A HYBRID APPROACH TO BEACH EROSION MITIGATION AND AMENITY ENHANCEMENT, ST FRANCIS BAY, SOUTH AFRICA

by

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DECLARATION

I, the undersigned declare that the work contained in this thesis is my own work and I have not previously, in its entirety or in part, submitted it at any university for a degree.

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Date

ABSTRACT

The St Francis Bay beach has experienced chronic erosion over the past three decades. This erosion can largely be attributed to the stabilisation of a large coastal dunefield which contributed +/- 80% of the sand supply to St Francis Bay. Stabilisation began in 1975 initially using plant cuttings and followed by the development of the Santareme holiday suburb resulting in complete stabilisation by 1985. Effects were felt from the late 1970's and since then the beach has retreated at between 0.5 - 3 $m.yr^{-1}$. Erosion has encroached on beachfront properties since the early 1990's, leading to the placement of 3-4 m high unsightly rock revetments along much of the beach. Where properly maintained these structures have proved successful in protecting the properties behind, however exacerbated erosion of areas in front and adjacent to these structures is evident. Currently no dry beach is present at high tide for most of the year, leading to a significant reduction in beach amenity value.

Several technical studies to investigate remediation of this beach erosion problem have been conducted since the early 1990's. This study includes investigations into the processes and dynamics of the existing environment and evaluation of the effectiveness and impacts of several elements of a hybrid approach to coastal protection and amenity enhancement for St Francis Bay beach. This proposal incorporated: Multi-Purpose Reefs (MPR's) offshore, for coastal protection and amenity enhancement in terms of surfing; beach nourishment with sand from the Kromme Estuary and dune rehabilitation with appropriate native sand binding species.

Extensive fieldwork and data collection were conducted, this included: a series of bathymetric surveys; diving surveys and a helicopter flight; sediment sampling; beach profiling and deployment of a wave/current meter. Analysis of these data provided a greater understanding of the existing environment and dynamics of St Francis Bay and provided reliable inputs for numerical modelling. Numerical and physical modelling was conducted to assess the existing processes and conduct MPR design testing. In addition calibrated hydrodynamic modelling of the Kromme Estuary was conducted in order to assess the impacts of sand extraction from the large sand banks within the mouth of the Kromme Estuary for use as beach nourishment.

Comparison of bathymetric survey data collected by the author in 2005/06 with survey data collected by the South African Navy Hydrographic Office (SANHO) in 1952 suggest a major loss of sand from the bay, with a volume difference of some 8.8 X 10^6 m^3 calculated. Greater losses were measured between 10-15 m water depths, with shallow areas of +/- 5 m water depth, remaining more stable. This can be attributed to the presence of shallow reef and rocky substrate through much of the bay at this depth range. Monthly RTK GPS survey data from September 2006 to September 2007 indicates a total loss of 40 000 m^3 over this period with the greatest losses measured along the northern part of the beach. The greatest losses were measured after large long period waves from a southerly to south-easterly direction occurred in conjunction with equinox tides in mid March 2007. Sediment sampling at over 100 locations within the bay indicated a high percentage of reef (26%) and fairly consistent grain size in the fine to medium size class throughout much of the beach, bay and large sand bank within the estuary.

While the majority of the South African Coast is exposed to the predominant south westerly winds and waves, St Francis Bay's orientation means that waves from a south easterly to easterly direction dominate. The results of the detailed numerical modelling of the hydrodynamics agree with previous calculations and modelling results which concluded that strong unidirectional longshore currents occur along the headland due to the oblique angle of wave incidence and the close to parallel angle of wave incidence along the beach leads to weak longshore currents of variable direction. Erosion along St Francis Bay beach is a result of cross-shore erosion due to large waves from a southerly to easterly direction.

Detached breakwaters are the most effective form of coastal protection in these environments and MPR's offer additional benefits over traditional breakwater structures. Results of empirical calculations and numerical modelling indicate that the MPR's will provide effective coastal protection through the processes of wave dissipation, wave rotation, salient formation and alteration of nearshore circulation. Physical modelling results allowed the MPR design to be assessed and refined in terms of surfing amenity enhancement and construction constraints. In addition numerical modelling results indicate that impacts due to the extraction of up to 600 000 m^3 of sand from the lower Kromme Estuary result in highly localised velocity reduction, mainly limited to the extraction areas. The calculated rate of sediment influx into the lower Kromme Estuary indicates that limited extraction, in the order of 20 000 – 40 000 m^3 per year, should be sustainable in the long term. Sedimentation of the lower estuary over recent years has had negative recreational and ecological impacts, through reduced navigability and water exchange respectively. Therefore both the estuary and beach systems prove to benefit from this approach.

Although not investigated in detail as part of this study, evidence from numerous projects worldwide indicates that foredunes help to trap wind-blown sand on the beach and form a buffer to storm erosion, therefore dune rehabilitation with native sand-binding plant species was recommended as the third element of the proposed remediation of St Francis Bay beach.

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CONTENTS

1 INTRODUCTION

1.1 Background

1.1.1 Multi-Purpose Reefs a New Paradigm in Coastal Protection

Roughly two-thirds of the world population lives within close proximity to the ocean and a large proportion of the worlds coastline is made up of sandy beaches, which attract thousands of visitors and are economically important to adjacent communities (Komar, 1998). Beach erosion poses a threat to all stakeholders, especially tourism which, according to the World Tourism Organisation (2001) is the world's largest industry. Research indicates that 70% of the world's beaches are experiencing coastal erosion (Bird, 1996). Climate change, particularly accelerated sea-level rise, is expected to exacerbate this problem (IPCC, 2007).

