse grain (Mean 0.43mm, standard deviation 0.36mm), poorly sorted gravelly sand with a low fines content (<63µm <5%).
- *Carbonate Banks (Carbonate sand).* High carbonate content (90%), an average mean grain size of 0.34mm (standard deviation 0.17mm) and a low fines content (<5%). This sediment type was encountered at Parmelia Bank, the northern and southern boundaries of Cockburn Sound and the eastern beaches of Garden Island.
- *Eastern Shoal Sediments (Carbonate muddy sand).* Average grain size of 0.29mm (Standard deviation 0.28mm) with an average fines content of 27%. The carbonate content frequently exceeds 80% in these areas. This sediment type was found on the eastern shoals and the eastern banks of the central basin.
- *Central Basin (Carbonate sandy mud/mud).* Average grain size of 0.062mm (Standard deviation 0.11mm) with a fines content ranging from 56% - 93% (average 76%) and a calcium carbonate content of approximately 80%. The mud content was found to increase to the southwest of the basin.

Parmelia and Success banks, which border Owen Anchorage are the predominant source of sediment for the shoreline. An approximated one million cubic metres was deposited on the shoreline between 1964 and 1994 (DPI 2008). Carbonate sands are the primary sediment type found in this location. This forms the 'shell sand' resource that is dredged by Cockburn Cement Limited for lime and cement production. These banks are mostly covered by seagrass and are influenced by tidal and wind induced currents along with ocean swells. This has resulted in the erosion of the fine sediments leaving predominantly sand sized carbonate grains (Skene *et al.* 2005).

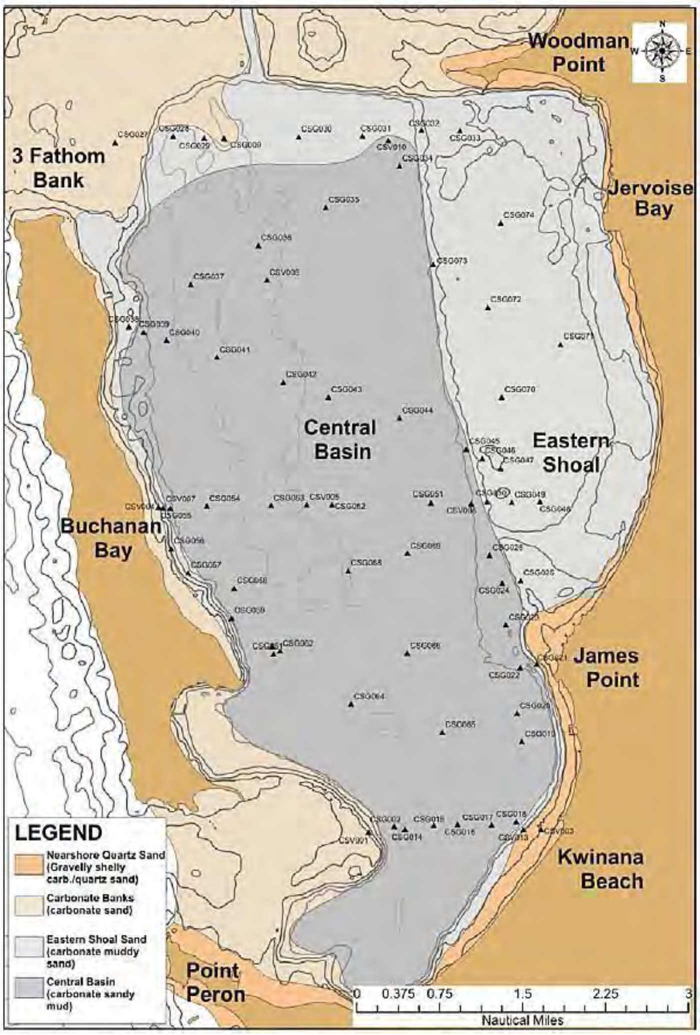

Figure 2: Map showing the distribution of distinctive sediment types identified in Cockburn Sound (Skene et al. 2005)

2.3 Bathymetry

The northern boundary of Cockburn Sound is bound by Parmelia and Success banks. Success bank at Point Catherine is known to be one of the major sources of material transported within Cockburn Sound and Owen Anchorage (DPI 2008). These banks cover the full northern width of the Sound and range in depth from 2 - 5 m. Owen Anchorage is located between these banks and this complex and spatially varying bathymetry within close proximity to Port Coogee Marina has a major influence on the wave propagation to the nearshore zone and hence the sediment transport characteristics. The large breakwaters of Fremantle harbour and associated dredging channels prevent sediment transport to or from the north while the Woodman Point Groyne prevents significant exchange with the Cockburn Sound basin. Due to this isolation it is assumed that the majority of the deposited sediment on the Owen Anchorage shoreline is due to onshore feed from these two large sand banks (Hamilton & Hunt 2011; Bowman *et al.* 2005). The bathymetry outside of this basin is critical to the study as this area will be included in the simulation to model the wave transformation and propagation into Owen Anchorage. This transformation of waves is believed to be the dominant driving force of the net southerly littoral drift experienced.

Extensive sheltering of Cockburn Sound and Owen Anchorage is due to the Pleistocene ridge system on almost the entire western boundary and due to Cape Peron and the Garden Island Causeway to the southwest (Travers 2007). The bathymetry of Cockburn Sound is such that it acts predominantly as a closed system with little sediment exchange through the boundaries (Steedman & Craig 1983). An offshore ridge and depression system including Five Fathom Bank, which is separated from Garden Island by Sepia Depression exists west of Garden Island (Department of Planning & Infrastructure 2008).

Between 1914 and 1918, the Gage Roads shipping channel was cut into the Owen Anchorage banks to allow the safe navigation of ships during World War 1. Periodically from then on, these channels were maintained via further dredging operations for the safe navigation of all large marine vessels into Cockburn Sound via Owen Anchorage. In addition to these channels, a dredging channel formed by Cockburn Cement Limited (CCL) exists to the east for the purpose of mining shell sand for the production of cement materials. No work has been undertaken considering the effects of the Gage Roads shipping channel on the wave climate however, wave climate models have been developed which show only minor hydrodynamic changes to Owen Anchorage from CCL's dredging activities. Wave energy from Owen Anchorage is now capable of penetrating deeper into Cockburn Sound as a result (EPA 1998; EPA 2001). It has also allowed a larger water exchange rate and hence increased sediment exchange between the ocean, Owen Anchorage and Cockburn Sound (Oceanica Consulting Pty Ltd. 2007). The bathymetry of the study area is presented as a digital elevation in Figure 3.

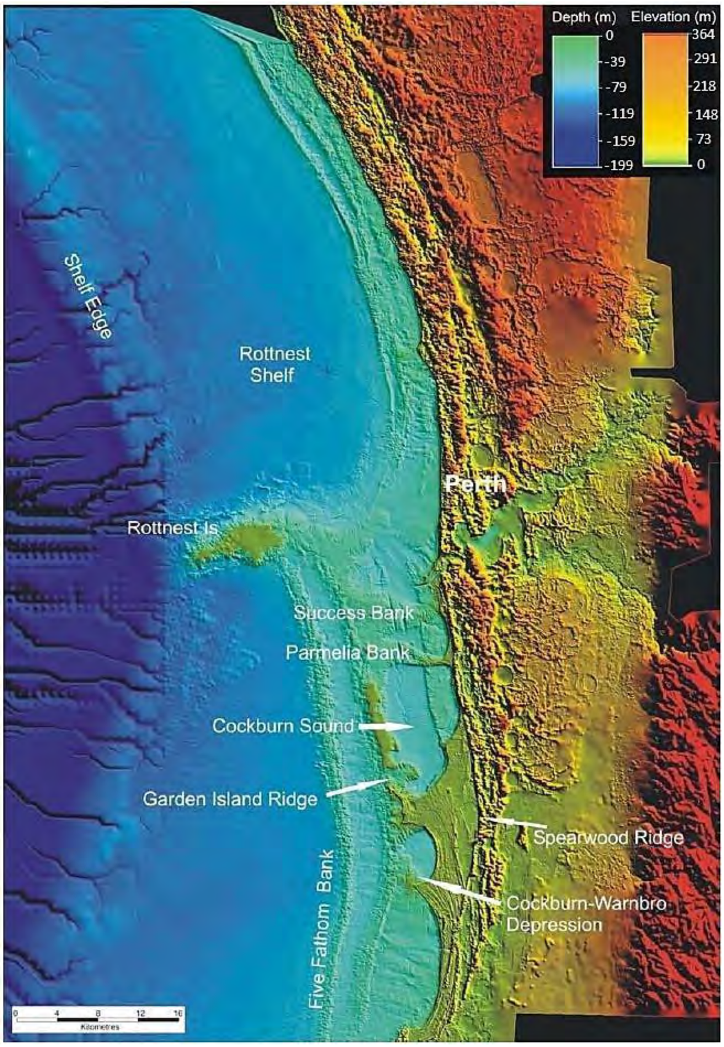

Figure 3: Digital elevation model of the Rottnest Shelf and Perth Coastal Plain showing the major geomorphic features of Cockburn Sound, Owen Anchorage and the adjacent coast. (Skene et al. 2005)

2.4 Wave Climate

The wave climate of the study area is complex, primarily due to the attenuation of the offshore waves caused by spatially varying bathymetry, differential seabed friction, refraction and reflection along the Pleistocene reef system west of the study area (Lemm *et al.* 1999). This causes significant sheltering from the offshore waves and causes transformation of the waves that do penetrate into Owen Anchorage and Cockburn Sound. This section will consider the local wave climate with a focus on the locally generated wind waves such as those formed by the sea breeze along with the exposure to offshore waves and the transformation processes that takes place. These locally generated waves are a dominant driving force causing longshore sediment transport on sheltered beaches (Masselink & Pattiaratchi 2001a). Given the sheltered nature of this location and the persistence and regularity of the sea breeze system in Perth, this was expected to be an important factor in the simulation process. Previous techniques used to model waves and their characteristics will be considered in this section focusing predominantly on local studies.

2.4.1 Exposure

Sheltering of a shoreline from offshore wave systems can occur as a result of aspect, structures or in this case Islands and reef systems such as the Pleistocene ridge system forming Garden, Carnac and Rottnest Islands and the associated reef systems (Hegge *et al.* 1996). Hegge *et al.* (1996) classifies the Perth metropolitan coast as a sheltered, low wave energy environment. As waves propagate from offshore regions to the nearshore, these features cause wave transformation and energy dissipation, reducing the amount of energy reaching the nearshore zone. The wave energy that penetrates into the Cockburn Sound can be as little as 5% of the initial offshore wave energy, which leaves the locally generated wind waves to dominate the local processes (Department of Environmental Protection 1996). The offshore wave climate is expected to play more of a dominant role in Owen Anchorage than that recorded in the previous Cockburn Sound study due to its setting further north giving the environment slightly more exposure.

2.4.2 Wave Transformation

A comprehensive summary of wave transformation processes for the purpose of coastal engineering is presented in Vincent *et al.* (2002). The paper presents procedures for transforming wave information from offshore locations to nearshore locations, which is a common requirement for coastal engineers. Wave transformation is summarised into three types.

a) Offshore wind generated deep water waves propagate into shallow water and grow in height due to local winds.
b) Offshore wind generated deep water waves propagate into shallow water but are affected by negligible local winds and approach the shore as swell.
c) No wave propagation from offshore but local wind generated waves grow large enough to interact with the bottom.

Type a and c are the most complex transformations and require numerical modelling techniques for adequate results. Transformation type a will be the most commonly experienced in this project and this interaction between swell and wind-waves will be considered.

Shallow water waves are strongly influenced by irregular bathymetry, currents and bottom conditions. These factors can result in significant changes to wave height and direction. The magnitude of these changes is sensitive to the wave period. Generally, shorter period waves such as those generated by local winds are less susceptible to transformation like refraction. The three dominant wave propagation effects include refraction, diffraction and shoaling. Waves can also reflect of hard boundaries, structures or beaches and this can result in wave-wave interaction.

The three methods of wave energy dissipation or sink mechanisms are bottom friction, percolation and wave breaking. The interaction of waves with currents or other waves will have an effect on all of these processes (Vincent *et al.* 2002). The difference in bottom friction between the sand banks and the Pleistocene reef system is believed to play a dominant role in the wave refraction and cause the unique net southerly littoral drift experienced within Owen Anchorage. This is discussed further in section 3.2.3.

2.4.3 Local Wave Climate

The local wave climate can be described by the offshore and nearshore wave climate with consideration for the sheltering and wave transformation characteristics of the nearshore. Superimposed on the background swell waves is a system of locally generated waves caused by local winds. Most significant of which is the local sea breeze system, which is most prevalent through summer. In fetch limited areas which are sheltered from the full impact of the offshore swell such as Owen Anchorage the locally generated waves play a significant role in determining the nearshore processes and in turn the beach morphology (Masselink & Pattiaratchi 2001a). The offshore wave rider buoy is located southwest of Rottnest in 48m of water. It was replaced for a directional wave rider buoy in September 2004. The Perth nearshore wave rider buoy is located at Cottesloe in 17m of water. The data from these buoys is difficult to transfer to nearshore zone of sheltered regions such as Owen Anchorage as the waves have already experienced transformation at these locations from features like the Continental Shelf. The average data recorded from these buoys is summarised in Table 1. This table clearly shows the energy dissipation that occurs between Rottnest and Cottesloe resulting in significantly smaller wave heights in the nearshore.

Lemm *et al.* (1999) analysed the offshore wave climate of Perth using 2.5 years of wave data collected from the Rottnest wave buoy between 1994 and 1996. The results of this study show a mean wave height (H_m) of 2.0m and a spectral mean wave period (T_m) of 8.8s. There is significant annual variation, which coincides with the distinct seasonality in the regional wind system. Masselink & Pattiaratchi (2001b) isolated the mean significant wave height and period for the summer and winter months in Perth. The results show a H_m of 1.8m in summer and 2.8m in winter with T_m of 7.6s and 9.7s respectively. The shorter summer period is associated with the superimposition of the shorter period waves generated by the sea breeze. Extreme storm events (H_s >4m) occur on average 30 times per year and are most prevalent through the month of July. This study focuses on 2009, which experienced a 100-year return period storm on the 20[th] July. Wave heights in excess of 9m were recorded at the Rottnest wave buoy during this event (Figure 4).

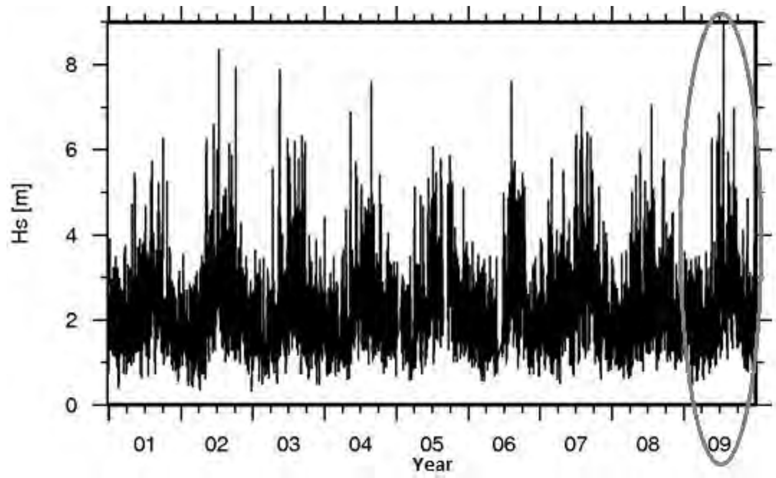

Figure 4: Recorded wave heights (m) (Rottnest wave buoy 2001-2009), Circled: 100-year return storm event (July 2009)

Swell approaches from a south to southwest direction in summer and from a west-southwest to west direction during the winter months. A constant low amplitude background swell (H_s ~0.5m) generated in the Indian and Southern Oceans is present all year (Lemm *et al.* 1999). Swell waves can produce average significant wave heights of 1.5-2.5m with periods of 10-20s (Pang *et al.* 1999; Sanderson & Eliot 1999). Refraction of swell waves at the Pleistocene ridge system results in a net southerly littoral drift along the coast south of Cottesloe (Bancroft 1999; Hegge 1994). It is expected that this southerly propagating wave system will be the most critical factor driving the nearshore sediment transport processes due to the extensive sheltering against the prevailing offshore swell directly from the southwest.

Locally generated waves are dominated by the summer sea breeze system and the winter storm systems generating short period waves. Generally the locally generated waves have a smaller average wave period (T_m) than the offshore waves leaving them less susceptible to refraction and reef attenuation. As a result, they are capable of approaching the shore at larger angles potentially causing large longshore currents (Jackson *et al.* 2002; Hegge *et al.* 1996). The sea breeze system is fetch and duration limited as the system only extends 100km offshore and lasts for an average of 7 hours generating seas with heights of 1-2m with periods of 4-6s. The winter cold fronts generate larger seas, which can exceed 7m with periods of 6-10s (Pang *et al.* 1999).

Table 1: Mean H_s and return-interval H_s for Rottnest and Cottesloe (DPI 2004)

Average Return Interval of Wave Height / Mean H_s	Rottnest (m) – 48m depth	Cottesloe (m) – 17m depth
Mean annual H_s	2.2	0.8
Mean winter H_s	2.8	1.1
Mean summer H_s	1.8	0.75
1 year	7.4	3.1
5 year	8.2	3.4
20 year	8.6	3.7
50 year	9.8	3.9
100 year	10.3	4

2.4.4 Modelling Waves

Numerical models are used to output nearshore wave information from gathered offshore wave data (Hamm *et al.* 1993). The most critical element in wave predictions from this method is the quality of the input data and in particular the wind and wave data (Liu *et al.* 2002; Kaihatu *et al.* 2002).

Bosserelle *et al.* (2011) created a 40-year wave hindcast of the southern Indian Ocean to access the inter-annual variability and longer-term changes in the wave climate of Western Australia between 1970 and 2009. The domain of the model is made up of a mosaic of four grids. A 10-min (~15 km) grid covering the continental shelf of WA, a 0.5° grid over the southeast Indian Ocean, 0.5° grid covering the storm track portion of the Southern Ocean and a 1° grid over the remaining Sothern Indian Ocean. They are all linked via an obstacle grid, which accounts for islands and shoals where the grid is not resolved. The model was validated against measured wave data from five wave buoys located on the WA coastline including Rottnest and Cottesloe. The model demonstrated strong correlation with the measured values at all 5 locations in WA. The short-lived, locally generated waves such as those generated by the sea breeze system in Perth are not accurately modelled due to the coarseness of the input wind data. The conclusions of this study show an increase in H_s and T_p both in the Southern Indian Ocean and Southwestern Australia which is believed to be due to intensification of the storm belt where larger swells propagate from. The number of large wave events reaching the shoreline was said to be balanced by the storm-tracks being relocated further south however.

2.5 Water Level Fluctuations

Water level fluctuations are significant when considering the nearshore processes within areas that are affected by significant wave attenuation, as the change in water level over reef systems and complex bathymetries affects the level of attenuation and the overall energy transferred to the nearshore zone. This in turn controls the intensity of nearshore currents and the sediment transport processes (Stul 2005). Together with the astronomical tidal pattern of the region, consideration is to be given to non-tidal water level fluctuations. These include changes in barometric pressure, wind setup storm surge, continental shelf waves, sea level change, El Nino Southern Oscillation (ENSO) events and the influence of the Leeuwin Current. Sea level fluctuation caused by these factors can often exceed the small astronomical tides of Perth by a factor of two (Hegge *et al.* 1996; Stul 2005). The amplitude and time scale of these mechanisms are presented in Table 2.