Whilst coastlines are often viewed as stable permanent assets, in reality they tend to be dynamic, responding to natural processes and human activities (Ketchum, 1972 in Phillips and Jones, 2006). In many instances man has literally drawn a line in the sand and built infrastructure, with little regard for the dynamics of the highly variable littoral zone, thus when the beach retreats infrastructure is threatened (Clarke, 1996). In numerous instances erosion is caused by man-induced interruption of sediment supply by means of coastal structures such as groynes (Basco and Pope, 2004), harbour breakwaters constructed in longshore dominant sediment transport regimes (Swart, 1996; Dean and Dalrymple, 2002), dune stabilisation (McLachlan *et al*., 1994; La Cock and Burkinshaw., 1999) and river impoundment (Frihy, 2003).

Until fairly recently traditional coastal structures were only constructed for one purpose for example: to trap sand or create protected anchorage, without much regard for down coast impacts (Dean and Dalrymple, 2002). Structures such as sea walls and revetments should really be termed land protection structures, when implemented properly they can protect the land behind but result in increased erosion of the beach in front of the structure (Komar, 1998; Silvester and Hsu, 1999; Dean and Dalrymple, 2002). The wider community is growing less tolerant of the loss or degradation of the public beach arising from the protection of the property of a few individuals. The traditional response of rock revetment will be rarely acceptable in the future. Additionally traditional coastal protection structures built from rock impact the natural beach environment negatively, disturbing the natural aesthetics of the beach and in many cases where used inappropriately without due cognisance of the existing coastal processes these structures can actually exacerbate erosion (Basco and Pope, 2004).

The above-mentioned problems and limitations of traditional coastal engineering structures and approaches prompted Professor Kerry Black of the Coastal Marine Group at the University of Waikato in New Zealand to initiate the Artificial Reefs Programme (ARP) in 1995. The underlying inspiration came from the numerous examples in nature where natural reefs act as barriers to wave energy protecting the shore and creating additional amenity benefits. A team of scientists and industry experts was involved, including biologists, physicists, engineers, planners and environmental managers. A series of related studies provided the input into the broader program so that engineers involved in offshore protection works could incorporate the proposed concepts into structural designs to fulfil the demands and requirements of the marine environment, recreational users and developers (Black *et al.*, 1997).

The term “Artificial Reef” has been used by several authors (Mead and Black, 2001a; Black and Andrews, 2001a&b; Black *et al*., 2001; Turner *et al*, 2001; Jackson, 2001; Pattiaratchi, 1999) while more recently the term “Multi-Purpose Reef” has gained popularity (Mead *et al.*, 2006; Mead *et al.*, 2007; Black and Mead, 2007). The use of the term ‘Artificial’ could have negative connotations, emphasising the ‘synthetic’ or ‘unnatural’ nature of the structure, while the latter term focuses on the varied positive benefits of these structures. For the reasons discussed above I have decided to use the term Multi-Purpose Reef (MPR) throughout the rest of this document although generally these terms have the same meaning and can be used interchangeably.

MPR’s exhibit several benefits over traditional forms of coastal protection such as groynes, breakwaters and seawalls. Firstly they are positioned offshore, and with submerged crests, visual and aesthetic impacts are reduced as compared to traditional emergent rock/rubble breakwaters and groynes. MPR’s act as control points within the beach system, breaking waves and reducing wave energy, bending/refracting waves and altering longshore currents and associated sediment transport (Black *et al*., 2001), and when placed at the appropriate distance offshore result in the creation of wave driven current circulation behind the reef which induces salient formation (Ranasinghe and Turner, 2006; Ranasinghe *et al.*, 2006). As opposed to solid emergent structures which act as an absolute barrier to wave energy and sediment transport with negative down-coast impacts, MPR’s can be designed to work within a system creating a salient without providing an absolute barrier to sediment transport

(Black *et al*., 2001). In addition the growing demand for 'soft' environmentally friendly coastal protection options makes the use of sand filled geotextile mega-containers for MPR construction a major positive benefit (Saathof *et al*., 2007).

1.1.2 Socio Economic Value of Beaches and Tourism

Sandy beaches are among the most valuable ecosystems used for outdoor recreation worldwide (Cervantes and Espejel, 2008). For example in the U.S. beaches are the leading tourist destination, receiving 85% of all tourist related revenue, or over $260 billion annually (Houston, 2002). Over 500,000,000 tourists visit the Californian beaches, with Californian State beaches receiving 72% of the visitors, even though they represent only 2.7% of the State parks (Houston, 2002). California beach tourism provides both direct and indirect services worth 27,000 million dollars, representing 3% of the state economic activity. Houston (2002) established a 600:1 return on investment for beach maintenance in the USA (Cervantes and Espejel, 2008). Erosion is perceived as the number one threat to beaches, but relatively very little has been spent on addressing erosion problems in California (Houston, 2002). In comparison, Miami's beach restoration experience has shown that the presence of wide sandy beaches is valued at a benefit/cost ratio of 500:1 (Houston, 2002). Houston (2002) proposes the need for "… a paradigm shift in attitudes toward the economic significance of travel and tourism and necessary infrastructure investment to maintain and restore beaches …". This project is an example of the current movement to develop novel erosion control methodologies with low negative environmental impacts while providing opportunities to enhance amenity value along the developed coastal areas.

Studies into the economic benefits of artificial reefs are now becoming increasingly common. For example, a socio-economic study of reefs in southeast Florida demonstrates the huge economic contribution of reef related expenditures (boating, fishing, Scuba diving and snorkelling) that artificial reefs make to the region (Johns *et al*., 2001) – this area of the US is a world-leader in multi-purpose reefs designed for habitat enhancement. Incorporating wide beaches and quality surfing conditions into artificial reefs creates added amenity enhancement. In addition, water sport and surfing events associated with the beach can be of considerable economic importance. A festival held at Noosa in Australia to celebrate the restoration of the beach attracted in the order of 20-30,000 visitors over the weekend, injecting at least AU$ 1M into the economy, if visitor spending was only AU$ 50/visitor. Surfing competitions are now heavily promoted and publicized - for instance, a single international level surfing event (short board or longboard or bodyboard, etc) can bring hundreds of thousands of dollars into the local economy. On the Gold Coast of Australia, it is estimated that a single high profile surfing event is worth AU$2.2M (Raybould and Mules, 1998 in Mead *et al*., 2006). In Cornwall, England, it is estimated that direct spend by surfers in the local economy is in the region of £21M each year (Ove Arup and Partners International, 2001).

Other studies of benefits associated with the construction of multi-purpose reefs at various locations around the world have all shown significant positive benefit/cost ratios. The lowest being approximately 20:1 for a small reef in Bournemouth, UK (Black *et al*., 2000), to over 60:1 for the Narrowneck reef on the Gold Coast, Australia (Raybould and Mules, 1998 in Mead *et al*., 2006) – since construction of the Narrowneck reef, the Benefit/cost ratio has since been re-evaluated at 70:1 (McGrath, 2002). A recent report for a multi-purpose reef in Wellington, New Zealand, estimated a "very conservative benefit:cost ratio of 24:1" (Baily and Lyons, 2003). Bournemouth Borough Council estimated that media exposure due to the planning and studies for the surfing reef at Boscombe (construction due in 2007) was worth at least £10M if the Council had paid for advertisements (Mead *et al*., 2006).

1.1.3 Study Site

St Francis Bay is one of several *log spiral* or *crenulate* bays situated on the south coast of South Africa (Bremner, 1983) (Figure 1.1). This coastline is exposed to relatively high wave energy, emanating predominately from the south-westerly quarter. The south east orientation of St Francis Bay results in a significantly lower and more variable wave energy regime than the exposed southern oriented coastlines of this area of South Africa. This is principally due to this beach being sheltered from the persistent waves and swells generated by west and southwest winds in the Southern Ocean. The predominant south westerly waves (>80% of the time) must refract over 90º around the Cape St Francis headland in order to enter the bay and thus waves from this direction are significantly reduced in height. Easterly and south-easterly wave events occur less frequently and are less significant when compared to offshore waves from the south-westerly quarter, however their direct approach and the fact that these waves are often generated relatively locally results in short period but high waves (steep waves) which result in direct cross-shore erosion of sand off of the beach face and into deeper water (Komar, 1998; Dean and Dalrymple, 2002).

Figure 1.1 Situated on the South African south coast, St Francis Bay beach is bounded by the rocky headland of Cape St Francis in the South and the Kromme Estuary mouth in the North (Mead *et al.*, 2006).

For the past two decades the municipality and residents of St Francis Bay have been seeking a solution to the chronic beach erosion experienced along the 3 km stretch of beach, between Cape St Francis in the south and the Kromme River mouth in the north, shown in Figure 1.1 above. This erosion can mainly be attributed to human interference in the natural sediment dynamics, which prior to human intervention, was dominated by a large sediment supply from coastal dunefields and intermittent supply of marine sediment accumulated in the Kromme Estuary. The primary sediment source was a large dunefield which actively supplied large quantities of sand into the south west corner of the bay (Figure 1.2). Due to the oblique angle of wave approach along the headland, this supply of sand was transported by constant longshore currents in a north-westerly direction along the Cape St Francis headland, before being distributed up and down the beach by varied cross-shore and longshore transport processes (CSIR, 1992). This abundant supply of sand was responsible for the presence of a wide sandy beach at St Francis Bay and the creation of the “perfect wave” on the inside of the headland, discovered by eminent surf film maker Bruce Brown in his quintessential surf movie Endless Summer filmed in the late 1960’s. In the movie two travelling surfers Michael Hynson and Robert August hike over endless sand dunes and arrive at the legendary wave, that later becomes known as Bruce’s Beauties.

However since this dunefield was stabilised between the 1960s and 1970's the beach has eroded at a rate of 1.5-3 m/yr and although waves still break occasionally at Bruces, the profile has deepened and the wave quality has been reduced.

Additionally prior to development flood events would have scoured sediment form the lower estuary supplying sediment to the beach and forming a submerged delta. River impoundment due to the construction of two large storage dams the Churchill and Mpofu, constructed in 1942 and 1983 respectively with a combined storage capacity greater than the Mean Annual Runoff (MAR) of the Kromme River catchment area has eliminated the ability of large flood events to scour sediment accumulated in the estuary mouth (Reddering and Esterhuysen, 1983; Bickerton and Pierce, 1988; CSIR, 1992).