Perth experiences mixed, predominantly diurnal tides which have been classified as micro-tidal (<2m) (Hegge & Eliot 1996). A maximum spring tide range of 0.7m and lowest to highest astronomical tide (LAT – HAT) of 1.1m is experienced (Department of Defence 2005).

Western Australia is the fastest growing Australian state and with much of this population and economy growth occurring in the coastal zone it becomes more vulnerable to extreme flooding events (Nicholls *et al.* 2007; DCC 2009). Haigh & Pattiaratchi (2010) developed a depth averaged tide-surge model for the entire WA coastline using the Danish Hydraulic Institute's Mike21 FM (flexible mesh) suite of modelling tools and presented a 60-year hindcast of sea levels. The developed mesh has a resolution of approximately 60km at the open boundary and reduces to 10km at the coastline with interpolated bathymetric data from Geoscience Australia. The astronomical tidal component is driven via sea level data at the boundaries obtained from Oregon State University Tidal Inversion Software. The surge component of sea levels is forced via barometric pressure and u and v components of wind from the US National Centre for Environmental Prediction's (NCEP) global reanalysis. The model was validated against observations from 10 tide-gauges around Western Australia. The output from this model has shown good agreement with physical observations with a root mean square error typically within 10cm. The incorporation of the astronomical tide with the surge component of sea level in a model which is designed specifically for the WA coast suggests the water level fluctuation data from this model will be the most applicable to this study.

Table 2: Local mechanisms for sea level variability (Pattiaratchi & Eliot 2005)

Mechanism	Time Scale	Maximum Amplitude
Astronomical Tide	12 – 24 hours	0.80m
Storm Surge	1 – 10 days	0.80m
Leeuwin Current	Seasonal	0.30m
ENSO	Inter-annual	0.30m
Global Warming	Decadal	0.015m per decade

2.6 Nearshore Currents

Nearshore currents are the primary process driving sediment transport on the Perth metropolitan coast and are caused by topographic forcing, wind forcing or longshore variation in wave climate (Noda 1974; Carter 1988; Komar 1988). Nearshore currents include alongshore currents and cross-shore currents such as rips and circulation cells (Komar 1998). The alongshore currents can be generated either by longshore variation in wave setup at the shoreline or by waves approaching the shore at oblique angles such as those caused by short period locally generated waves (Carter 1988).

Within this study area, the nearshore currents are caused by local weather systems such as sea breeze activity. The longshore currents of Perth generally travel northward in summer and southward during winter with speeds of 0.04-0.2ms^{-1} (Searle & Semeniuk 1985; Pattiaratchi *et al.* 1997). This thesis discusses the driving forces that cause the unique net southerly littoral drift which occurs in Owen Anchorage even when under the influence of a southerly summer wind regime in Chapter 4. Pattiaratchi *et al.* (1997) considered the nearshore currents generated by the sea breeze and noted a significant and almost instantaneous response to the sea breeze caused by increased wave energy and propagation angle. The effects of sea breeze systems on nearshore processes are often discounted elsewhere in the world as wind speeds may rarely exceed $5ms^{-1}$. In Perth, the sea breeze frequently exceeds $15ms^{-1}$ and has a significant effect on these processes. The northward summer longshore current increased from $<0.05ms^{-1}$ to $1ms^{-1}$ in less than 3 hours. This increase is limited to the nearshore zone as offshore currents in this region rarely exceed $0.2ms^{-1}$ (Pattiaratchi *et al.* 1997).

In environments such as Owen Anchorage and Cockburn Sound that act predominantly as closed systems, nearshore currents act in distinct circulation cells. This is caused by the wave energy being converged or diverged by irregular bathymetry or reef systems (Searle & Semeniuk 1985). These cells are particularly sensitive to wind directional changes and can migrate significantly. In some cases, the littoral drift direction is completely reversed (Clarke & Eliot 1983). This is considered in the comparison of summer and winter results.

2.7 Meteorology

Prevailing weather systems and their interaction with each other and the local environment influence the wind climate, local wave climate, near shore currents and non-tidal water level fluctuations (Stul 2005).

The prevailing weather system within this study area is dominated by anti-cyclonic high-pressure systems with periodic tropical and extra-tropical cyclones known as mid-latitude depressions and the local seasonal sea breeze (Eliot & Clarke 1986). A detailed review of the dominant Perth weather systems is presented in Gentilli (1971; 1972). Anti-cyclones cross the coast in an easterly direction approximately every 3-10 days and the location of this anti-cyclonic band migrates from around 38°S in summer to around 30° in winter. As a result of this, Perth experiences dominant offshore winds through the summer months and dominant onshore winds through winter (Gentilli 1971; 1972). Mid-latitude depressions bring northerly winds, which shift to a south-westerly direction as the system crosses the coast. This is a dominant system through the winter month of July and presents the strongest winds (usually from the northwest). This system often generates cold fronts from the southwest (Gentilli 1971; Lemm *et al.* 1999). Tropical cyclones infrequently travel from the northwest coast. This system is experienced in the later summer months. (Eliot & Clarke 1986; Lemm 1996).

Perth experiences a strong sea breeze in summer caused by diurnal heating and differential thermal properties of the land and sea. The superposition of the West Coast Trough and the local sea breeze results in a unique alongshore nature of this sea breeze system (Masselink & Pattiaratchi 1998). The morning offshore easterly breeze shifts to a south-southwesterly direction around noon and the wind strengthens into the afternoon until evening when it weakens and shifts back offshore (Lemm *et al.* 1999). In this micro-tidal region, the described local wind system is expected to play a dominant role in the nearshore and foreshore processes (Pattiaratchi *et al.* 1997). The study conducted by Pattiaratchi *et al.* (1997) recorded the change in wind direction occurs over a period of approximately 15-45 minutes and noted that nearshore hydrodynamics and morphology responded rapidly to changes in wind speed and direction. The pronounced changes to the nearshore morphology were similar to that of a storm event and it was noted that the longshore sediment transport rate was approximately one-hundred times greater than that recorded before the sea breeze was present (Masselink & Pattiaratchi 1998). Pattiaratchi *et al.* (1997) suggests during the sea breeze season the shoreline is constantly adjusting to changing hydrodynamic conditions. Erosion occurs during the sea breeze and accretion during the remainder of the day. It was suggested in this study that the sediment transport induced by the Perth sea breeze system may account for practically all of the northward littoral drift that occurs along the Perth metropolitan coastline. The wind data recorded during February 2009 from the Rottnest meteorological station is presented in Figure 5. The sea breeze system is well represented in this month.

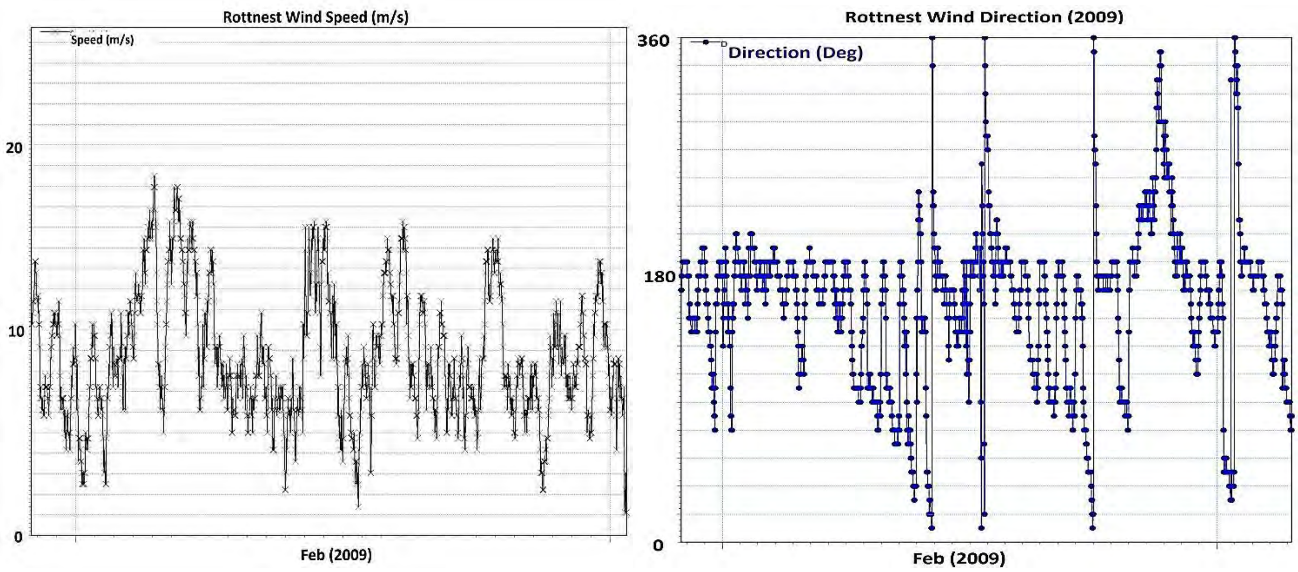

Figure 5: Rottnest meteorological station February 2009, Left: Wind speed (ms^{-1}), Right: Wind direction (°)

2.8 Anthropogenic Effects

2.8.1 Anthropogenic Effects in Cockburn Sound & Owen Anchorage

The anthropogenic pressures on the coast have a significant impact on the nearshore zone. The pressures on the Owen Anchorage coastline are caused by a variety of historical and current activities in close proximity to and within the marine environment and are analysed in Oceanica (2007). This section considers the construction of hard structures such as the variety of groynes, the Garden Island Causeway and Port Coogee Marina. The effect of the historic industrial usage of the area and dredging operations is discussed to consider their effect on the nearshore processes. Pressures such as habitat loss, recreational fishing and pollution can also be classified as anthropogenic, however will not be considered in this project.

The varied uses and placement of infrastructure in Cockburn Sound and Owen Anchorage over its history has resulted in the need for engineering works that have altered the coastal processes (DPI 2008). The majority of previous mitigation works in the area directly relate to the South Fremantle Power Station (SFPS) construction on the shoreline and mitigation works consist of three groynes and a rock revetment. Initially SFPS groynes 1 and 2 were constructed forming the intake area for the station however this resulted in the erosion of the beach south of the groynes and giving cause for the rock revetment construction to protect the shoreline. Groyne 3 was then constructed with the purpose of controlling sediment in the intake area and resulted in accretion north of the groyne. This also had the benefit of counteracting the down drift erosion to the south of Point Catherine.

The construction of Port Coogee Marina commenced in 2006 and consists of two breakwaters to protect the inner harbour water from waves and revetments within the marina forming two land reclamations. The outer breakwaters were complete by the end of 2006. Oceania Consulting Pty. Ltd. (2007) expects approximately 33 $000m^3yr^{-1}$ of sand to build up behind the northern groyne of the marina, which can be maintained by the use of a sand bypassing process, whereby sand is manually pumped from the northern beach to replenish the southern beach. This estimation was calculated assuming up-drift structures such as Point Catherine are saturated to account for future conditions. It was estimated the bypassing process would be necessary every three years. This thesis will compare simulations with the estimations in Hamilton & Hunt (2011) and access the validity of this management plan. Hamilton & Hunt's (2011) study is discussed in the next section.

As mentioned previously a variety of dredging operations have occurred in Cockburn Sound and will require remediation in the future to maintain maximum functionality. Initially the Gage Roads shipping channel was created for the safe navigation of ships during World War 1. They span an area approximately 8km long and 200m wide. The Cockburn Cement Limited dredging area exists to the east and spans an area of approximately 160ha. Shell sand for cement production was dredged at a rate of 2mil tonne per year in 2003 and was increased to 2.5mil tonne per year by mid-2010 (DAL 2003). These dredging operations change the bathymetric conditions and increase the amount of wave energy that can propagate into the nearshore zone and the sediment exchange with the ocean and adjacent sediment cells.

In 1973, the construction of the Garden Island Causeway was completed (Skene *et al.* 2005). It was constructed with the purpose of allowing vehicular traffic to access the naval base at Careening Bay. It links the south of Garden Island to the mainland at Point Peron. Two openings remain to allow some water exchange to remain however the originally 2km wide opening was reduced to a 305m and a 610m opening (DAL 2002). This has resulted in a reduction of 30-50% of the overall flushing time of the Sound resulting in reduced sediment exchange with the ocean (Department of Environmental Protection 1996).

2.8.2 Coastal Monitoring at Port Coogee

Prior to the approval and construction of the Port Coogee project, it went through an extensive Public Environmental Review (PER) process that considered its effect on the popular recreational beach adjacent the proposed marina. Hamilton & Hunt (2011) review how the impact on the surrounding coastline has been managed since its construction in 2006 through proper consideration of the coastal processes in the area. The paper reviews a series of 51 hydrographic surveys covering 4km of adjacent coastline and reviews the sand-bypassing operation (November 2009) which bypassed 15000m^3 material from the northern beach to the southern beach.

The PER investigation based on 1942-1994 data estimated a historical annual net southerly transport of 5000m^{3}yr^{-1}. This is expected to increase to 33,000 m^{3}yr^{-1} in future years as up-drift coastal structures such as Point Catherine become saturated with material (Bowman *et al.* 2005; Hamilton & Hunt 2011). The predicted sediment fluxes in Owen Anchorage are presented in Figure 6. It was predicted during the PER that the interruption of this southerly longshore transport would result in the formation of a 50m wide beach on the northern side of the marina within 4 years of its construction and erosion at a rate of 5000m^{3}yr^{-1} of Coogee Beach to the south. This was deemed unacceptable by the local community and authorities, prompting the implementation of the sand-bypassing program (Hamilton & Hunt 2011).

A semi-annual beach monitoring process has taken place since 2005 where hydrographic survey data sets are taken at the end of summer (March) and winter (September). Hamilton & Hunt (2011) review this data and it was shown that by 2009 a number of beach profiles exceeded the 5m recession trigger value. Net sediment fluxes were estimated for the period of 2005 – 2009 and it is estimated approximately 17,000 m^{3}yr^{-1} accumulated on the northern beach, which is far less than the predicted 33,000 m^{3}yr^{-1}. This was expected as the up-drift structures are not saturated yet. The southern beach experienced erosion at a rate of approximately 6750 m^{3}yr^{-1}, which is in excess of the predicted erosion of 5000 m^{3}yr^{-1}. These results are compared in Figure 6. Analysis of the offshore wave data from this period was used to determine the number of key events and determined an above average number of moderate and severe storm events in the years since construction of the breakwaters. This is assumed to potentially increase beach erosion and the southerly transport. Hamilton & Hunt (2011) suggest that the excessive recession experienced on the southern beach was not a result of the Port Coogee development but a result of the increased storm activity during these years. This suggestion is reviewed in this thesis.

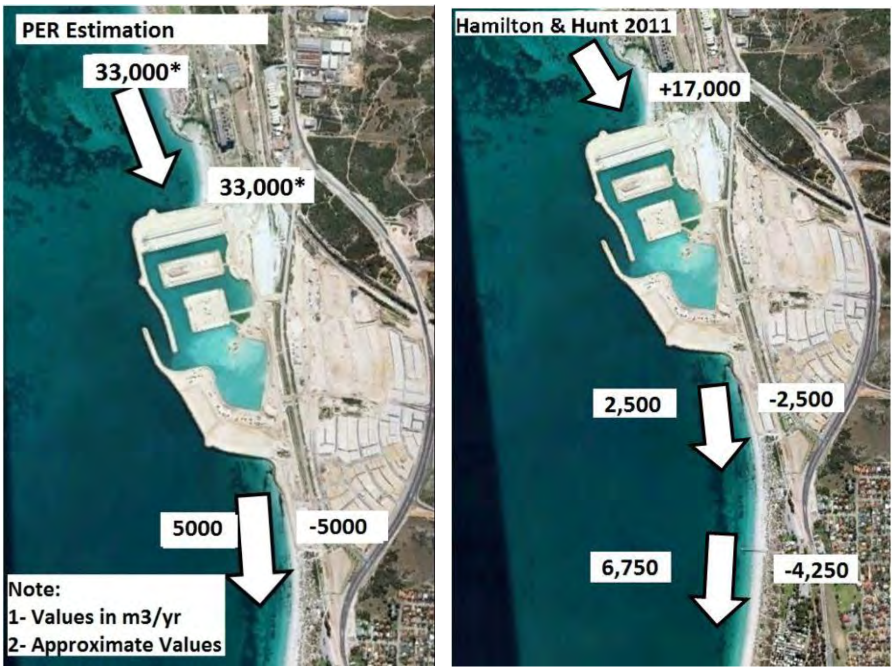

Figure 6: Estimated net sediment movement 2005 to 2009 prior to first sand bypassing operation. (Hamilton & Hunt 2011)

2.9 Shoreline Response

The structure, geology and availability of source material, combined with spatiotemporal variation in wave forcing, currents and sediment transport results in beach profile and planform morphologic responses (Stul 2005). These shoreline responses have a complex feedback relationship with the hydrodynamic forces (Wright & Thom 1977). Masselink & Pattiaratchi (2001b) characterised Perth by a net northward littoral drift through the summer months and a net southerly littoral drift in winter due to the persistent weather systems (Figure 7) while the Owen Anchorage shoreline is shown to experience a net annual southerly littoral drift (Figure 6). The driving factors of this unique characteristic are analysed within this thesis. The longshore sediment transport rates are significantly larger than the cross-shore transport rates due to the large longshore currents experienced (Masselink & Pattiaratchi 1998a).

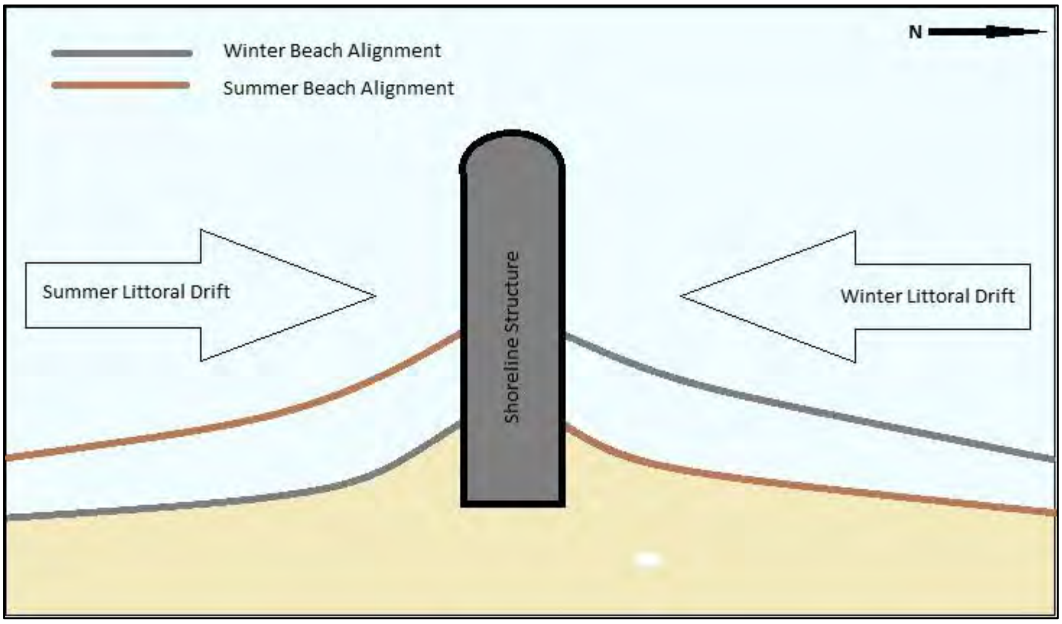

Figure 7: Characteristic littoral drift of Perth, Western Australia

Structures built in the nearshore zone will not only alter the local wave and current climate but also have a significant effect on the sediment transport processes (Walker *et al.* 1991). An element of the design process of any nearshore structure is estimating the impact on the bathymetry. The given structure can be designed primarily to change the bathymetry such as the construction of Point Catherine or to have negligible effects such as a harbour or marina. Being such an integral part of coastal developments such as that at Coogee, many studies have been conducted to predict the shoreline response to coastal structures.