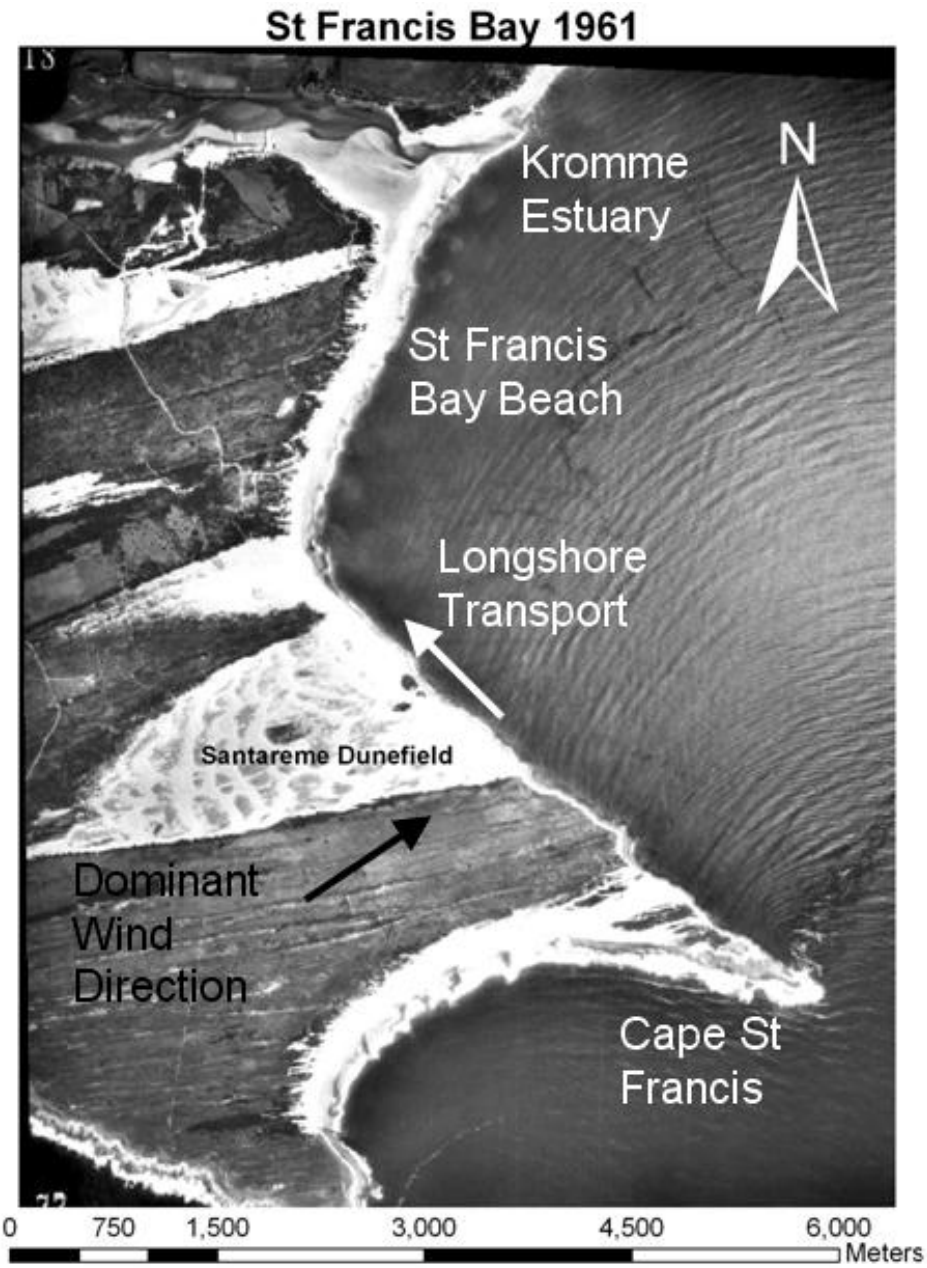

Figure 1.2 Aerial photograph of St Francis Bay in 1961 prior to development, when the Santareme dunefield situated along the south western corner of St Francis Bay actively supplied large volumes of sediment to the bay.

Since the early 1990's the erosion of the St Francis Bay beach has threatened to undermine beachfront properties, leading property owners to place 2-4m high rock revetments in front of their properties (Figure 1.3) Where properly maintained the revetments have been successful in protecting the land behind them, however much of the amenity value has been lost in terms of the wide sandy beach which once existed. Revetments are recognised as an effective land protection measure, however when subject to regular wave action increased levels of turbulence and reflection exacerbate erosion of the beach immediately in front of the revetment (Silvester and Hsu, 1999; Dean and Dalrymple, 2002), and depending on the site conditions can cause increased erosion of the adjacent unprotected areas due to “end/flanking effect” (McDougal, Sturtevant and Komar, 1987 in Sumer and Fredsoe, 2002), “groyne” or “cross wave” effects (Tooue and Wang, 1990 in Sumer and Fredsoe, 2002). Significant end effects are evident at revetment ends on St Francis Bay beach as seen in Figure 1.4.

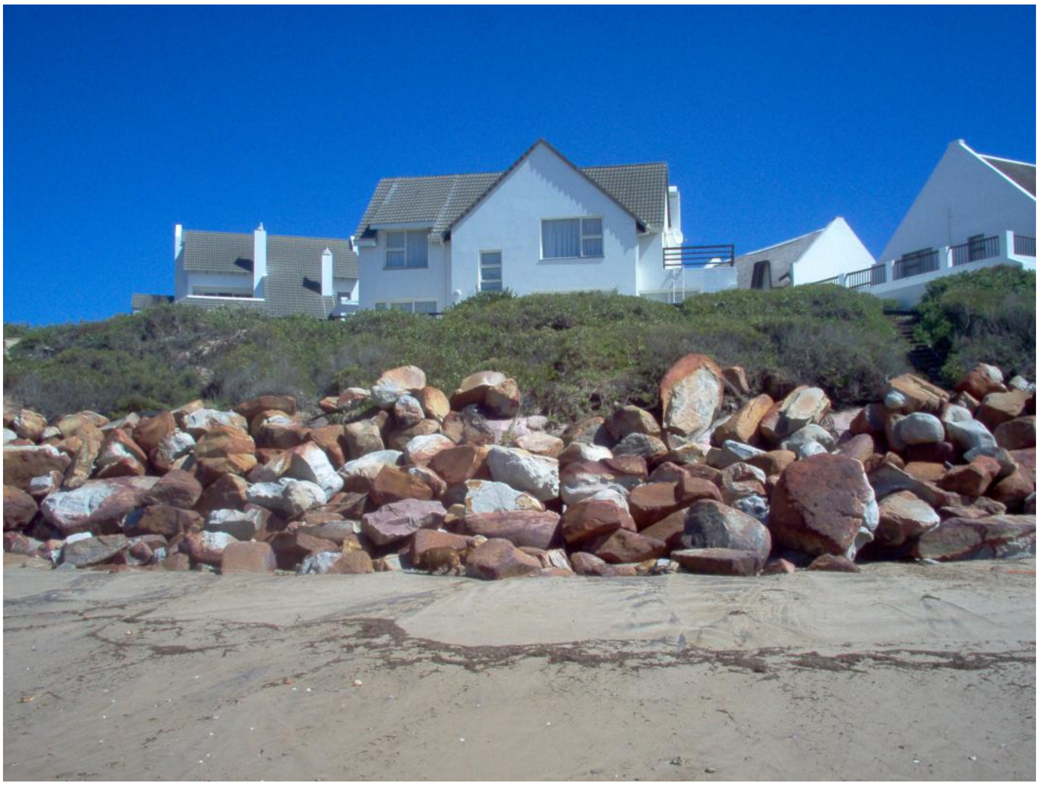

Figure 1.3 This picture taken at low tide on 20 March 2007 shows rock revetments placed along much of St Francis Bay Beach in order to protect beachfront properties at the expense of the beach, which continues to erode. Note the level of the high water line meets the revetments, indicating little or no dry beach exists at high tide.

Figure 1.4 Photograph taken 20 March 2007, showing increased erosion adjacent to revetments and behind the end of revetment, known as “end effect” or “flanking effect”.

Investigations into remediation of the beach erosion were first initiated in the early 1990’s, when the feasibility of a single groyne at the mouth of the Kromme was investigated, (WPR 1993). This did not progress any further until 1999 when SRK Consulting was appointed to undertake an Environmental Impact Assessment (EIA). Due to funding issues this EIA was discontinued until 2001 when SRK were reappointed to complete the EIA including several specialist studies. The most important of these studies were the evaluation of several coastal protection options (Entech, 2002a) and the evaluation of several sand sources (Entech, 2002b). These studies concluded that the preferable technical solution incorporated multiple groynes and beach nourishment from several sand sources. Details of this preferred solution was then assessed as part of the Environmental Impact Report (EIR) which was submitted to the Kouga Municipality (SRK, 2003).

No further progress was made until 2006 when local residents in St Francis Bay formed the St Francis Bay Beach Trust (SFBBT), with the aim of finding a more appropriate solution to the continued beach erosion problem. The SFBBT revisited previous studies in search of a more suitable solution, and the option of Multi-Purpose Reefs was considered preferable for aesthetic, environmental and amenity enhancement reasons. This led to the appointment of ASR Marine Consulting and Research Ltd of New Zealand, leading experts in the field of numerical modelling, coastal hydrodynamics and multi-purpose artificial reef design. In February 2006 ASR Ltd were contracted to investigate the feasibility of the construction of multi-purpose reefs as a form of coastal protection and amenity enhancement at St Francis Bay. Initial inspection of the site revealed several factors that provided good confidence in the suitability of MPR technology in addressing the erosion of St Francis Bay beach including: a small tidal range; small wave climate and the many good examples of strong salient responses in the lee of natural reefs in the vicinity Figure 1.5) including the large salient which gives St Francis Bay beach its characteristic 'dog-leg' plan form formed by a large reef in the central area of the beach (Figure 1.6).

Previous studies of the St Francis Bay beach erosion problem have concluded that beach nourishment will need to be conducted and this nourishment should be protected by structures in order to be successful (CSIR, 1992; WPR, 1993; Entech, 2002a). The lower reaches of the Kromme Estuary were considered a preferable source of sediment for beach nourishment for several reasons, namely proximity to the beach, suitability of sand, ongoing sedimentation in the Kromme Estuary (Reddering and Esterhuysen, 1983; Bickerton and Pierce, 1988); CSIR, 1992; Entech, 2002b) with resulting decreased navigability (Bickerton and Pierce, 1988)) and reduced tidal exchange resulting in hypersaline conditions in the upper reaches during summer months, with associated negative biological impacts (Wooldridge, 2007) .

Importantly removal of sand accumulated in the lover reaches of the Kromme Estuary would mimic the natural process of scouring due to floods which no longer occurs due to the construction of two large storage dams (Bickerton and Esterhuysen, 1983; Bickerton and Pierce, 1988)). Additionally the flood dominant nature of the Kromme Estuary (Bickerton and Pierce, 1988; CSIR, 1992; WPR, 1993 and Schumann and de Meillon, 1993) and input of sediment from the Oyster Bay dunefield via the Sand River, will ensure that this supply will be constantly renewed (Entech, 2002c).

Findings from numerous studies have shown the benefit of a natural functioning dune system at the back of the beach. During periods of accretion wind-blown sand is trapped by dune plants, to be released during storm activity, thus acting as a natural defence or 'buffer' (French, 2001).

Therefore Mead *et al*. (2006) proposed that the remediation be carried out as a hybrid approach incorporating artificial reefs offshore, beach nourishment and dune rehabilitation.

Figure 1.5 Existing examples of salients formed in the lee of natural reefs north of the Kromme Estuary (Google Earth, 2008).

Figure 1.6 Oblique aerial photo of St Francis Bay taken in 1989 looking north, showing the impacts of a submerged reef on the plan shape of the beach, resulting in the ‘dog-leg’ plan shape, rather than a linear or subtly curving beach between the hard headland of Cape St Francis (out of picture to the bottom left) and the Kromme Entrance in the distance.

After completion of the above mentioned feasibility study, the EIA process was re-visited, because the new proposal was only a slight variation of what had been proposed by Entech (2002a), in terms of coastal protection structures, multi-purpose reefs were effectively replacing multiple groynes proposed by Entech (2002a). Therefore the Department of Environmental Affairs, Economics and Tourism (DEAET) for the Eastern Cape Province concluded that the existing EIA could be updated to include details of the latest remediation solution proposed by Mead *et al.* (2006), however in terms of sand sourcing for beach nourishment, DEAET stipulated that additional hydrodynamic modelling would be necessary to assess the impacts of sand extraction on the dynamics of the estuary and canal system.