Early studies into the effects of structures in the nearshore zone were often physical models, which have been found to be often unreliable due to sediment scaling effects (Walker *et al.* 1991). This has led to the development of numerical models. Walker *et al.* (1991) developed a bathymetric evolution model to predict the bottom changes where structures are present. This model employs finite difference models of the wave and nearshore current climate and uses the information provided by these to predict the behaviour of sediment transport near the structure. Kraus *et al.* (1996) presented a literature review that synthesised previous knowledge on beach profile change, longshore sediment transport and scour in the vicinity of seawalls. Seawalls can interrupt the natural excursions of the beach between its natural summer (swell) and winter (storm) conditions. It suggests that the scour experienced is a result of longshore transport rather than direct cross-shore wave action and questions the validity of physical models.

Hard structures attached to the shore such as groynes, breakwaters and jetties induce a similar shoreline response to that of a headland. That is interrupting the natural littoral drift processes and ultimately depriving the down drift beaches of sediment (Short & Masselink 1999). Masselink & Pattiaratchi (2001b) considered the littoral drift characteristics between Fremantle and Trigg and found a net northward littoral drift in summer and a net southward littoral drift in winter due to the local weather conditions and sea breeze activity. It was found that this shift in littoral drift was exemplified in the vicinity of coastal structures. Beaches to the south of these structures accumulated sediment in summer due to the northward littoral drift and eroded through the winter months while the beaches to the north of the structures showed the opposite trends (Masselink & Pattiaratchi 2001b). (Figure 7)

Masselink & Pattiaratchi (1998a) considered the effects of the seabreeze on Perth's beach morphology and noted a six-fold increase in the suspended sediment load. The net sediment transport during summer was estimated as 100,000 m^3yr^{-1} (Pattiaratchi *et al.* 1997). Tonk (2004) used an impoundment study and a combination of streamer traps and optical backscatter sensors to determine a higher rate of 138,000-200,000 m^3yr^{-1}. Pattiaratchi *et al.* (1997) was based at Trigg beach, while Tonk (2004) was based at City Beach. Bowman *et al.* (2005) suggested that the northern beach at Port Coogee tended to rotate between its summer and winter alignments while Coogee Beach to the south of the development was more protected from the sea breeze due to Woodman Point and does not rotate significantly from winter to summer. This is validated in Chapter 4.

CHAPTER 3. METHODS AND PROCEEDURE

For the purpose of this study, the Danish Hydraulic Institute's (DHI) Mike 21 coupled FM (flexible mesh) model has been utilised. This coupled model enables dynamic simulation of waves and currents and provides full bathymetric evolution making it ideal for this project. This section provides an introduction into the modelling software, followed by an account of the model setup used for this project and a summary of the primary simulations. The results of these simulations are presented in the next chapter.

3.1 Mike21 FM model

The coupled model is composed of several components including hydrodynamic (HD), spectral wave (SW) and non-cohesive sediment transport (ST) modules. This enables dynamic simulation of the interaction between waves and current at each time step and includes full feedback of bathymetric evolution to calculate sediment transport rates via the ST model. This process is presented as a schematic in Figure 8. This software package has been used extensively throughout the world for analysing hydrodynamics, wave dynamics, sediment transport and water quality related processes in coastal and estuarine environments. It has also been a tool for the design and optimisation of coastal structures such as the seagrass wrack analysis of Port Geographe, Busselton by Pattiaratchi & Wijeratne (2011).

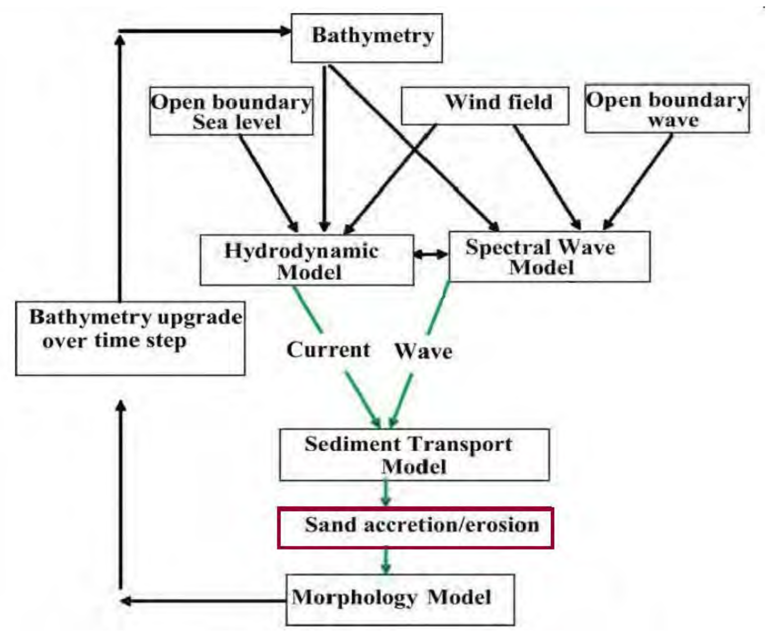

Figure 8: Schematic of coupled MIKE21 FM model (Pattiaratchi & Wijeratne (2011))

3.1.1 Hydrodynamic (HD) Module

The hydrodynamic (HD) module calculates the flow field by solving depth averaged continuity and momentum equations. This module can be forced by water level fluctuations and waves at the open boundaries and by a wind field over the entire domain. By coupling this module with the SW and ST modules, the movable seabed updates at each computational time step allowing the hydrodynamic flow calculations to be carried out with dynamic bathymetric information.

3.1.2 Spectral Wave (SW) Module

The inbuilt spectral wave (SW) module simulates the transformation of offshore waves as they propagate to the nearshore zone. The SW module is a fully spectral wave model capable of modelling the evolution of a 2D wave energy spectrum against time. Mike21 iteratively couples these modules to model wave-current interaction and includes all relevant wave phenomena such as shoaling, breaking, refraction and wind generated waves. This module is forced using wave data on the open boundaries and wind fields over the entire domain. The coupled model simulates wave, current and rates of bed level change and includes feedback from the developing bathymetry to all additional modules.

3.1.3 Sediment Transport (ST) Module

The sediment transport (ST) module is used to analyse the sediment transport and bathymetric evolution. This module calculates rates of sediment transport for non-cohesive (sand) sediments. Either pure current driven or combined current-wave driven sediment transport can be modelled. The ST model interprets the outputs from the coupled model to integrate water level, flow and wave climate information. Using this data the model updates the bathymetric data at each computational time-step and provides this feedback to all modules.

3.2 Model Setup

3.2.1 Boundary and Computational Grid

The initial and most critical stage of setting up the sediment transport model is to input the boundaries and bathymetry of the project domain to create the computational grid. The boundary used in this study extends north to Yanchep, south of Point Peron and west of Rottnest Island. The northern boundary was chosen so the software can simulate the transformation of waves due to the Pleistocene dune ridge system and model the unique southward propagation into Owen

Anchorage from the north. The southern boundary was chosen due to the minimal sediment transfer recorded through the southern boundary of Cockburn Sound (Steedman & Craig 1983). Google Earth software was used to create the coastline alignment and this was used in DHI's inbuilt mesh generator. Initially a boundary that extended west to the Rottnest Island wave buoy and north to Hillarys was trialled. The smaller boundary encountered issues as the wave data were forced too close to Owen Anchorage and caused unrealistic results. Changing the western boundary also required updated wave data and this is discussed in section 3.2.2. The larger domain was chosen which resolved this, however resulted in a significant increase in computational requirements. The boundary and computational grid used is presented in Figure 9.

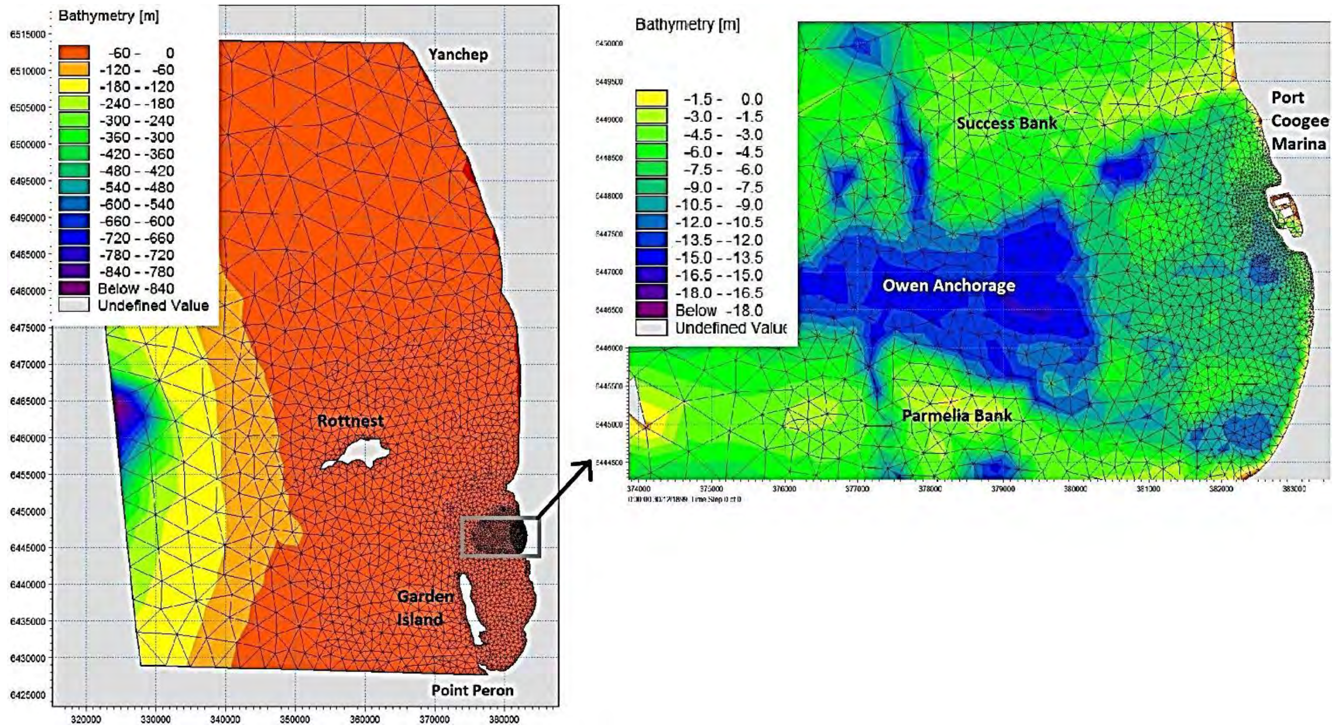

Figure 9: Model boundary and computational grid

The bathymetric data used is a combination of LIDAR data and data taken from the grid used in Stul (2005). This was input with a grid resolution of 10m for an area of approximately 35ha surrounding the marina, 30m resolution west to Rottnest and 1000m resolution for the remaining offshore regions.

Using DHI's inbuilt mesh generator a series of trial unstructured triangular mesh were created. Initial results had shown unrealistic, excessive scour around the pockets and outer corners of the marina. It was discovered to be a result of a mesh that was too coarse to simulate the shedding of eddy-currents off the marina's outer breakwaters. The mesh was refined to a minimum area of 200m^2 (20m resolution) for the area in the nearshore zone adjacent the marina. The mesh was refined such that it created a smooth transition of increasing element sizes to a maximum of 1400ha (5km resolution) size elements in the offshore regions to the northwest of the domain. This smooth transition of increasing element sizes was also used along the entire coastline with increasing distance from Owen Anchorage. The mesh was refined around complex coastline alignments such as that experienced at Rottnest and Garden Islands to a resolution of approximately 300m. Minimal elements were used within the walls of the marina as the flows within the marina are outside the scope of this project. Only sufficient elements to allow flow in and out of the marina were created, as the entrance opens into the southerly sediment transport direction.

3.2.2 Model Forcing Data

Forcing data was taken from various sources and applied on the three open-water boundaries, along with wind data applied as a field over the entire domain to drive the HD and SW modules. This section will present the data used for waves, water level fluctuation and meteorological inputs and discuss the reasoning behind the selected data.

Waves

The wave data were taken from the model proposed by Bosserelle *et al.* (2011) as discussed in section 2.4.4. This data was provided as a profile series and was applied to the entire western boundary of the model. The northern and southern boundaries were modelled as lateral boundaries. The wave data were provided with a 3-hour time-step. This data will form the offshore component of the model's wave field and the SW module will simulate the wave transformation as the waves propagate into the nearshore zone. This data was chosen in favour of the recorded Rottenest Island wave buoy data as the data recorded in this location has already been affected by significant wave transformation by features such as the Continental Shelf. The Rottnest buoy is located immediately southwest of Rottnest (32˚05'39"S, 115˚24'28"E) in approximately 48m of water (Department of Transport 2011). The dataset output from Bosserelle *et al.* (2011) is created for the exact location of the desired boundary. It also has the benefit of applying the subtle differences in wave characteristics over the extent of the boundary that plays a minor role when considering the size of the chosen domain. An example of the propagating waves is presented in Figure 10.

The data provided included significant wave height (H_s, m), peak period (T_p, s) and mean wave direction (˚). Directional spread (˚) accounts for the variability of wave direction. Generally, shorter period waves are characterised by a larger directional spread as their directions are more variable. For the purpose of this study, directional spread was calculated using the following empirical relationship (1) suggested by Bosserelle et al (2011).

$$Directional\ Spread = \frac{(T_p - 5) + 12(20 - T_p)}{3} \tag{1}$$

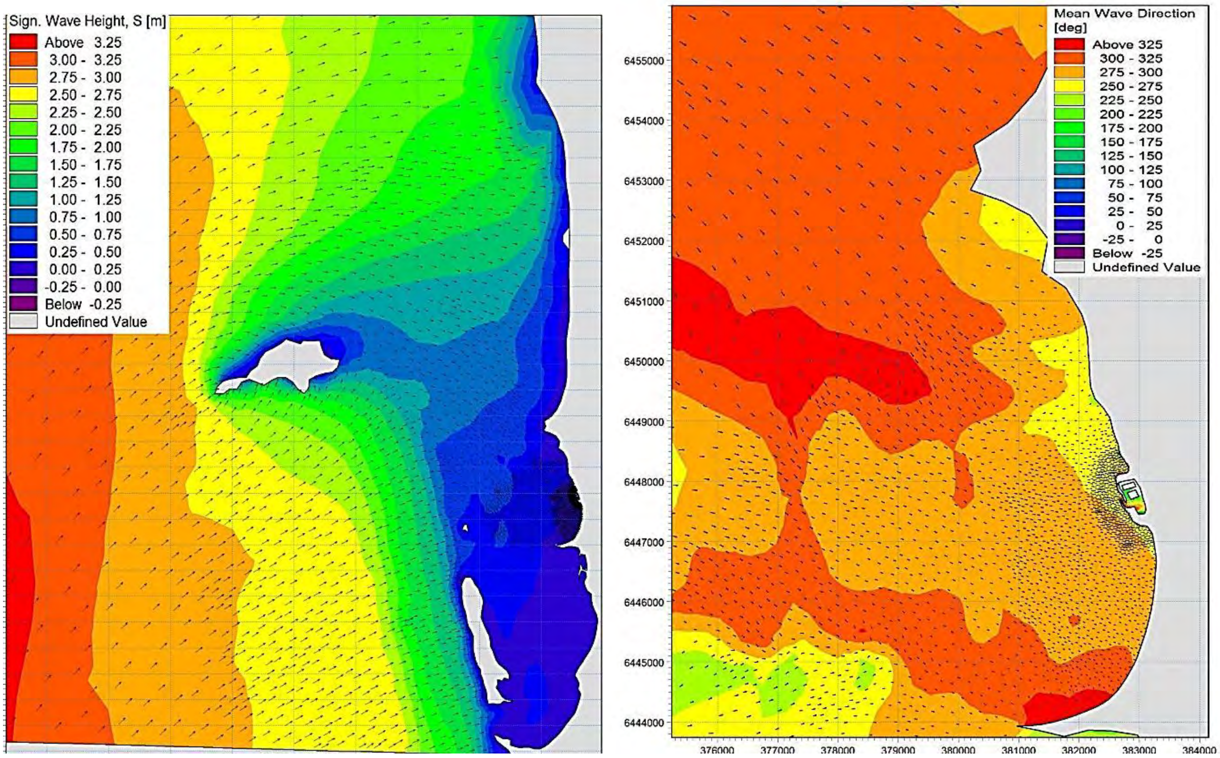

Figure 10: Wave transformation from western boundary. Left: H_s (m) from western boundary, Right: mean wave direction (˚) within Owen Anchorage (example: July 2009)

Water Level Fluctuation

Water level fluctuation data were taken from Haigh & Pattiaratchi's (2010) depth-averaged tide-surge model discussed in section 2.5. This accounts for both the astronomical and storm-surge components of water level fluctuation. This is critical for locations such as Perth where the storm-surge component can significantly exceed the astronomical component (Hegge *et al.* 1996; Stul

2005). This data was available in a 1-hour time-step. This enables the simulation of the rapid change in tidal flow direction. The unfavourable option for this boundary condition was to apply measured data from the Fremantle tide gauge with a time variation between the northern and southern boundary. This is a common approach for small hydrodynamic simulations. Given the size of the project domain, this was not applicable as this method would force flow in a directly north-south oscillating direction, which does not accurately model the characteristics of this environment on a larger scale. The chosen data was applied as a profile series along all three open boundaries (northern, southern & western). Using a profile series data file enabled the water level fluctuation to vary along the full extent of the boundaries, accounting for minor changes in tidal range between the northern and southern extent of the domain.

Meteorology

For the purpose of this study, only the wind component of the local meteorology was considered as factors such as differential barometric pressure were expected to have only a minimal effect on the results of this study. Wind data for 2009 were taken from the Rottnest meteorological station dataset with a time step of 30-minutes. This shorter time-step is beneficial when simulating rapidly changing wind speed and directions such as that characterising the local sea-breeze system. Data includes wind speed (ms^{-1}) and direction (˚). The wind field was applied only varying with time, not in domain and was applied as a constant field over the entirety of the domain. Incorporation of wind speed & direction varying over the domain would enable simulation of minor wind transformations due to sheltering by structures and coastal features. This information is very difficult to gather. The wind field is used to drive both the hydrodynamic and spectral wave modules enabling the dynamic simulation of both wind driven currents and waves. The friction factor for wind driving currents was chosen to vary with wind speed. The friction values used range from 0.001255 at $7ms^{-1}$ to 0.002425 at $25ms^{-1}$. These are default values used in MIKE21. This method was chosen in favour of a constant friction factor, as the model will be simulating more extreme winter events with large wind speeds.

3.2.3 Other Parameters

The coupled model incorporates a number of parameters and coefficients in all modules. These include sediment properties, friction factors to calculate flow rates and wave transformation and wave shoaling coefficients to incorporate energy dissipation from shoaling and breaking waves.

For this initial model, the site-unique factors such as the sediment parameters and bottom conditions have been considered only. The bottom friction was expected to have a significant impact on the wave transformation and was believed to play a dominant role causing the unique southerly littoral drift experienced. Coefficients for wave energy dissipation were kept as the default values.