This thesis comes out of elements of work conducted by the author towards the above mentioned proposals and studies and includes additional independent work conducted by the author in order to develop a better understanding of the dynamics of the environment at St Francis Bay and test the effectiveness and impacts of different aspects of the proposed multi-faceted approach to beach erosion mitigation and amenity enhancement at St Francis Bay.

1.2 Objectives

The purpose of this study was to investigate and quantify the existing environment of St Francis Bay, with a view to finding a sustainable solution to the ongoing coastal erosion problem. This was achieved by undertaking fieldwork and data collection, which was analysed and utilised for numerical modelling to improve the understanding of the dynamics of the bay. The calibrated numerical models were then used to conduct design testing for MPR's for coastal protection and amenity enhancement. While the primary objective was coastal protection, additional design considerations included the creation of high quality surfing waves, for which physical modelling tests were conducted to finalise reef design for surfing wave quality. In addition in order to investigate the suitability of the Lower Reaches of the Kromme Estuary as a sand source for beach nourishment and identify possible impacts on the estuary and canal system, calibrated hydrodynamic modelling was conducted, which included the simulation of different sand extraction scenarios.

Specifically the objectives are to:

- Describe the background, physical environment and processes relating to the erosion of St Francis bay beach
- Describe the proposed hybrid approach
- Describe the fieldwork and data collection conducted towards this study
- To develop further understanding of the nearshore environment at St Francis Bay
- Conduct MPR design testing
- To test reef design for surfing wave quality and wave energy dissipation
- To simulate hydrodynamics of the Kromme Estuary and assess the impacts of sand extraction.

The Objectives were achieved by:

- Reviewing the data and results of all previous studies specifically those relating to the erosion of St Francis Bay beach and the sedimentation of the Kromme Estuary.
- Describing and contextualising the different components of the Hybrid solution.
- Presenting results of all fieldwork conducted, including: bathymetric survey of the bay for comparison with the previous survey data to calculate changes in the bathymetry and to create an accurate bathymetry grid for MPR design testing, dive and aerial surveys, beach profiling, sediment sampling and collection of wave and current data.
- Reviewing recent results of investigations into physical processes and use numerical modelling to: developing a nearshore wave climate and simulate waves, currents and sediment transport conditions at the study site.
- Using the nearshore wave climate to conduct numerical model testing of MPR design
- Conducting physical modelling tests in order to test reef design for surfing wave quality and wave energy dissipation
- Conducting calibrated numerical modelling to simulate hydrodynamics of the Kromme Estuary and assess the impacts of sand extraction.

1.3 Thesis Structure

The thesis is structured as follows:

Chapter 2 provides a detailed description of existing information pertaining to the St Francis Bay environment, including a review of the results and recommendations of previous studies.

Chapter 3 describes the different elements of the proposed hybrid solution.

Chapter 4 describes the fieldwork and data collection including: bathymetric surveys; dive investigations; beach profiling; sediment sampling for grain size analysis and the collection of wave and current data.

Chapter 5 briefly describes recent results of investigations into the physical processes and dynamics affecting St Francis Bay beach, before presenting calibrated wave refraction modelling of offshore hind-cast wave data used to develop a nearshore wave climate and the results of numerical modelling investigations into the nearshore dynamics of St Francis Bay.

Chapter 6 describes the background to artificial reef design and presents the results of the iterative process of reef design testing and functional assessment using numerical modelling.

Chapter 7 describes the laboratory physical modelling tests conducted in order to finalise reef design specifically for wave quality and includes analyses of overhead and oblique photography and video imagery and measurement of wave transformation.

Chapter 8 presents the process and results of calibrated numerical modelling of the hydrodynamics of the Kromme Estuary in order to assess the impacts of extracting sand from the lower reaches of the Kromme Estuary for use as beach fill.

2 BACKGROUND AND DESCRIPTION OF ENVIRONMENT

2.1 Regional Socio Economics

St Francis Bay falls within the "Sunshine Coast" in the Eastern Cape Province (Figure 2.1), South Africa. This region extends 385 km from the boundary of the Western and Eastern Cape provinces to the Great Fish River. About 84% of the population lives in Port Elizabeth. Other coastal towns include St Francis Bay, Jeffreys Bay, Kenton-on-Sea and Port Alfred. Infrastructure in the region is good and tourism and recreational development and services are significant in the region. St Francis Bay falls within the Kouga Municipal district, which includes Jeffreys Bay and Humansdorp.

Figure 2.1 Eastern Cape Province Showing major towns and national roads (www.ectourism.co.za))

The economy is dominated by the manufacturing, commercial and industrial activities of Port Elizabeth. The most important fishing activities relate to squid (locally known as 'chokka'), kingklip and sole, as well as abalone farming. Sand mining for the cement industry occurs in Algoa Bay. Other activities include forestry, particularly in the Humansdorp district, and a range of agricultural practices. One limitation to further development is the lack of fresh-water resources, which is particularly notable in the St Francis Bay region (Coastal Policy

Green Paper, 1998).The Eastern Cape is the second poorest province in South Africa measured by several indicators[1] Along with rest of South Africa, tourism is the fastest growing industry in the province. The Eastern Cape combines many features which make it a truly extraordinary tourist destination. Widespread poverty, increasing unemployment and the influx of people from the former bantustan “homelands” of the Ciskei and Transkei to Port Elizabeth has added impetus to the need for large-scale industrial projects, such as the Coega harbour and Industrial Development Zone. Such developments could potentially have far-reaching consequences and are the subject of intense debate (Coastal Policy Green Paper, 1998).

A major feature of the Eastern Cape is its astonishing coastline lapped by the Indian Ocean, with long stretches of undisturbed sandy beaches, rocky coves and secluded lagoons. Protected from the predominant swell direction, several half-heart shaped embayments such as St Francis Bay offer safe bathing opportunities.

Perhaps the greatest feature of the Eastern Cape is the juxtaposition of wildlife tourism and beach tourism, attracting many international tourists to the area. St Francis Bay is special in this regard, offering high quality beach and coastal tourism immediately adjacent to the Baviaanskloof Conservation Area, a World Heritage Site and mega-park of extraordinary scenic beauty and ecological diversity www.baviaanskloof.co.za .

St Francis Bay has over 45 tourist establishments offering visitors differing levels of accommodation ranging from 5 Star Guest Lodges to basic Bed and Breakfasts. Entertainment is plentiful with high quality restaurants and sporting activities such as fishing, surfing, diving, golf, tennis and bowls. The St. Francis Bay Links includes a Jack Nicklaus designed golf course and housing estate. All the above factors combine to make St. Francis Bay a highly attractive beach destination for the discerning holidaymaker. The various tourist accommodation and restaurants provide employment for well over 250 individuals with varying levels of skills.   Many of the properties in St. Francis Bay are holiday homes, with a only +/-1500 permanent residents, however during the December-January holiday period the population increases to +/- 20 000. A large number of extra job opportunities are available during this time.

[1] Thus, according to the South African Institute of Race Relations, the Eastern Cape has the second highest population increase between 1996 and 2001; the second lowest Gross Geographical Product per capita; the second lowest proportion of the working age population that is economically active; the second lowest average annual income per household; the lowest proportion of adults with grade 12 education; and the lowest university entrance pass rate; the lowest proportion of households using electricity for lighting and heating.

The erosion of the beach at St. Francis Bay is a serious threat to beach tourism, which in turn compromises the sustainability of socio-economic development based on ecosystem services such as the beach, estuary and coastal scenery.

Sea Vista, a township of modest homes and squatter shacks, is an integral part of St Francis Bay yet it has suffered from years of neglect by the local council. It is estimated that up to 2500 people make up this fragmented and dysfunctional community. The community is comprised of a settled, largely coloured community and recent new arrivals, mainly from the old Ciskei Homeland area, who live under appalling conditions. In addition, a significant component of the community are involved in the fishing industry which supports a transient lifestyle. The collapse of beach tourism will undoubtedly hamper the sustainable growth of the regions economy, causing job losses in an area already plagued by high unemployment (ca 50%).

In addition surfing is a major tourist attraction along this stretch of coast, with many high quality surf breaks between Cape St Francis and Port Elizabeth. The annual Billabong Pro international surfing contest held at Jeffreys bay, half an hours drive from St Francis Bay, attracts thousands of people and brings significant revenue to the area. Therefore, the incorporation of surfing breaks into the proposed beach protection structures will provide additional positive socio economic benefits to the St Francis Bay area.

2.2 History

The greater St Francis Bay extending from Cape St Francis in the south west to Cape Recife in the north east was originally called Golfo dos Pastores by Portuguese explorer Bartholemew Dias in 1488 and was also known as Golfo dos Vaqueiros, until in 1575 another Portuguese explorer Manuel Perestrello called it Baia de San Francisco.

Coastal development in the area started at Jeffreys Bay where a trading store was established in 1849. Prior to the opening of the narrow gauge railway line from Port Elizabeth to Humansdorp, the beach in front of the store was used for landing and off-loading cargo. For years Cape St Francis was very difficult to reach, its only access being a sandy track through the dunes. This all changed with the arrival of Mr Leighton Hulett and his family in 1954. Mr Hulett was a driving force behind the development of what is now known as the ‘’St Francis Bay” township, situated in the south western corner of the bay between the Kromme Estaury in the north and Cape St Francis in the south and includes the Marina Glades canal system on the southern banks of the Kromme(Bickerton and Pierce, 1988)). St Francis Bay Township was proclaimed in 1965, initially named Cape St Francis, then Sea Vista and since 1979 it has been called St Francis Bay (McDonald, 1985 in Bickerton and Pierce, 1988)). The current name “St Francis Bay” is used throughout this document, however it should be noted that this name is shared with the greater half heart bay extending between Cape St Francis and Cape Recife as discussed above.

St Francis Bay was put on the world map in 1967 when the famed surf cinematographer Bruce Brown, produced his seminal surf move “Endless Summer”, documenting the adventures of two surfers Robert August and Michael Hynson as they searched the world for the perfect waves. During their travels in South Africa the two intrepid surfers stop off at Cape St Francis following reports from local fisherman of “good surf in the corner of the bay”. This leads to one of the most memorable scenes in the movie which sees the two surfers walking over what seems like endless dunes before finally reaching the beach and the sight of waves running seamlessly down the inside of Cape St Francis. The wave became known as “Bruce’s Beauties” in honour of the man who first showed the world this ‘perfect wave’ as he referred to it (Figure 2.2).

Figure 2.2 Surfing at Bruce's Beauties in 1967, from the film Endless Summer, produced by surf film maker Bruce Brown (**www.wavescape.co.za**).

2.3 Physical Setting

2.3.1 Coastline

More than 55% of the Sunshine coast is comprised of sandy beaches, while rocky headlands make up 24% and wave-cut rocky platforms 21% (Coastal Green Policy Paper, 1988). The region is dominated by two large crenulate bays, St Francis and Algoa Bay (Bremner, 1983).

There are several large estuaries, such as the Swartkops, Kromme, Kowie, Boesmans, Great Fish, Gamtoos and Sundays. The Alexandria dunefield on the northern shores of Algoa Bay is the largest dunefield in South Africa. The region is noted for the diversity of vegetation types, including large forests in the wetter western areas, fynbos on coastal cliffs and thicket in the drier eastern sections. Grasslands and pastures have high agricultural potential. The warm coastal waters, with occasional cold-water upwellings, support more than 70 species of fish, such as mullet, steenbras, zebra, blacktail and sole, as well as chokka and rock lobsters (Coastal Green Policy Paper, 1988).