Sediment parameters were chosen with consideration for the previous research by Skene *et al.* (2005) discussed in section 2.2. The mean grain size was taken as 0.34mm which coincides with sediments found on the large carbonate sand banks (Parmelia & Success) which are assumed to be the primary source of deposited material on the coastline at Owen Anchorage (Skene *et al.* 2005; Hamilton & Hunt 2011). The default value of 0.4 was used for sediment porosity. These sediment parameters were applied as a constant value over the entire domain. This is not entirely accurate as the sediment parameters differ significantly over the domain. As this study is only considering sediment transport directly adjacent the marina, this was believed to provide sufficient simulation of the sediment transport from Success and Parmelia banks to the coastline. The outer regions of the domain exist primarily for simulating wave-current interaction and it has been shown in previous research that there is little sediment exchange between Owen Anchorage and the open ocean. The sediment properties of these outer locations were assumed not to be critical to the simulation.

Consideration needed to be given to the Pleistocene dune ridge system and its resulting wave transformation caused by differential bottom friction factors (f_w). Initially the default value of 0.02 was applied over the entire domain, which is a commonly used value for carbonate type sands. This was seen as a source of large inaccuracy in the areas with reef-like bottom conditions. It was expected that a component of the wave transformation experienced over this ridge system can be attributed to increased f_w due to reef bottom conditions. A friction factor of 0.3 in the vicinity of reef is being used in current research. This value was applied for the previously mentioned dune ridge system and minor reef systems near Hillarys and Cottesloe as shown in Figure 11. Incorporation of this factor resulted in well-modelled wave transformation forcing the net southerly wave propagation experienced in Owen Anchorage. This wave transformation is well represented in Figure 10.

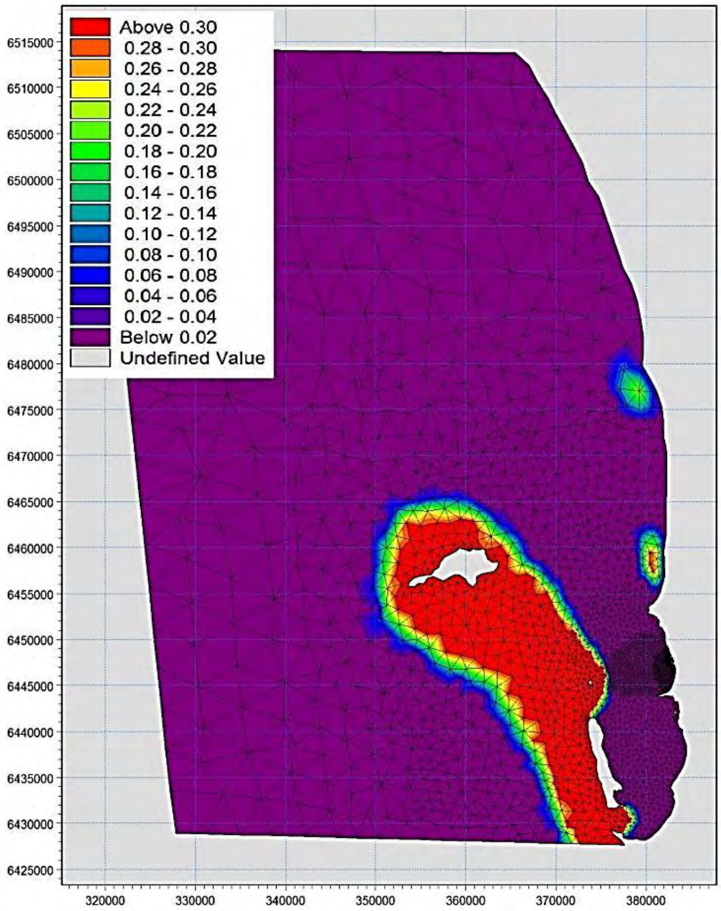

Figure 11: Friction factor (f_w) variation over domain

3.3 Simulations

This section summarises the techniques and parameters used in the different simulation phases of this project. Prior to the primary simulations used for analysis a series of trial simulations were undertaken. The purpose of these trial simulations was to ensure sufficient modelling of all the input forcing data individually. Trials were then undertaken for individual events such as extreme storm events in July or sea breeze events in summer to ensure the model's capability to handle a range of conditions. A short time-scale of 4-7days of data was used for this trial purpose. These only required approximately 1-day of computational time each. Once satisfied with the trial simulations the parameters were used to undertake the primary coupled simulations. These required significant computational time, often in the range of 1-2weeks.

Simulations were undertaken for the three months of winter to consider the impact storm activity and extreme storm events have on the coastline. These simulations were undertaken individually for June, July and August as the focus was on the impact of individual events, which could later be compiled to analyse the impact of the entire winter season. This also had the benefit of faster computational time as the three simulations could be undertaken simultaneously on separate systems. A simulation was then carried out to consider the effects of the persistent summer sea-breeze system on the nearshore processes. This was to provide a comparison of the impacts on the coastline between the different summer and winter regimes.

Initially all simulations began using a 1-hour time-step and this required copious computational time. It was discovered during the trial phases that increasing this time-step up to 4-hours had negligible impact on the results. A time-step of 4-hours was chosen for the winter models while a shorter 3-hour time-step was chosen for the summer model. This was to incorporate the rapid change in direction of the sea breeze while still maintaining reasonable computational requirements. The four primary simulations are summarised in Table 3. The results and analysis of the simulations are discussed in Chapter 4.

Table 3: Summary of primary simulations

Simulation no.	Month	Time Step (hours)	Modules
1	June 2009	4 (14400s)	HD, SW, ST
2	July 2009	4 (14400s)	HD, SW, ST
3	August 2009	4 (14400s)	HD, SW, ST
4	February 2009	3 (10800s)	HD, SW, ST

CHAPTER 4. RESULTS & DISCUSSION

This section will present the results and analyse the simulations mentioned in Table 3. Key features of the nearshore processes shown by the model to drive the sediment transport around the marina are discussed. Sediment budgets are presented for each simulation that clearly show correspondence between increased storm activity and excessive erosion from the southern beach. These sediment budgets are compared with those presented by Hamilton & Hunt (2011) to validate the results of this numerical method.

4.1 Winter 2009

Full bathymetric evolution models were undertaken for June, July and August 2009. Results from all three models have shown the net southward littoral drift expected, which intensifies during storm events. An example of this dominant net southward current is presented in Figure 12.

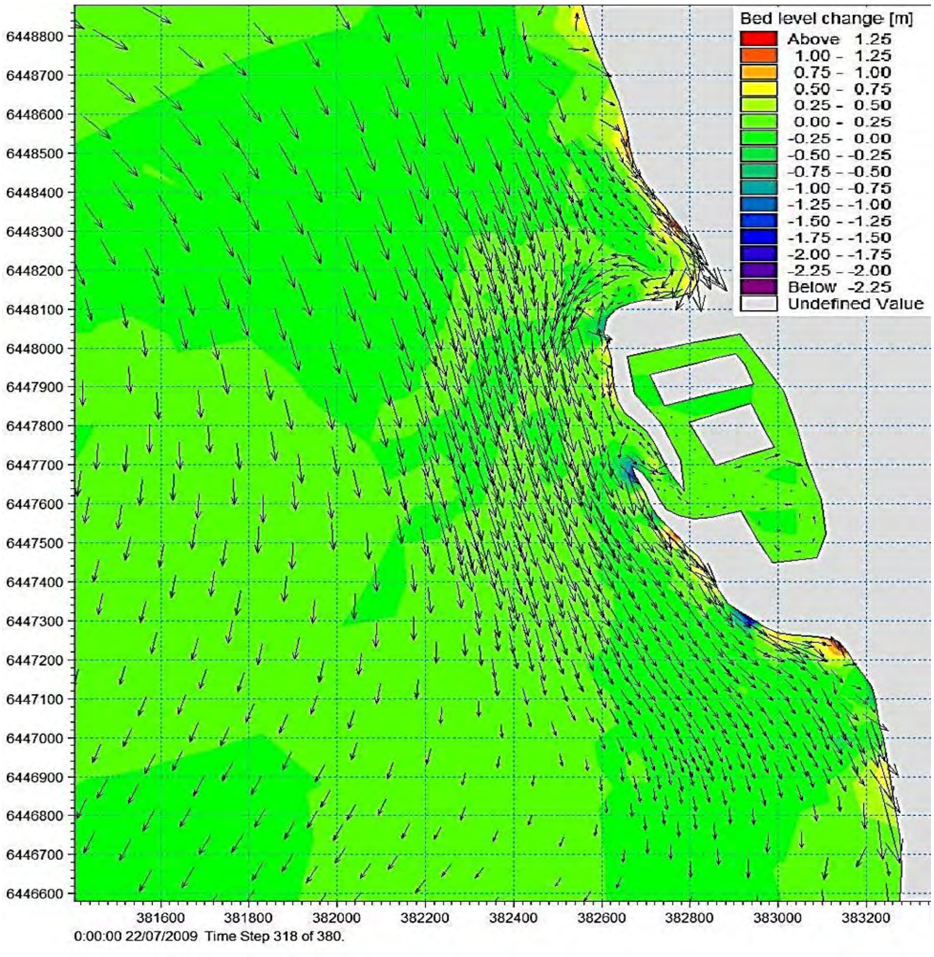

Figure 12: Dominant winter southerly nearshore current (22/July/2009)

Using the cumulative bed level change during each month a net accumulation on the northern beach and net erosion from the southern beach was estimated. This coincides with the measured net sediment transport presented within Hamilton & Hunt (2011). This phenomena still occurs even under the influence of strong southerly winds. Figure 13 presents a comparison between wind direction and mean wave direction. In the example, the mean wave direction is propagating from a north-westerly to westerly direction even when under the influence of a 11ms^{-1} south-westerly wind field. The higher energy winter offshore waves penetrate deeper into Owen Anchorage and are shown to be less sensitive to the wind conditions.

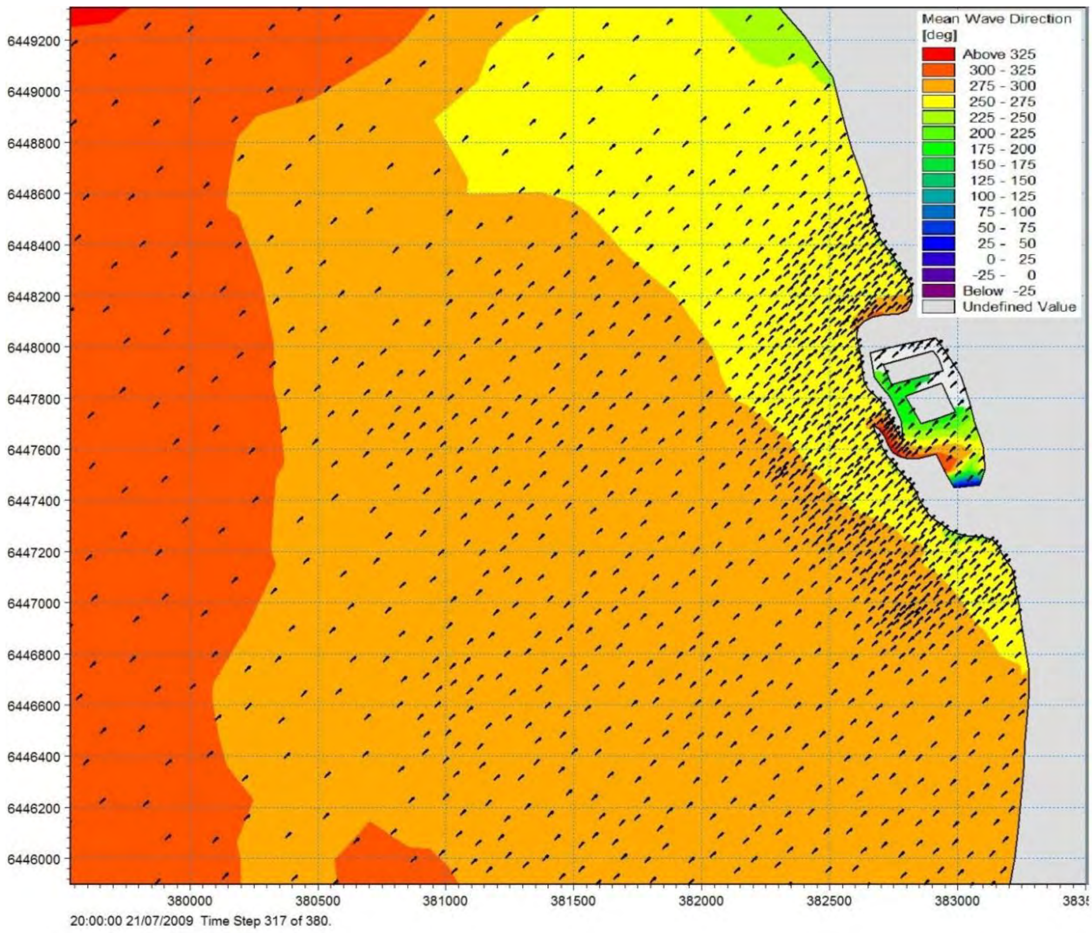

Figure 13: Wind direction (vectors) vs. Mean wave direction (chromatically indicated); (21/7/2009 20:00, wind speed = 11ms^{-1})

In addition to this, eddy-currents form off both ends of the marina causing a unique sediment transport processes at each beach. The northern eddy forces a southward littoral drift into the northern pocket, resulting in net accumulation in this area. This eddy forces this accumulation even under the influence of southerly winds, suggesting it is also a dominant driving force of the net southerly sediment migration. The southern breakwater eddy-current approaches the beach and splits eroding the beach and forcing the majority of material in a southward direction. A minor accumulation is experienced in the southern pocket of the marina. The southward sediment migration dominates the south beach system however, resulting in net erosion. This eddy-current process is presented Figure 14.

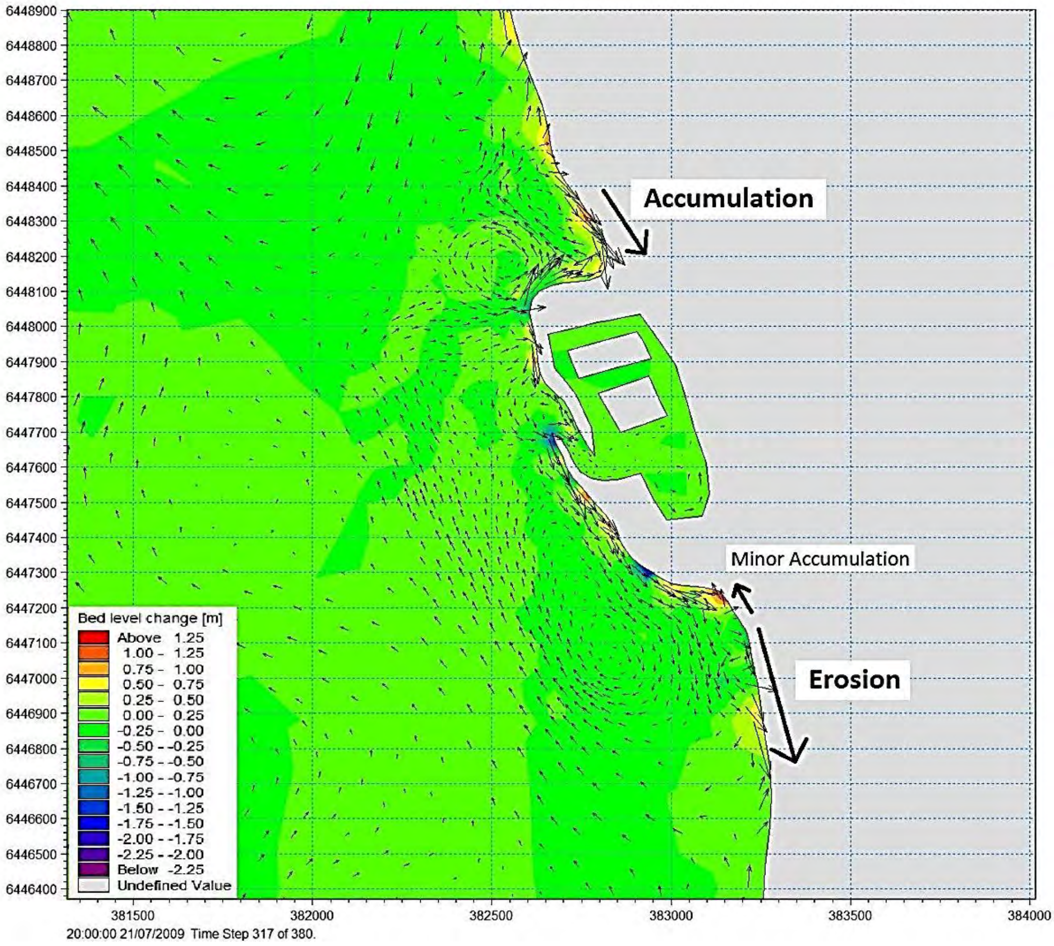

Figure 14: Winter eddy-currents forcing sediment activity (21/July/2011)

To calculate sediment budgets only the pocket of beach immediately north and south of the marina, which are directly impacted by the marina have been considered. The bed levels (m) at three intervals during winter are presented in Figures 15 through 17. These figures show a good representation of the sediment migration experienced. The northern pocket of the marina shows net accumulation. The southern beach shows net erosion and the migration of material primarily in a southward direction is evident. As a result of this erosion, the beach profiles steepen. This steepening is most evident after the large storms in July 2009. The minor accumulation in the northern pocket discussed previously is clearly notable from these bathymetric plots.

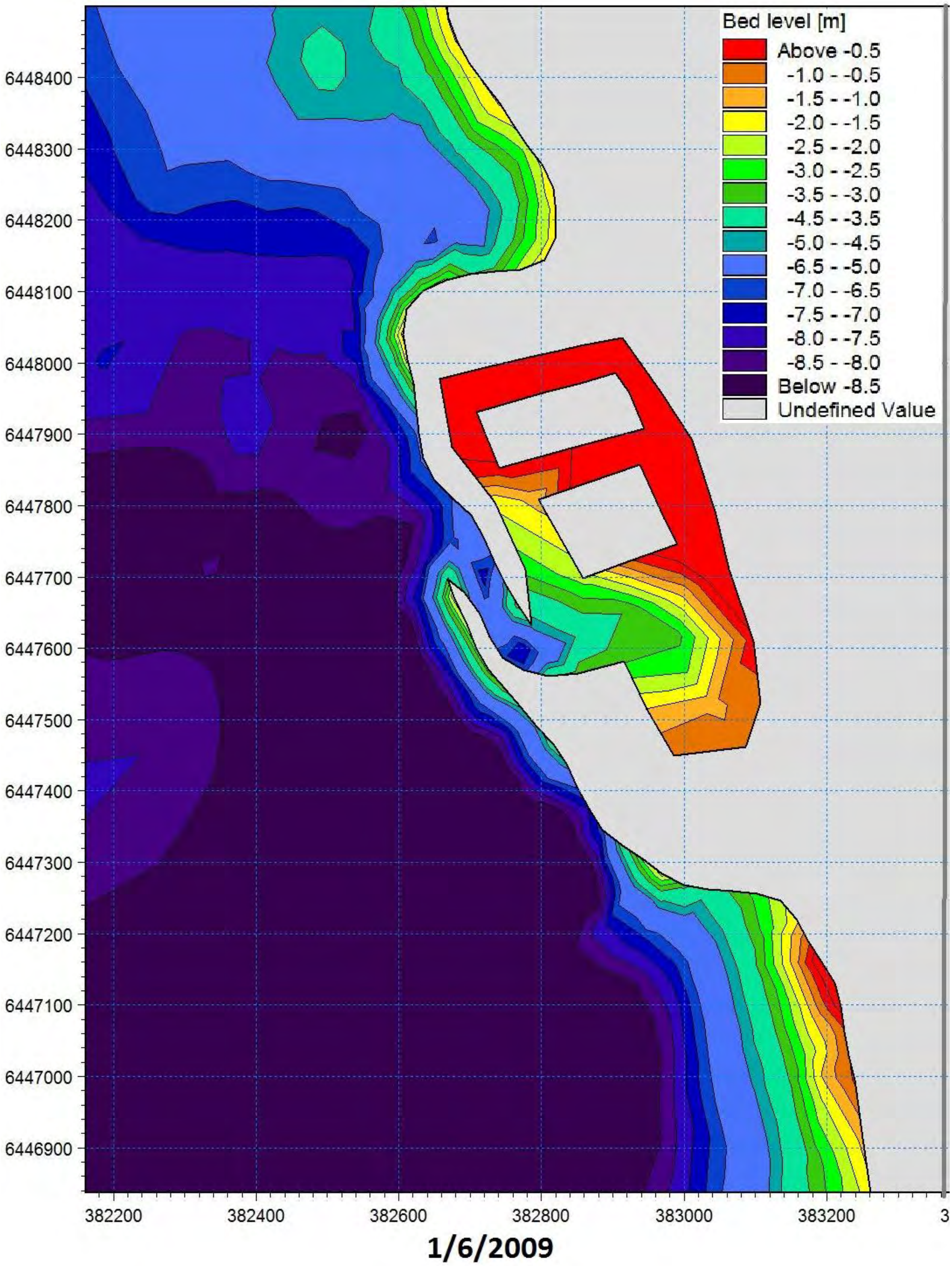

Figure 15: Port Coogee nearshore bed level (m) 1/June/2009 00:00

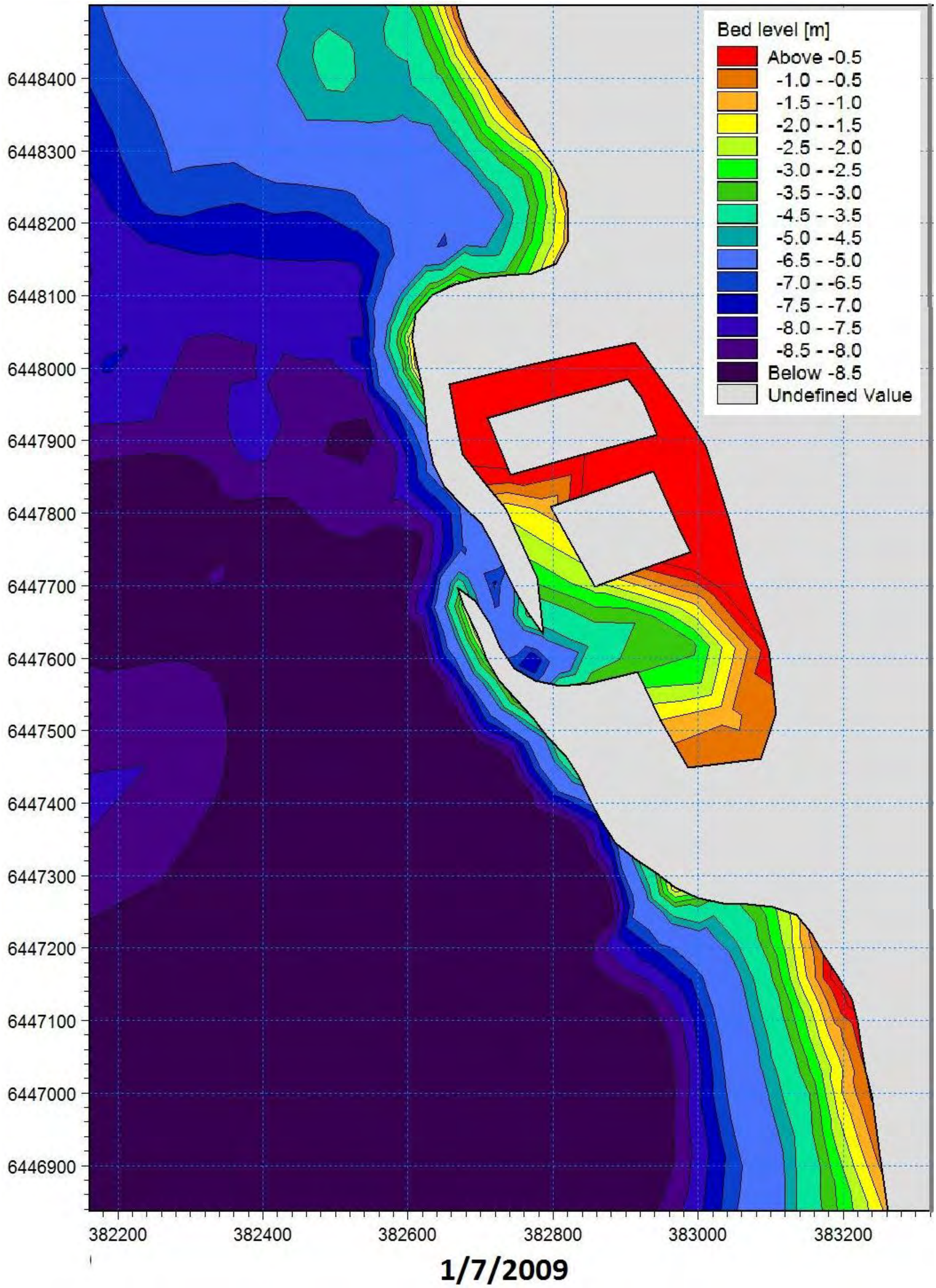

Figure 16: Port Coogee nearshore bed level (m) 1/July/2011 00:00

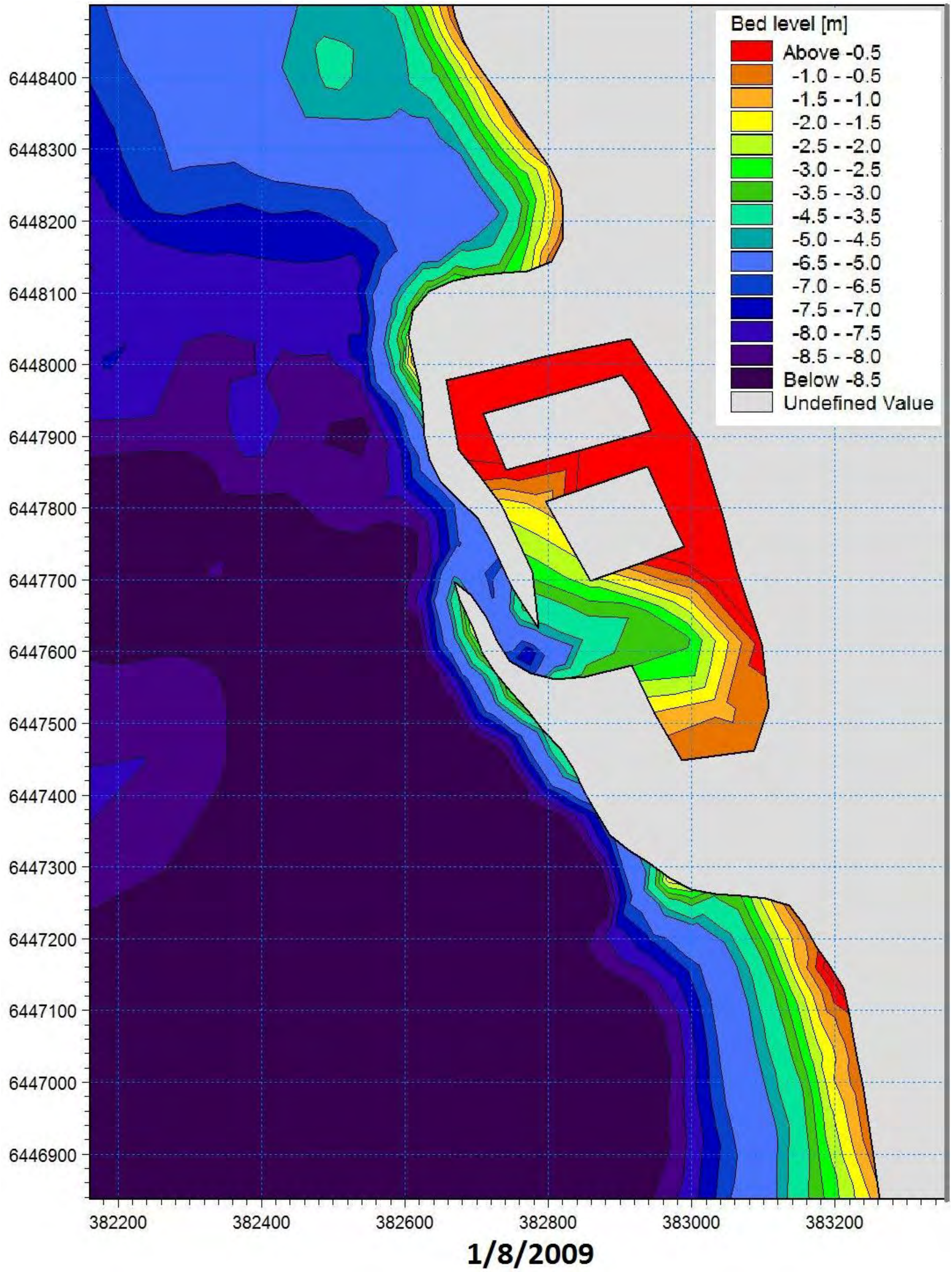

Figure 17: Port Coogee nearshore bed level (m) 1/August/2011 00:00

The sediment volumes were calculated using the following equation:

$$\Delta v^t = \sum_{j=1}^{n} \Delta a_j (h_j^t - h_j^{t-1}) \tag{2}$$

Where Δv is total accumulated or eroded sand volume in a selected area, Δa is the mesh element area and h is the bed level. The total number of elements within the selected area is n and t denotes the time step. Using this method the sediment budgets for the winter months were created and are presented in Figure 18. The calculations used to form these sediment budgets are given in Appendix B.

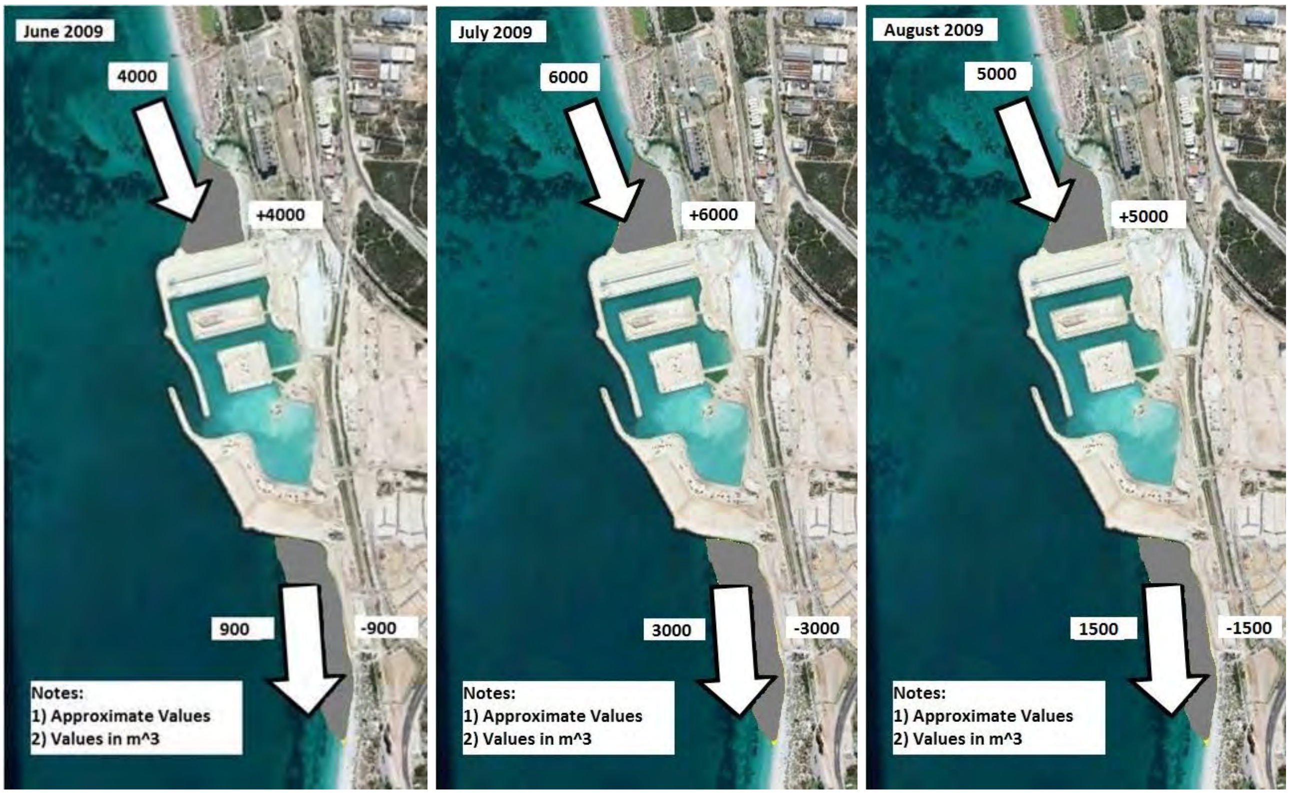

Figure 18: Port Coogee winter 2009 sediment budgets 1/6/2009 – 1/9/2009

July experienced the most sediment activity coinciding with the larger storm activity occurring during this month. An increase in both accumulation and erosion rates occurred during the storm events of July 2009. The southern beach shows higher sensitivity to increasing storm activity. Approximately a 3-fold increase in erosion from the southern beach is shown between June and July. The erosion from the southern beach during winter totals approximately 5400m^3, which comprises 80% of the net annual erosion from the entire southern beach estimated by Hamilton &

Hunt (2011). This shows the erosion from the southern beach occurs primarily during the winter months and highlights the sensitivity of the coastal system to the frequency and intensity of storm events coinciding with the conclusions of Hamilton & Hunt's (2011) research.

4.2 Summer 2009

Due to the predictable and common nature of the summer sea breeze system in Perth it was decided to undertake a summer model for the month of February only to further the understanding of the summer sediment transport processes in Owen Anchorage. As discussed in section 2.7 the summer wind system plays a dominant role in determining the nearshore processes as the shorter period wind-generated waves are less susceptible to refraction and can approach the shore at larger angles and due to the sheltering from offshore swell waves. The separation of the swell and locally generated waves emphasises this and is shown in Figure 19.

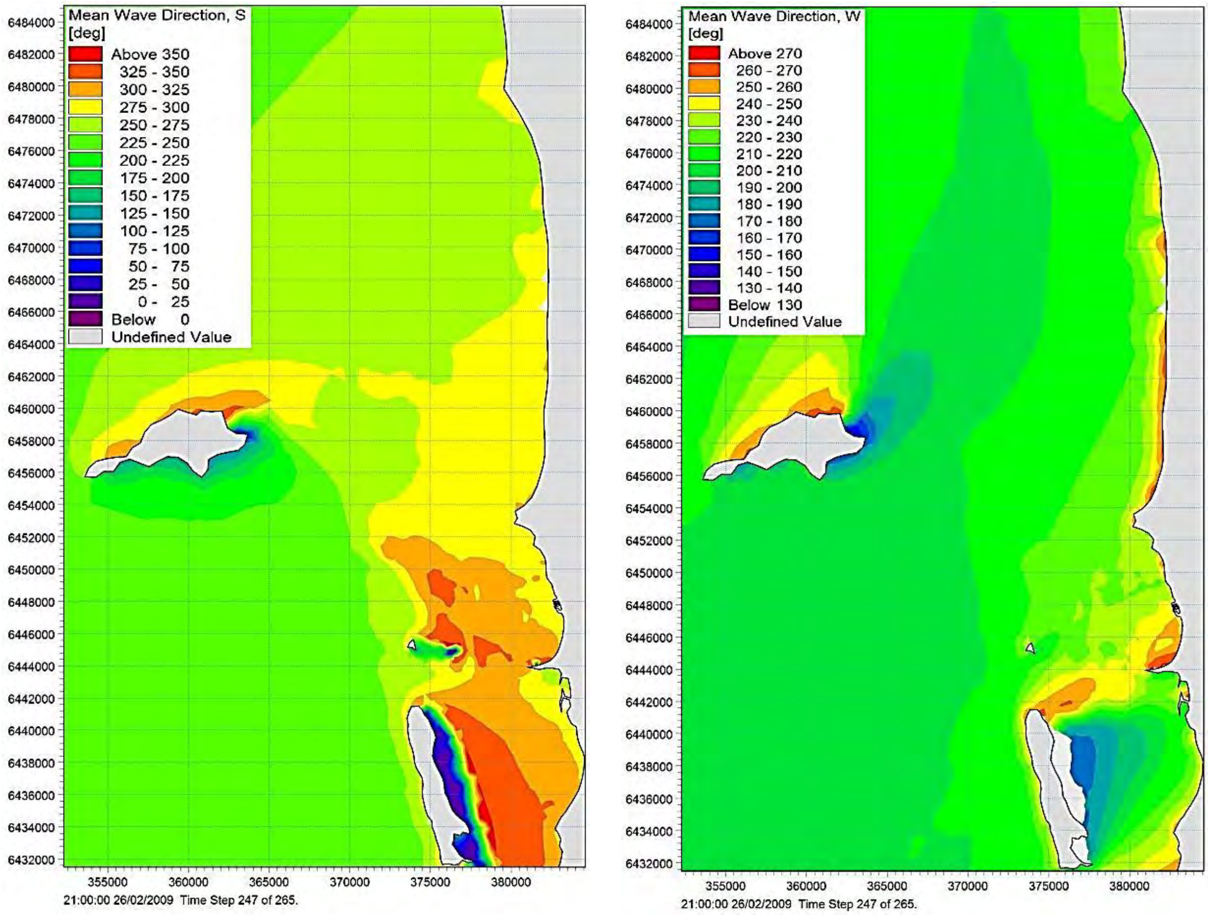

Figure 19: February 2009, Wave direction (˚) Left: Swell waves, Right: Wind waves

The locally generated waves are separated from the swell waves by the peak period (T_p). Waves with a period higher than 8s are classed as swell and those with a shorter period classed as locally generated wind waves. This is a commonly used parameter in spectral wave models and is the default value used in the MIKE21 model. The longer period swell-waves show more susceptibility to refraction and significant transformation occurs because of the dune ridge system. This results in more of a northerly component being present in the penetrating swell waves. The wind-waves shown in the right-hand diagram (Figure 19) show less transformation over the dune-ridge system and their direction is influenced by the wind direction. As a result of these dominant wind-waves through summer an overall northward current is experienced for the majority of the month. This can be seen in Figure 20.

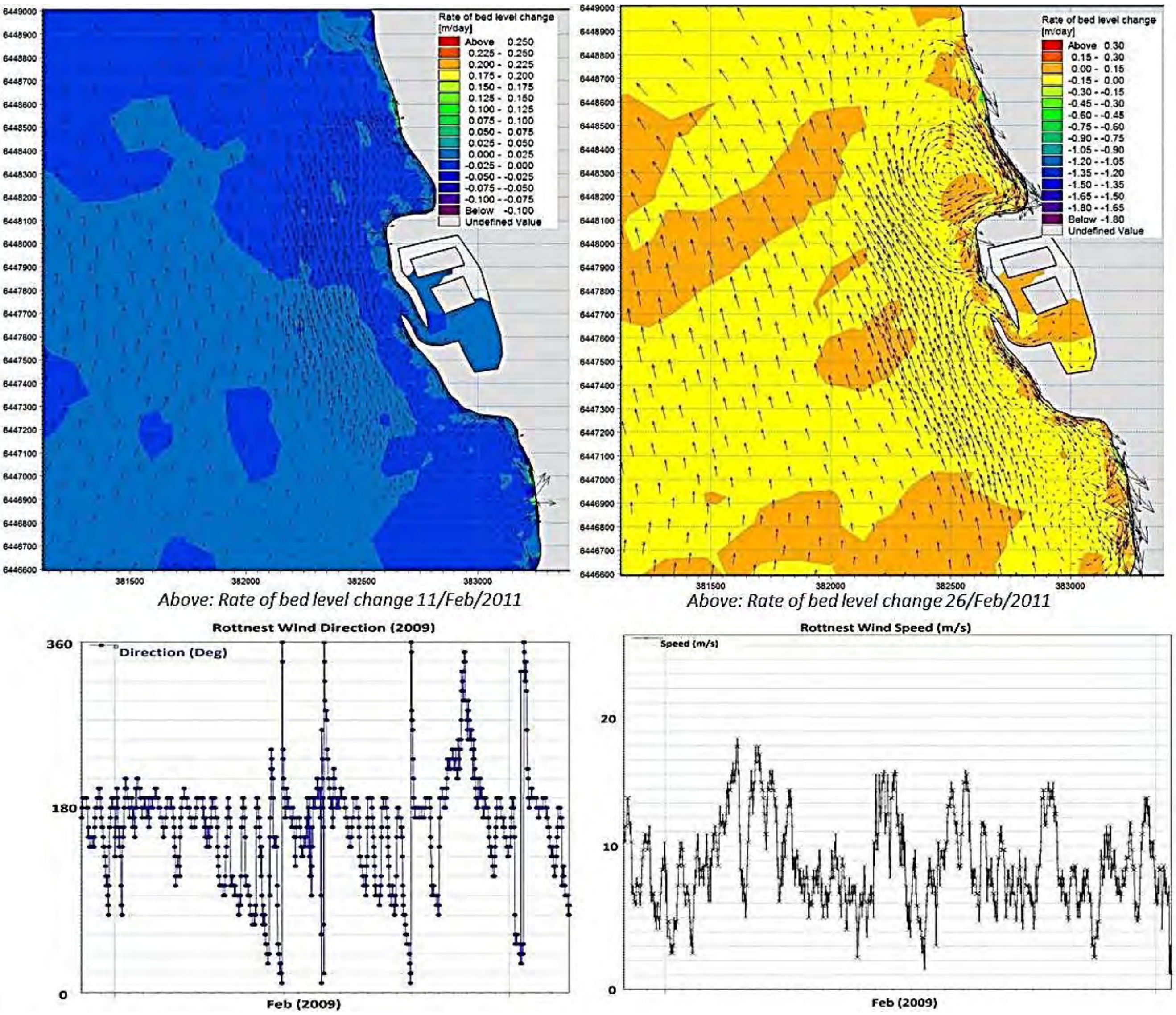

Figure 20: Rate of bed level change (m/day) comparison (11/Feb/2009 & 26/Feb/2009)

An eddy-current phenomenon similar to that experienced during the winter months occurs off the northern breakwater during the summer months. This is a common event during strong sea breezes or during rapid changes in wind direction and drives significant increases in the rate of bed level change (m/day). Figure 20 shows a comparison between the days of 11th/Feb/2009 and 26th/Feb/2009. The latter date experienced higher and more variable wind speed and direction and has shown approximately a 6-fold increase in the rate of bed level change (m/day) from the example on the left. The majority of sediment transport during summer occurred during these events. Similarly, to the winter months, this eddy-current forces a southerly littoral drift on the northern beach even when under the influence of a strong southerly or southwest sea breeze. This phenomenon plays a dominant role in the accumulation of material on the northern beach. The eddy-current off the southern breakwater is less dominant during the summer months and the locally generated waves dominate the southern beach nearshore zone resulting in a net accumulation on this beach. This is a complete reversal to the process experienced on the southern beach during the winter months.

Figures 21 and 22 present the bed level (m) of the nearshore zone directly adjacent the marina at the beginning and end of February 2009. The net accumulation on both beaches is evident from this comparison. The northern beach experiences accumulation in a similar manner to that experienced during the winter months while a reversed littoral drift influences the southern beach profile. This drives a net sediment accumulation on the southern beach. From the diagrams shown the beach profile shows only minor changes to its gradient during the summer months suggesting even deposition over the slope. The magnitude of the bed level changes through the presented summer month are significantly less than those experienced during the winter months suggesting the system is more sensitive to storm activity.

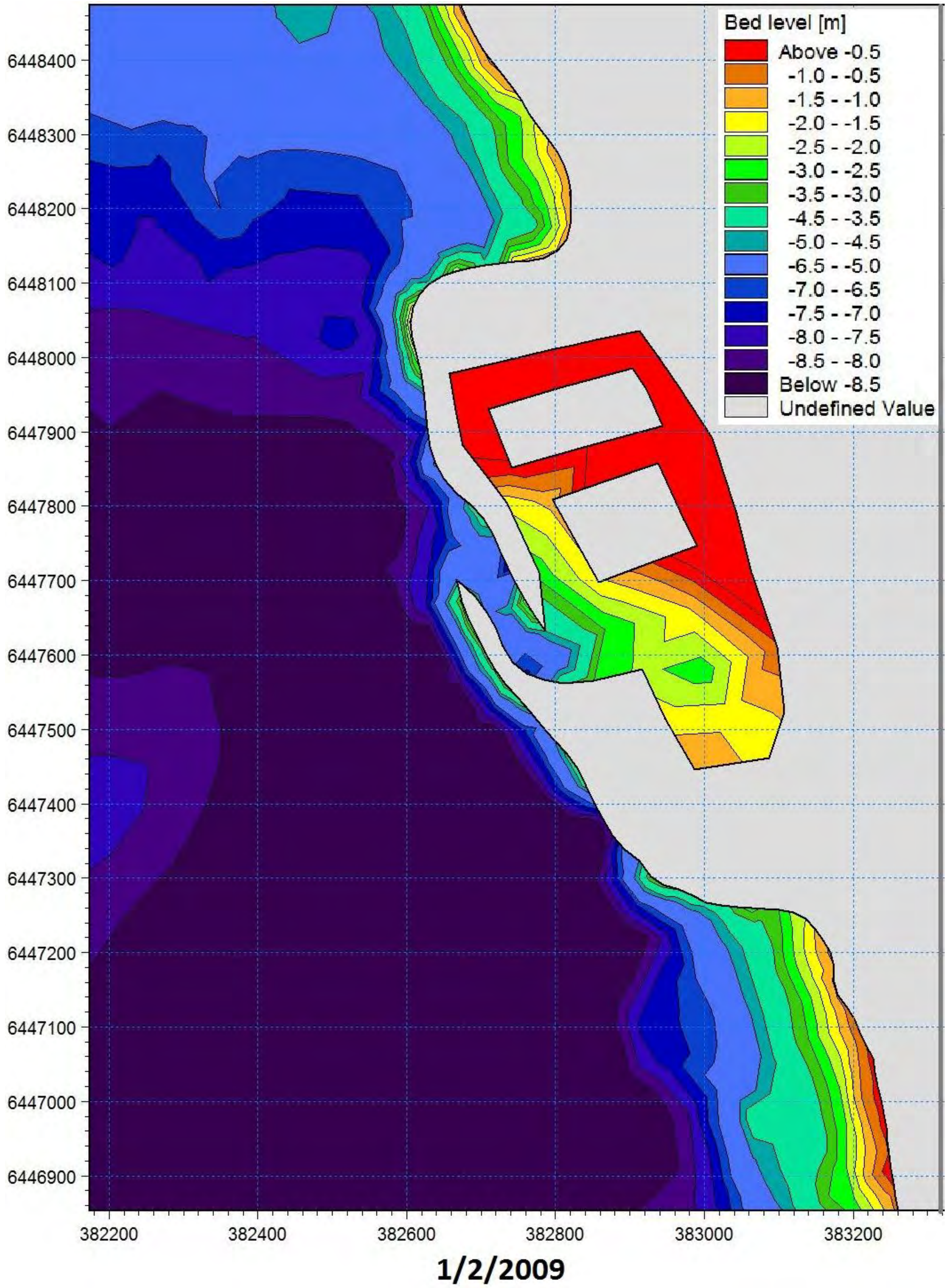

Figure 21: Port Coogee nearshore bed level (m) 1/February/2009 00:00

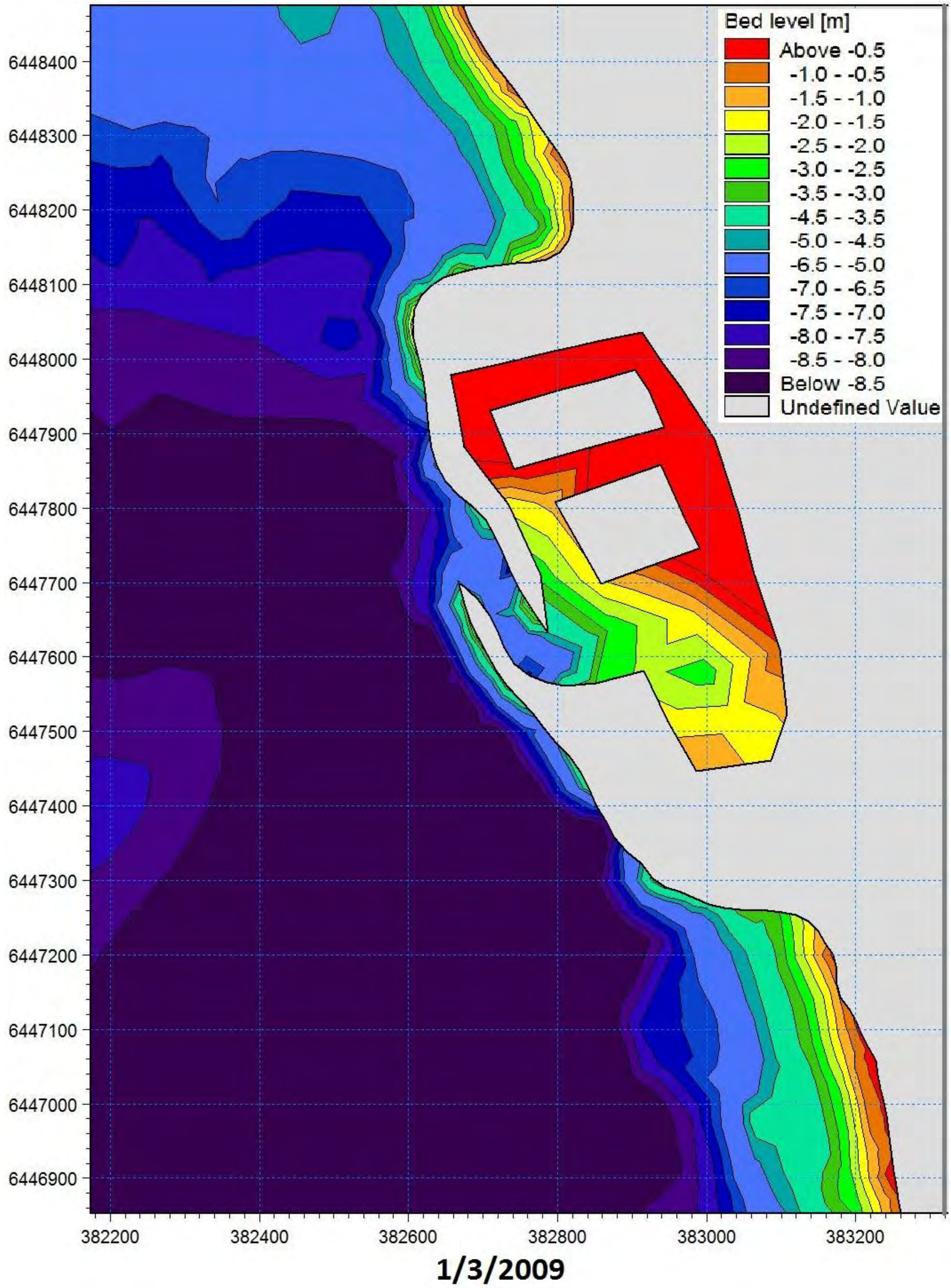

Figure 22: Port Coogee nearshore bed level (m) 1/March/2009 00:00

Using the same calculation methods used for the winter simulation analysis, a sediment budget was created for February 2009. Calculations for these results are presented in Appendix B. Results show accumulation on both sides of the marina during a typical summer month. The results show approximately 800m^3 accumulated on the northern beach and approximately 1000m^3 accumulated on the southern beach in February 2009. This shows the southern beach is susceptible to rotation between a summer and winter profile and the coinciding nearshore processes during the year. During winter, the beach erodes and during the summer months, the beach repairs and accumulates material. Due to the southern beach's sensitivity to the storm-activity, the volume of eroded material exceeds the volume of material accumulated during summer and hence the winter system is seen to dominate the annual sediment erosion from this beach. The northern beach experiences accumulation in a similar manner to that experienced during winter however the volume accumulated was as little as one-quarter of that experienced in winter. The majority of summer sediment transport activity was experienced during higher intensity local wind events or during the variability of wind direction. The unique systems shown on the northern and southern beaches demonstrate that the marina has broken the beach into two distinct sediment cells.

Figure 23: Port Coogee sediment budget 1/2/2009 – 1/3/2009

4.3 Discussion

4.3.1 Analysis

These simulations have shown that the marina has created a coastal barrier structure that interrupts the natural southward sediment migration along the coast. Effectively it has divided the beach into two separate sediment cells, each with its own unique littoral drift characteristics. This impact was predicted and accounted for prior to construction. The northern beach is dominated by the prevailing offshore swell, which transforms over a Pleistocene reef system and propagates from a northerly direction. When under the influence of a southerly wind this combines with the formation of an eddy-current that forces sediment migration southward causing further accumulation on the northern beach. The southern beach is more susceptible to the impacts of locally generated waves and rotates between summer and winter characteristics throughout the year. This contradicts the suggestion by Hamilton & Hunt (2011) that the southern beach is protected from the effects of local wind-waves.

During the winter months, the marina acts as a barrier stopping sediment migrating from the north, resulting in accumulation on the northern beach and significant erosion from the southern beach. When effected by sea breeze systems during summer the littoral drift reverses on the southern beach similarly to that seen on more exposed metropolitan beach locations and sediment migrates north and accumulates south of the marina. This accumulation volume is significantly less than the volume of erosion experienced during the winter months. This volume is not sufficient to replenish the beach and as a result, the winter months dominate the sediment transport characteristics of the southern beach system.

The littoral drift characteristics of the southern beach show increasing sediment activity with increased frequency and/or intensity of storm and storm-like events. In particular, erosion from the southern beach shows sensitivity to extreme storm events. Figure 24 presents this by comparing the sediment activity on the southern beach with the recorded wave heights for July. The rate of bed change is shown to increase up to 10-fold when influenced by extreme storm events. This sensitivity to storm events suggests that the winter processes dominate the erosion rates from the southern beach. Although it is known the erosion from southern beach is a direct result of the marinas construction, these results show that the erosion in excess of these predicted values can be attributed to the intensity and frequency of storm events since construction.

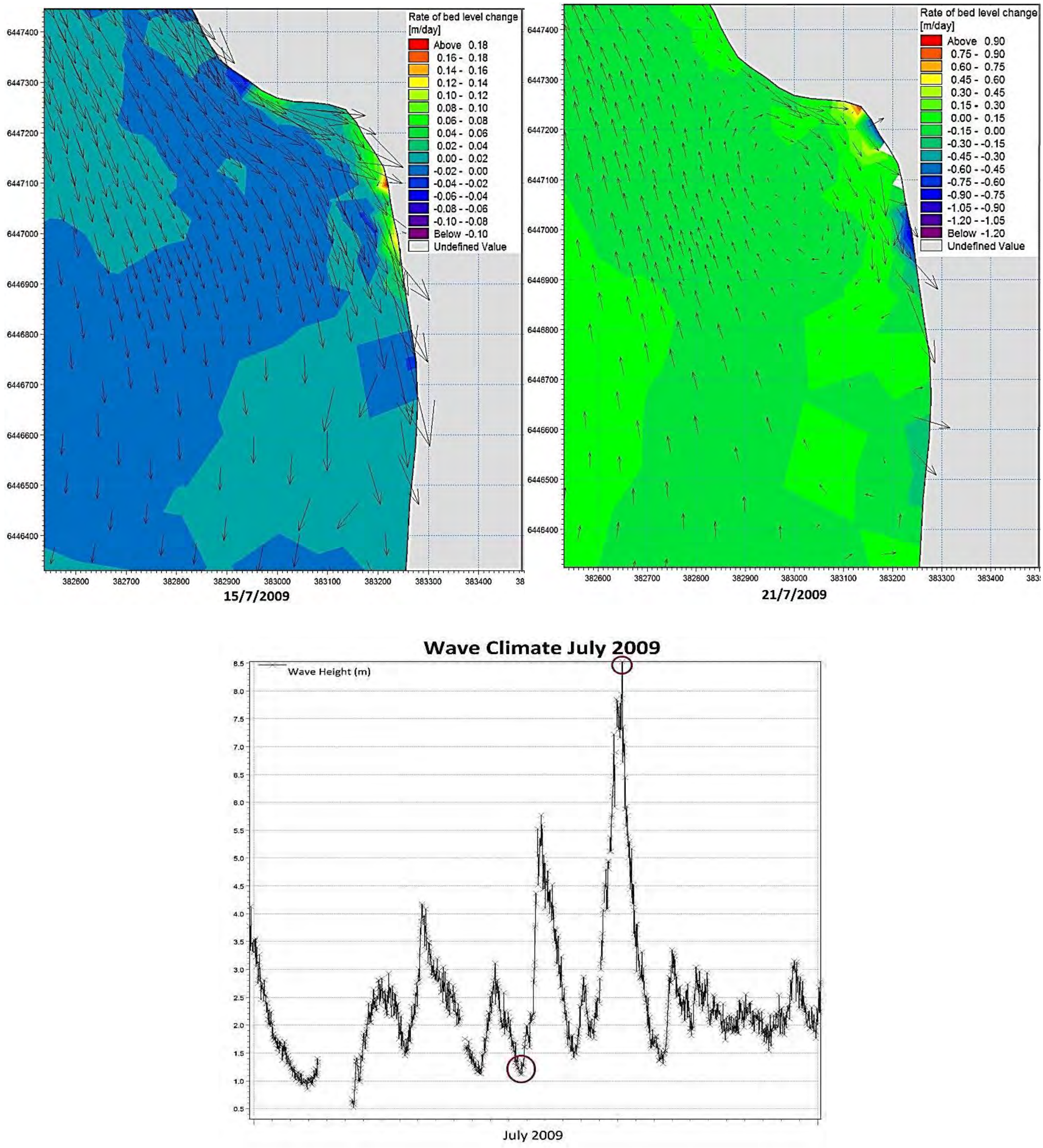

Figure 24: Impact of winter storms on rate of bed level change (m/day) on the marina's southern beach (Top left: 15/7/2009, Top right: 21/7/2009, Bottom: H_m (m) July 2009)

4.3.2 Comparison with Previous Estimates

For the purpose of a comparison with Hamilton & Hunt's (2011) estimations, the results from winter and summer simulations have been summed to form a 6-month estimate. The summer month totals have been taken using February as a typical summer month. Since the dominant wave and meteorological activity in Perth occurs during the summer and winter months, only these months have been considered. A comparison of previous studies discussed earlier in this report with the proposed 6-month estimate is presented in Figure 25.

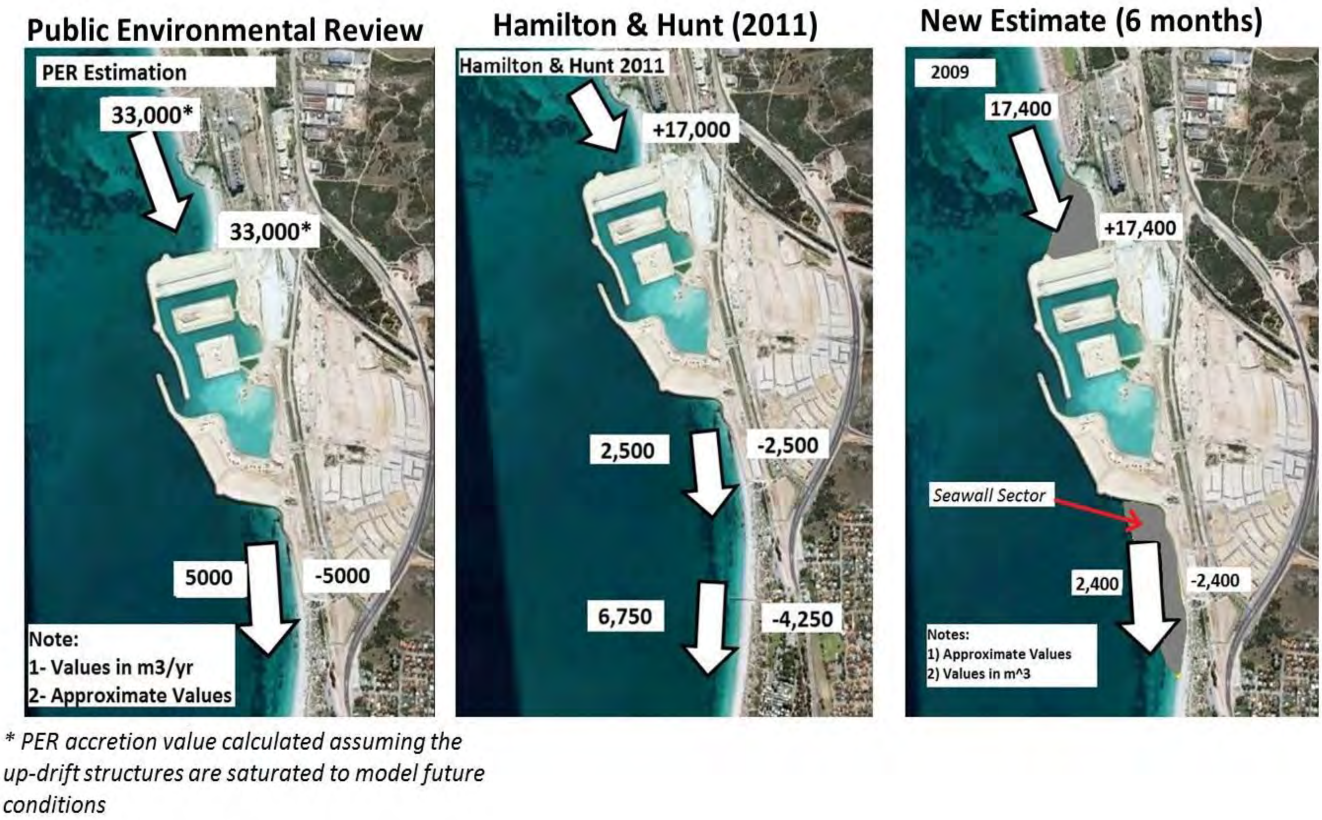

Figure 25: Comparison of PER estimate, Hamilton & Hunt (2011) & the proposed 6-month estimate

The proposed estimates have only considered the regions directly adjacent the marinas breakwaters. When considering the seawall sector and the northern beach the proposed 6-month estimate approximates sediment budgets within 5% of those estimated from the annual hydrographic surveys presented in Hamilton & Hunt (2011). The 6-month results presented show good agreement with previous works and this validates the theory that the majority of sediment transport occurs during the six months of summer and winter. These results also validate the suggestion that the above-expected erosion from the southern beach is a result of the increased frequency and intensity of storm events since the marina's construction suggested by Hamilton & Hunt (2011).

CHAPTER 5. CONCLUSION

This project was necessary to further understand the complex hydrodynamic processes occurring within Owen Anchorage and its newly developed coastline. Given the evolution of the coastline to an environment of increasing recreational activities, the impact of coastal structures must be well understood. As the current bathymetric evolution data is duration limited due to the recent construction of the marina, numerical modelling methods were the chosen for this thesis.

It was predicted prior to construction during the PER process that the marina would form a barrier to the natural southerly sediment migration resulting in accumulation on the northern beach and erosion from the southern beach. This prediction was shown to be valid in Hamilton & Hunt's (2011) study. It is evident that the marina's construction has broken the beach into two distinct and unique sediment cells, each with unique littoral drift characteristics.

The northern beach is shown to be dominated by penetrating offshore swell waves that are transformed by the Pleistocene dune ridge system driving the unique southerly wave propagation within Owen Anchorage. The northern beach shows less sensitivity to southerly winds due to an eddy-current system and as a result experiences accumulation in both winter and summer. The southern beach is sensitive to storm activity and experiences erosion during the winter months. Higher erosion is experienced from the southern beach during higher intensity storm events. During summer, the majority of sediment activity occurs during high wind speed or variable wind direction events. The southern beach experiences minor accumulation and replenishment during summer. This accumulation is minor compared to the erosion through winter. As a result, the winter storms dominate the net annual sediment transport volumes.

This project has presented a 6-month estimate that shows correspondence with the annual estimate presented in Hamilton & Hunt (2011). This supports the theory that the majority of sediment transport occurs during the summer and winter months. Port Coogee Marina has had a direct impact on its adjacent beaches and this has resulted in erosion from the southern beach. This study suggests that the above-expected erosion from the southern beach can be attributed to the intensity and frequency of the storms since construction rather than as a direct result of construction of the marina. Further research into this environment may consider the improvement of the suggested sand-bypassing program to include measures during above-average intensity storm events or years experiencing a high frequency of storm events.

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APPENDIX A. NOMENCLATURE

Parameter	Definition	Unit
a_j	Mesh element size	m^2
h	Bed level	m
f_w	Friction factor	
H_m	Mean wave height	m
H_s	Significant wave height	m
n	Number of mesh elements	
t	Time-step	
T_m	Mean wave period	s
T_p	Peak wave period	s
Δv^t	Accumulated/eroded sediment volume for the given time-step (t)	m^3

APPENDIX B. RESULTS

Table 4: June 2009, Northern beach results

Element No.	*1/06/2009 Bed Level Change (m)*	*1/07/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
2619	0.00126939	0.0826112	695.877	56.60389472
2620	-0.0142583	0.40307	700.894	292.5029015
2621	-0.0284209	-0.257577	989.296	-226.7032131
2622	0.0292361	0.680073	728.485	474.1249191
4421	0.00410733	0.21964	989.296	213.2256083
4432	-0.00248337	-0.101744	765.699	-76.00376513
4440	0.00768082	0.318258	856.997	266.1637115
4441	7.19E-05	-0.013694	947.49	-13.04303317
4442	0.00512773	0.455342	962.389	433.2812611
4443	0.000106	0.0505608	633.572	31.96674855
4451	-0.00529992	0.402538	1151.01	469.4255243
4452	0.000163666	-0.0267842	1084.64	-29.22873338
4453	-3.90E-05	0.789402	924.458	729.8050313
4457	0.00738462	0.470212	617.93	285.9949229
4460	-0.000739384	0.00246917	1251.64	4.015954529
4461	0.00211112	-0.0225343	993.486	-24.48487973
4465	0.0111479	-0.105576	659.771	-77.01104423
4466	-0.000521942	0.023312	1303.68	31.07183351
4468	-6.14E-05	-0.0874984	1040.65	-90.99129501
4469	-0.000465486	-0.0477296	1462.76	-69.13605539
4472	-0.00400184	-0.0379969	961.459	-32.68485639
4474	-0.000510964	-0.0406804	1283.23	-51.54662536
4478	0.0113406	0.300372	854	246.8328156
4479	8.98E-05	-0.0186521	1003.51	-18.8076925
4480	-0.00492638	0.0837154	1179.85	104.5840041
4483	-0.000557528	-0.0723469	994.905	-71.42360515
4484	-0.00517925	-0.31362	1266.68	-390.6957292
4486	0.0175417	1.00092	861.103	846.7900043
4487	-0.00268988	-0.175368	1161.07	-200.4913848
4488	-0.00860485	0.777407	1084.96	852.7914168
			TOTAL	**3966.92864**

Table 5: June 2009, Southern beach results

Element No.	*1/06/2009 Bed Level Change (m)*	*1/07/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
5321	0.0787158	0.492358	2188.07	905.0780886
5323	-0.174485	-0.309351	701.963	-94.67094196
5324	-0.0414538	0.0276308	1016.74	70.2410762
5325	-0.00369314	-0.196188	1980.15	-381.168697
5326	0.100674	0.380691	938.179	262.706069
5327	-0.0184916	-0.484316	1034.62	-481.9512407
5328	-0.00375767	-0.147265	1378.37	-197.8061985
5329	-0.00893315	-0.0757914	735.597	-49.18072813
5330	2.60E-02	0.364569	986.191	333.9128328
5331	-0.0164627	-0.526013	905.894	-461.5985595
5332	-0.00150103	-0.100704	1462.56	-145.0902958
5333	-0.00114553	-0.0712573	1305.27	-91.51479003
5334	0	-0.540215	739.755	-399.6267473
5335	-0.0166906	0.393769	1146.62	470.6411866
5336	-1.60E-03	-0.106956	1025.56	-108.0464995
5337	-0.00115197	-0.079371	996.329	-77.93188794
5338	-6.36E-04	-0.0429851	1071.53	-45.37791001
5339	-0.00108381	-0.0651018	1035.75	-66.30663314
5340	0	0	625.692	0
5341	0.00889332	0.49063	1542.82	743.2329846
5342	-0.00425194	-0.128401	1485.15	-184.3799765
5343	-1.82E-03	-0.0656749	1142.04	-72.92856163
5344	-0.00162973	-0.121277	858.582	-102.7269924
5345	-0.000521518	-0.0272039	1407.55	-37.55678678
5346	-0.000899275	-0.0620098	1154.55	-70.55515664
5353	0	-0.710096	604.729	-429.415644
5354	0.0247672	0.990162	679.892	656.3642014
5355	0.00612121	0.169828	1494.61	244.6778054
5357	-0.00603266	-0.177253	1451.57	-248.5383089
5358	-0.00202758	-0.117956	840.777	-97.46994918
5359	-0.000776721	-0.0462504	1058.16	-48.11842817
5360	-0.000593758	-0.0368031	1212.55	-43.90563764
5369	0.00615155	0.943056	628.173	588.5380791
5372	-0.00187217	0.418149	993.656	417.3565557
5373	-0.0035412	-0.120523	1444.29	-168.9556439
5375	-0.00174574	-0.141576	1313.37	-183.6488686
5376	-0.00106109	-0.0750249	1248.66	-92.35565099
5377	-0.00148113	-0.108026	1120.46	-119.379265

5378	-0.000676826	-0.0366127	1553.27	-55.81811501
5387	-1.20E-03	0.102655	752.087	78.10451322
5390	-0.00348689	-0.156368	1618.65	-247.4610087
5391	-1.67E-03	-0.101914	1418.03	-142.1530691
5393	-0.00111134	-0.0771589	1412.79	-107.4392323
5394	-0.000481734	-0.0320141	1480.02	-46.66853233
5401	0.000709583	0.0111259	1440.58	15.00553794
5403	-0.000985618	-0.0803929	1694.5	-134.5556393
5404	-0.000989864	-0.0711698	1256.45	-88.17758059
5406	-0.00154076	-0.117587	1274.55	-147.9067352
5407	-0.000586905	-0.0393256	1627.55	-63.04916305
5414	1.88E-03	0.187203	753.036	139.5584525
5416	-0.00146294	-0.086838	1456.82	-124.3760949
5417	-0.00100784	-0.0960277	1260.91	-119.8114917
5419	-0.000487428	-0.0309826	1550.79	-47.29160779
5426	-0.00104881	-0.0720902	743.664	-52.83092425
5428	-0.000327106	-0.100282	1273.97	-127.3395363
5429	-0.000776029	-0.0588786	1099.52	-63.88493887
5431	-0.000617341	-0.0531385	1379.53	-72.45451448
5439	0.000401152	0.0735039	1367.08	99.93730474
5441	-0.000209612	-0.0404697	1238.28	-49.85326177
5449	0.00284388	0.301829	934.96	279.5391278
5452	-0.000405955	-0.0109322	1690	-17.78935405
			TOTAL	**-904.1729841**

Table 6: July 2009, Northern beach results

Element No.	*1/07/2009 Bed Level Change (m)*	*1/08/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
2619	0.0826112	0.0751936	695.877	-5.161737235
2620	0.40307	0.3975	700.894	-3.90397958
2621	-0.257577	0.258732	989.296	510.7824285
2622	0.680073	1.01851	728.485	246.5462779
4421	0.21964	0.95106	696.943	509.7580491
4432	-0.101744	-0.174456	765.699	-55.67550569
4440	0.318258	1.15325	856.997	715.585639
4441	-0.013694	-0.0771464	947.49	-60.12051448
4442	0.455342	0.432658	962.389	-21.83083208
4443	0.0505608	0.259986	633.572	132.6859428
4451	0.402538	0.762502	1151.01	414.3221636
4452	-0.0267842	-0.153071	1084.64	-136.9757148
4453	0.789402	1.8056	924.458	939.4323707
4457	0.470212	0.468531	617.93	-1.03874033
4460	0.00246917	0.266658	1251.64	330.6693072
4461	-0.0225343	-0.050225	993.486	-27.51032278
4465	-0.105576	0.0417745	659.771	97.21758674
4466	0.023312	-0.0100826	1303.68	-43.53587213
4468	-0.0874984	-0.0869262	1040.65	0.59545993
4469	-0.0477296	-0.22403	1462.76	-257.8851731
4472	-0.0379969	0.933111	961.459	933.6804304
4474	-0.0406804	-0.141626	1283.23	-129.5364223
4478	0.300372	1.31858	854	869.549632
4480	-0.0186521	-0.0633831	1179.85	-52.77587035
4483	0.0837154	0.89538	994.905	807.5291689
4484	-0.0723469	-0.255044	1266.68	-231.4187626
4485	-0.31362	-0.674744	980.113	-353.942327
4486	1.00092	1.57145	861.103	491.2850946
4487	-0.175368	-0.378845	1161.07	-236.2510404
4488	0.777407	1.37864	1084.96	652.3137557
			TOTAL	**6034.390492**

Table 7: July 2009, Southern beach results

Element No.	*1/07/2009 Bed Level Change (m)*	*1/08/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
5321	0.492358	0.283244	2188.07	-457.55607
5323	-0.309351	-0.671073	701.963	-253.9154603
5324	0.0276308	-0.0942636	1016.74	-123.9349123
5325	-0.196188	-0.44168	1980.15	-486.1109838
5326	0.380691	0.361034	938.179	-18.4417846
5327	-0.484316	-0.400056	1034.62	87.1770812
5328	-0.147265	-0.240612	1378.37	-128.6667044
5329	-0.0757914	-0.352677	735.597	-203.6762167
5330	0.364569	0.205748	986.191	-156.6278408
5331	-0.526013	-0.0287236	905.894	450.4914837
5332	-0.100704	-0.234421	1462.56	-195.5691355
5333	-0.0712573	-0.184544	1305.27	-147.8697309
5334	-0.540215	-0.809161	739.755	-198.9541482
5335	0.393769	0.692516	1146.62	342.5492851
5336	-0.106956	-0.224379	1025.56	-120.4243319
5337	-0.079371	-0.212249	996.329	-132.3902049
5338	-0.0429851	-0.116044	1071.53	-78.28480312
5339	-0.0651018	-0.173438	1035.75	-112.2092192
5340	0	0	625.692	0
5341	0.49063	0.553229	1542.82	96.57898918
5342	-0.128401	-0.318317	1485.15	-282.0537474
5343	-0.0656749	-0.0797443	1142.04	-16.06781758
5344	-0.121277	-0.312824	858.582	-164.4588064
5345	-0.0272039	-0.0730247	1407.55	-64.49506704
5346	-0.0620098	-0.155733	1154.55	-108.2081206
5353	-0.710096	-0.924972	604.729	-129.9417486
5354	0.990162	0.737553	679.892	-171.7468382
5355	0.169828	0.146266	1494.61	-35.21600082
5357	-0.177253	-0.0279475	1451.57	216.7273846
5358	-0.117956	-0.302628	840.777	-155.2679701
5359	-0.0462504	-0.132859	1058.16	-91.64575618
5360	-0.0368031	-0.103499	1212.55	-80.87211355
5369	0.943056	1.17479	628.173	145.569042
5372	0.418149	0.983836	993.656	562.0982817
5373	-0.120523	-0.314729	1444.29	-280.4897837
5375	-0.141576	-0.39244	1313.37	-329.4772517
5376	-0.0750249	-0.203858	1248.66	-160.8687386
5377	-0.108026	-0.26987	1120.46	-181.3397282
5378	-0.0366127	-0.107546	1553.27	-110.1785669

5387	0.102655	1.61142	752.087	1134.722543
5390	-0.156368	0.0592949	1618.65	349.0827531
5391	-0.101914	-0.234091	1418.03	-187.4309513
5393	-0.0771589	-0.26476	1412.79	-265.0409581
5394	-0.0320141	-0.100529	1480.02	-101.4034223
5401	0.0111259	0.0175696	1440.58	9.282665346
5403	-0.0803929	-0.213038	1694.5	-224.767122
5404	-0.0711698	-0.214337	1256.45	-179.8824284
5406	-0.117587	-0.292945	1274.55	-223.5025389
5407	-0.0393256	-0.118632	1627.55	-129.0751313
5414	0.187203	0.457695	753.036	203.6902137
5416	-0.086838	-0.263347	1456.82	-257.1418414
5417	-0.0960277	-0.299416	1260.91	-256.4543414
5419	-0.0309826	-0.101692	1550.79	-109.6554304
5426	-0.0720902	-0.0492892	743.664	16.95628286
5428	-0.100282	-0.345124	1273.97	-311.9213627
5429	-0.0588786	-0.183982	1099.52	-137.5536904
5431	-0.0531385	-0.165171	1379.53	-154.5521947
5439	0.0735039	0.408577	1367.08	458.0717335
5441	-0.0404697	-0.0974062	1238.28	-70.50332922
5449	0.301829	1.0464	934.96	696.1441022
5452	-0.0109322	-0.0330058	1690	-37.304384
			TOTAL	**-3054.006888**

Table 8: August 2009, Northern beach results

Element No.	*1/08/2009 Bed Level Change (m)*	*1/09/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
4079	-0.0685086	0.505751	217.981	125.1776819
4080	-0.377888	0.333416	242.554	172.5296304
4081	0.071275	1.21451	270.894	309.6955021
4082	0.31493	0.942255	253.817	159.2257495
4098	0.0124477	0.930959	232.541	213.5915362
4099	0.336688	1.9484	484.557	780.9663316
4100	-0.349973	-1.05009	262.361	-183.6833962
4117	0.327496	1.17418	450.88	381.7528819
4118	-0.262007	0.230381	292.711	144.1273839
4119	0.00968879	0.489288	304.988	146.2720039
4120	0.0235866	-1.09156	497.943	-555.2794434
4121	-0.172129	-1.04755	290.677	-254.46475
4122	0.00822685	0.615047	225.261	136.6929138
4141	0.0127315	0.269797	224.402	57.68601233
4142	-0.14474	-1.46041	250.252	-329.2490488
4143	-0.39387	-1.04766	266.709	-174.3716771
4144	0.0813976	1.43902	444.942	604.0632259
4145	-0.282596	0.105502	302.247	117.3014562
4146	-0.0102984	-0.304802	383.187	-112.849951
4147	0.0783269	0.277751	422.409	84.23853466
4165	0.136358	1.76244	379.275	616.7322506
4166	0.216395	-0.709627	353.615	-327.4552695
4167	-0.210431	0.898989	240.231	266.517076
4168	-0.278113	0.201887	391.067	187.71216
4169	-0.26166	0.643225	225.182	203.7638141
4170	0.00569689	0.450584	661.408	294.2518937
4171	0.314012	0.706467	647.455	254.096952
4172	-0.00627295	0.10548	708.569	79.18467603
4173	-0.00454698	-0.0294434	426.703	-10.6233771
4189	0.0251404	0.622869	401.087	239.741171
4190	0.012788	0.45577	570.341	252.6507969
4192	-0.243538	0.209716	235.783	106.8695879
4193	0.105609	0.651029	769.944	419.9428565
4194	-0.00734099	0.0383461	856.957	39.15187159
4207	-0.00776407	-0.101085	859.909	-80.2475076
4209	-0.00809092	0.0233198	784.01	24.62631859
4210	0.0326042	-0.257011	671.702	-194.5351091
4211	0.356043	1.95194	397.078	633.695589
4212	-0.00527749	-0.18041	1053.3	-184.4670728

4213	0.0136543	0.107248	970.795	90.86029599
4227	-0.0110931	1.44418	258.027	375.4997522
4228	-0.00176546	-0.118742	1090.64	-127.5792936
4229	-0.0336089	-0.075838	618.748	-26.12917117
4230	0.0136193	-0.0524131	1135.92	-75.00752381
4243	0.0608259	2.1625	420.08	882.8712559
4245	0.0019863	0.11069	1082.48	117.6695812
4246	-0.0355308	-0.467717	590.844	-255.3546232
4247	-0.0229864	-0.715753	1085.59	-752.0604933
4259	-0.194186	0.671416	255.709	221.3422218
4260	0.0351731	1.50524	400.743	589.1190197
4261	-0.160345	0.890319	262.574	275.8770491
4262	-0.00226947	-0.0490846	1029.42	-48.19243112
4263	-0.00367264	-0.304113	876.027	-263.1938672
4264	-0.0296894	-0.670753	1051.33	-673.9693946
4277	-0.0838841	0.683031	256.836	196.9714066
4278	0.157439	1.14188	742.006	730.4611286
4279	-0.00522113	-0.188977	1135.49	-208.6529528
4280	-0.00132409	-0.0920159	1013.69	-91.93338088
4290	0.0140731	0.009665	950.546	-4.190101823
4291	-0.000157292	-0.00860912	1282.33	-10.8380326
4303	0.014403	-0.222185	756.788	-179.0469593
4304	-0.000155011	-0.0618566	1576	-97.24170426
4311	0.20081	-0.168409	1018.4	-376.0126296
			TOTAL	**4936.300407**

Table 9: August 2009, Southern beach results

Element No.	*1/08/2009 Bed Level Change (m)*	*1/09/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
6133	-0.0810819	-0.299689	215.707	-47.15508172
6144	-0.168	-0.435861	221.064	-59.2144241
6146	-0.0268329	-0.438269	236.954	-97.49142964
6147	-0.290168	-0.135797	227.524	35.1231074
6148	-0.132349	-0.275703	235.997	-33.83111394
6158	-0.196539	-0.0131407	421.34	77.27303972
6160	-0.0208464	0.0953377	468.458	54.42737112
6161	-0.207583	-0.198537	256.307	2.318553122
6170	0.327867	0.634665	515.605	158.1865828
6172	0.0853285	0.742701	528.42	347.3687765
6173	-0.222442	0.478933	511.336	358.638287
6174	-0.299778	0.274334	354.591	203.5749482
6175	-0.279729	0.370493	226.012	146.9579747
6185	0.208179	0.974963	717.196	549.9344177
6186	0.00278065	-0.116688	914.168	-109.2144168
6187	-0.295237	0.550076	223.378	188.8243273
6188	0.325487	1.32032	521.876	519.1794667
6189	0.321306	0.725139	428.503	173.043652
6190	-0.305834	0.209815	290.251	149.6676379
6191	-0.282487	0.276327	231.979	129.6331129
6205	0.0339181	0.0799016	1022.6	47.0227271
6206	0.000659776	-0.0652627	907.014	-59.79260865
6207	-0.143765	0.96809	219.3	243.8298015
6208	-0.312718	0.757684	225.284	241.1444442
6209	-0.307315	0.632487	272.571	256.1627709
6210	-0.00567414	1.39653	212.892	298.5180438
6211	0.0146276	0.394055	969.298	367.77822
6212	-0.280763	-0.106558	218.944	38.14113952
6213	-0.291579	0.273375	344.847	194.822692
6214	0.315051	0.561955	325.325	80.3240438
6215	0.129982	-0.0572171	688.432	-128.8738508
6216	0.315488	0.578695	421.328	110.8964789
6228	-0.00229076	0.173408	906.602	159.2888472
6229	0.00821933	0.366504	1128.96	404.489061
6230	0.328539	1.33219	434.212	435.797308
6231	0.329676	0.963896	522.892	331.6285642
6232	0.0792236	0.946378	232.977	202.0270306
6233	0.0410313	-0.0590617	1044.42	-104.5391311
6234	0.208497	0.326518	363.523	42.90334798

6235	0.113296	-0.0790377	419.97	-80.77438399
6236	0.255188	0.20537	591.631	-29.47387316
6247	-0.0061514	-0.330836	1313.29	-426.4050383
6248	-0.00169222	0.00580059	1100.14	8.243139993
6249	-0.00691099	-0.231679	979.466	-220.1526237
6250	0.0309567	-0.0834295	478.506	-54.73448302
6251	0.0445718	0.237231	438.224	84.42788526
6252	-0.00195019	0.459976	428.771	198.0605544
6253	0.0127648	1.2643	235.408	294.6213984
6254	-0.00688093	1.12691	232.513	263.6211305
6255	-0.00269447	-0.13713	1240.7	-166.7941621
6256	0.324816	-0.342268	437.434	-291.8052225
6257	0.0163851	-0.426277	760.596	-336.6870226
6266	-0.00251671	-0.149048	1190.48	-174.4425701
6268	-0.0120551	-0.638966	1186.74	-743.9802415
6269	-0.00238414	-0.123986	1111.14	-135.1166907
6270	-0.00225005	-0.233817	1287.72	-298.1933929
6271	0.0377822	-0.414397	393.706	-178.0256641
6272	0.054309	-0.430923	578.515	-280.7139905
6273	-0.00117279	0.045041	541.042	25.00360137
6274	-0.0126534	-0.358633	233.998	-80.95853444
6275	-0.00331028	-0.281627	1656.11	-460.9231032
6276	4.63E-05	-0.30384	954.027	-289.915714
6277	-0.000783135	-0.204587	1369.42	-279.0930888
6287	-0.00854324	-0.599726	1132.36	-669.4317101
6288	-0.00054577	-0.0386206	1485.14	-56.54645303
6289	-0.00426827	-0.646133	510.642	-327.7630895
6290	-0.000963022	0.0596597	537.84	32.6053248
6291	0.0168429	-0.1964	451.212	-96.21775539
6292	-0.00261305	-0.182126	1234.01	-221.5207754
6293	-0.00272592	-0.193693	1359.03	-259.5299907
6302	-0.00167953	-0.111911	1322.4	-145.7700959
6303	0.00381741	0.0351642	283.836	8.897347486
6304	-0.00257008	-0.168462	1046.68	-173.6357548
6305	-0.00125977	0.0988544	493.781	49.43447498
6306	-0.00198533	-0.114887	1211	-136.7239224
6307	-0.00261953	-0.137218	1526.51	-205.4659104
6316	-0.000881036	0.00711852	1030.13	8.240582622
6318	-0.00206917	-0.104461	817.283	-83.683102
6319	-0.000965593	-0.0439212	1116.89	-47.9766879
6320	-0.00154574	-0.0689069	684.376	-46.10036124
6321	-0.00161793	-0.101251	1408.57	-140.3401534
6330	-0.000914008	-0.022486	1352.7	-29.18043358
6331	-0.00182423	-0.201531	518.273	-103.5026268

6332	-0.000207244	-0.0210352	892.268	-18.58411864
6333	-0.00234351	-0.12804	1022.15	-128.4806673
6334	-0.00205301	-0.10916	1049.51	-112.4098571
6342	0.0012467	0.0567718	1090.26	60.53679553
6343	-0.00242793	-0.264945	555.071	-145.7156126
6344	6.26E-06	0.00171119	1010.61	1.723019459
6345	-0.00252941	-0.14253	1060.65	-148.4916258
6346	0.00309964	-0.225293	390.478	-89.18230128
6353	-0.00175736	-0.262463	742.06	-193.4592272
6354	0.0015406	0.0453851	979.064	42.92657155
6355	-0.00109573	-0.137948	798.219	-109.2380821
6362	0.000197578	-0.0627694	777.032	-48.92735685
6363	-0.00114597	-0.102822	749.547	-76.21096326
6369	-0.000587248	-0.117686	787.553	-92.22147343
			TOTAL	**-1447.344362**

Table 10: February 2009, Northern beach results

Element No.	*1/02/2009 Bed Level Change (m)*	*1/03/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
4079	0.232399	0.334513	217.981	22.25891183
4080	-0.225135	-0.468011	242.554	-58.9105453
4081	0.068975	0.880073	270.894	219.7215816
4082	0.431711	0.471696	253.817	10.14887275
4098	0.0869434	0.784834	232.541	162.288178
4099	0.00993176	0.123095	484.557	54.83404008
4100	-0.326945	-0.619822	262.361	-76.8395026
4117	0.090324	0.349742	450.88	116.9663878
4118	0.209753	0.310131	292.711	29.38174476
4119	0.00519199	0.031316	304.988	7.967509562
4120	-0.0262133	-0.161058	497.943	-67.14497445
4121	-0.0752993	-0.449836	290.677	-108.8692043
4122	0.0115428	0.0636006	225.261	11.72659209
4141	0.00793137	0.0733703	224.402	14.68462677
4142	-0.178792	-0.659953	250.252	-120.4115026
4143	-0.24529	-0.806106	266.709	-149.5746745
4144	-0.000442141	-0.0102592	444.942	-4.368021866
4145	-0.201333	-0.112944	302.247	26.71531008
4146	0.00456276	0.00707488	383.187	0.962611726
4147	-0.00259565	-0.0281678	422.409	-10.80190631
4165	0.244567	1.09043	379.275	320.8146893
4166	0.0579962	-0.0203432	353.615	-27.70198693
4167	0.188992	0.917486	240.231	175.0068421
4168	0.00492441	0.0296374	391.067	9.66443486
4169	0.222959	0.809166	225.182	132.0032647
4170	-0.00104606	0.00557748	661.408	4.380862344
4171	0.0155489	0.126091	647.455	71.57103536
4172	0.000603176	-0.00558435	708.569	-4.38428911
4173	-0.00749637	-0.0528035	426.703	-19.33268829
4189	-0.0031938	-0.0117517	401.087	-3.432462437
4190	0.0180331	0.125391	570.341	61.23061204
4192	0.0488956	0.122088	235.783	17.25752365
4193	0.0196874	0.134061	769.944	88.06126708
4194	-0.00525164	-0.028924	856.957	-20.28619461
4207	-0.00488573	-0.0302244	859.909	-21.78895038
4209	0.00413612	0.0164013	784.01	9.616023772
4210	-0.0299804	-0.219963	671.702	-127.6116924
4211	0.127941	0.53434	397.078	161.3721021
4212	-0.0358052	-0.174402	1053.3	-145.9840094

4213	-0.0060495	-0.0222561	970.795	-15.73328625
4227	0.102283	0.512644	258.027	105.8842177
4228	-0.00201463	-0.00500279	1090.64	-3.259006822
4229	0.0101065	-0.136821	618.748	-90.91109677
4230	-0.0472433	-0.151824	1135.92	-118.7953087
4243	0.107526	0.296914	420.08	79.55811104
4245	-0.00534385	-0.014121	1082.48	-9.501089332
4246	-0.0914701	-0.379427	590.844	-170.1376066
4247	-0.0339732	-0.167638	1085.59	-145.1051702
4259	0.345727	0.969845	255.709	159.5925897
4260	0.0473461	0.411285	400.743	145.8459666
4261	0.0262939	1.23062	262.574	316.2247214
4262	-0.00337832	-0.0191628	1029.42	-16.2488594
4263	-0.00682855	-0.065571	876.027	-51.45997225
4264	-0.0718496	-0.241572	1051.33	-178.4342508
4277	0.366898	0.38727	256.836	5.232262992
4278	-0.0505415	0.385032	742.006	323.1981504
4279	-0.00532453	-0.018808	1135.49	-15.31034535
4280	-0.0121478	-0.0498728	1013.69	-38.24145525
4290	-0.0132344	-0.0660867	950.546	-50.23854236
4291	-0.002259	-0.00775212	1282.33	-7.04399257
4303	-0.0137323	-0.0835861	756.788	-52.86451759
4304	-0.00278114	-0.0201656	1576	-27.39790896
4311	-0.013597	-0.0624883	1018.4	-49.79089992
			TOTAL	**856.2551295**

Table 11: February 2009, Southern beach results

Element No.	*1/02/2009 Bed Level Change (m)*	*1/03/2009 Bed Level Change (m)*	*Element Area (m2)*	*Volume Change (m3)*
6133	-0.068116	-0.137749	215.707	-15.02032553
6144	-0.236082	-0.294518	221.064	-12.9180959
6146	-0.219839	-0.318541	236.954	-23.38783371
6147	0.0289399	0.217032	227.524	42.79546696
6148	-0.170971	0.0136652	235.997	43.57358929
6158	0.151256	0.239079	421.34	37.00334282
6160	0.0825757	0.147354	468.458	30.34591286
6161	-0.00286575	0.131658	256.307	34.47937879
6170	0.0766788	0.19248	515.605	59.70767773
6172	0.214556	0.258965	528.42	23.46660378
6173	0.351746	0.951577	511.336	306.7151842
6174	0.204396	0.68309	354.591	169.7405842
6175	0.309694	0.565462	226.012	57.80663722
6185	-0.113907	-0.514607	717.196	-287.3804372
6186	-0.00790403	-0.064926	914.168	-52.12766027
6187	0.238685	0.686823	223.378	100.1041702
6188	-0.0342089	0.823265	521.876	447.495049
6189	0.0511627	0.786628	428.503	315.1490874
6190	0.171333	0.253218	290.251	23.76720314
6191	0.253296	0.591953	231.979	78.5613122
6205	-0.0485026	-0.106801	1022.6	-59.61594384
6206	-0.00462584	-0.0222677	907.014	-16.00141401
6207	0.0397189	0.259197	219.3	48.13154733
6208	0.122531	0.189574	225.284	15.10371521
6209	0.0679658	0.876461	272.571	220.3723452
6210	0.0708167	0.265783	212.892	41.50676554
6211	-0.00598316	0.0294836	969.298	34.37785953
6212	0.0647488	0.058732	218.944	-1.317342259
6213	-0.0406356	-0.0735716	344.847	-11.35788079
6214	-0.00136141	0.159306	325.325	52.26912516
6215	-0.0660025	-0.314911	688.432	-171.3565765
6216	-0.0584885	0.234635	421.328	123.501138
6228	-0.00586404	-0.0268845	906.602	-19.05719108
6229	0.0510382	0.187566	1128.96	154.1344251
6230	0.0457225	0.178706	434.212	57.7430315
6231	0.220751	0.455502	522.892	122.7494199
6232	0.0415051	0.143099	232.977	23.66904204
6233	-0.0424033	-0.104807	1044.42	-65.17567235
6234	-0.25074	-0.649685	363.523	-145.0256832

6235	0.0180056	0.173089	419.97	65.1303755
6236	-0.0176784	-0.124944	591.631	-63.46165419
6247	-0.0418007	-0.177494	1313.29	-178.204654
6248	-0.00317669	-0.0298055	1100.14	-29.29541903
6249	0.0071436	0.00811828	979.466	0.954665921
6250	0.00272479	-0.000959509	478.506	-1.762959177
6251	-0.081174	-0.00198037	438.224	34.70454931
6252	0.0227588	0.146464	428.771	53.04120231
6253	-0.000860712	-0.00541357	235.408	-1.071779196
6254	-0.0273879	-0.166955	232.513	-32.45116512
6255	-0.00827905	-0.0494525	1240.7	-51.08389942
6256	-0.056615	-0.138407	437.434	-35.77860173
6257	-0.0236281	-0.0489734	760.596	-19.2775338
6266	-0.00521487	-0.023728	1190.48	-22.039511
6268	-0.0371774	-0.171385	1186.74	-159.2695272
6269	-0.0132456	-0.0302079	1111.14	-18.84749002
6270	-0.00664825	-0.0309189	1287.72	-31.25380142
6271	0.0518844	0.106696	393.706	21.57965579
6272	-0.028919	-0.142447	578.515	-65.67765092
6273	0.0041899	0.0223974	541.042	9.851022215
6274	-0.143972	-0.486017	233.998	-80.03784591
6275	-0.0145186	-0.0547256	1656.11	-66.58721477
6276	-0.0141085	-0.071482	954.027	-54.73586808
6277	-0.0203344	-0.046591	1369.42	-35.95631317
6287	-0.0177422	-0.0891558	1132.36	-80.8659041
6288	0.0217015	0.0913035	1485.14	103.3687143
6289	-0.0140532	-0.0291454	510.642	-7.706711192
6290	0.00653882	0.0322732	537.84	13.84097894
6291	0.0814605	0.245696	451.212	74.10502843
6292	-0.00628013	-0.0389264	1234.01	-40.28582364
6293	0.000642484	0.0101489	1359.03	12.91950454
6302	-0.00666723	-0.0171336	1322.4	-13.84072769
6303	-0.00689226	-0.0444723	283.836	-10.66656823
6304	-0.00114362	-0.0133516	1046.68	-12.77784851
6305	0.00352368	0.0309883	493.781	13.56150753
6306	0.000258201	-0.00639761	1211	-8.060187121
6307	-0.00228027	-0.0147471	1526.51	-19.03074066
6316	0.00559089	0.0169982	1030.13	11.75101225
6318	-0.00776955	-0.0207914	817.283	-10.64253663
6319	-0.000894256	-0.00118572	1116.89	-0.325533227
6320	0.00472483	0.0199228	684.376	10.40112592
6321	0.00101793	-0.006121	1408.57	-10.05568263
6330	-0.00823655	-0.0226892	1352.7	-19.55009966
6331	-0.00100351	0.00460264	518.273	2.905516179

6332	0.00579718	0.0106976	892.268	4.372487953
6333	-0.00267016	-0.0202019	1022.15	-17.92006804
6334	-0.000930807	0.000899742	1049.51	1.921179481
6342	0.0101079	0.00792708	1090.26	-2.377660813
6343	-0.00159954	0.00621804	555.071	4.339311948
6344	-0.000386699	-0.00133142	1010.61	-0.95474449
6345	-0.00177483	-0.00129831	1060.65	0.505420938
6346	-0.00458889	-0.0924577	390.478	-34.31083719
6353	0.00351971	0.0173845	742.06	10.28850607
6354	0.00199372	0.0157296	979.064	13.44830562
6355	0.00234035	0.0128703	798.219	8.405206159
6362	0.00762161	0.0434066	777.032	27.80608235
6363	-0.000181888	0.0032715	749.547	2.588476615
6369	0.00124265	0.00625879	787.553	3.950476105
			TOTAL	**1054.103308**