This region is renowned for its beautiful white sandy beaches and when St Francis Bay first became a popular holiday destination 30 years ago a wide sandy beach extended for 3km between the headland of Cape St. Francis and the mouth of the Kromme Estuary (Figure 2.3).

Figure 2.3 Photograph from the 1960's looking south along St Francis Bay beach, notice the wide sandy beach, backed by natural dunes and the extensive Santareme dunefield in the background.

Prior to development several large headland bypass dune-fields (Tinley, 1985) extended across Cape St Francis. These dunefields transported sediment across the headland, intermittently supplying sediment to St Francis Bay beach, contributing significantly to the sediment budget of St Francis Bay (McLachlan *et al*., 1994; La Cock and Burkinshaw, 1996). Figure 2.4 below shows the situation in 1961 dominated by the Santareme dunefield which was actively supplying sand into the south western corner of the bay at the time.

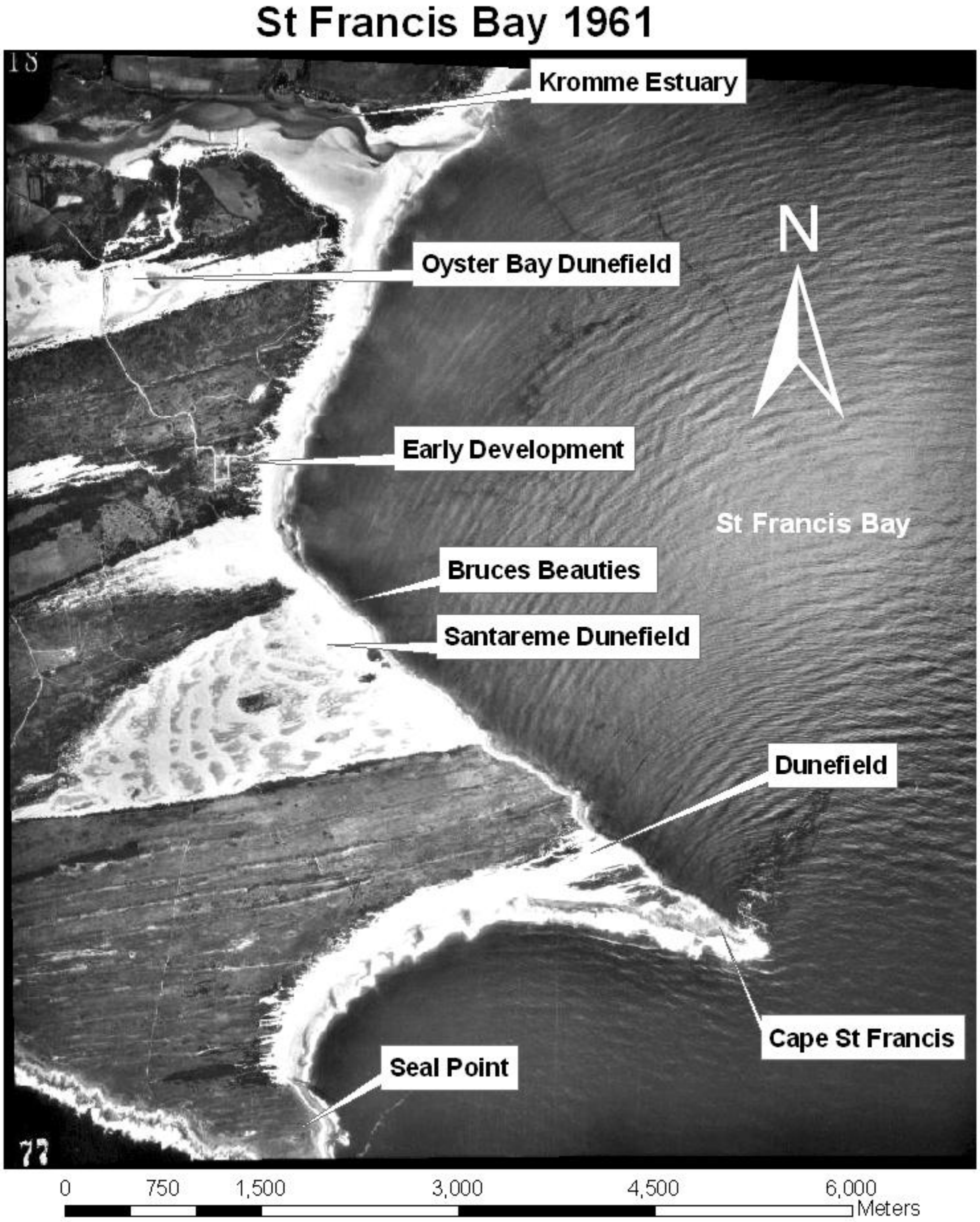

Figure 2.4 Aerial photograph of St Francis Bay in 1961, prior to development and dune stabilization.

Beginning in the 1970's large sections of the dunefields were irreversibly stabilised in particular due to the construction of the "Santareme" housing development: this interruption in sediment supply is the major factor resulting in chronic erosion along the St Francis Bay beach over the last 30 years (McLachlan *et al*., 1994; La Cock and Burkinshaw., 1996). Development of the St Francis Bay township extended onto the foredunes providing much sought after beachfront holiday properties. The wide and variable Kromme Estuary mouth was restricted due to the construction of an artificial sand spit/barrier dune using dredge spoils during excavation of the Marina Glades canal system in the late 1960's. Additional development along Cape St Francis includes the construction of Port St Francis completed in 1997, providing anchorage to a small fleet of commercial fishing boats, sport fishing boats and sailing yachts. Figure 2.5 below shows the present state of development along the coast of St Francis Bay.

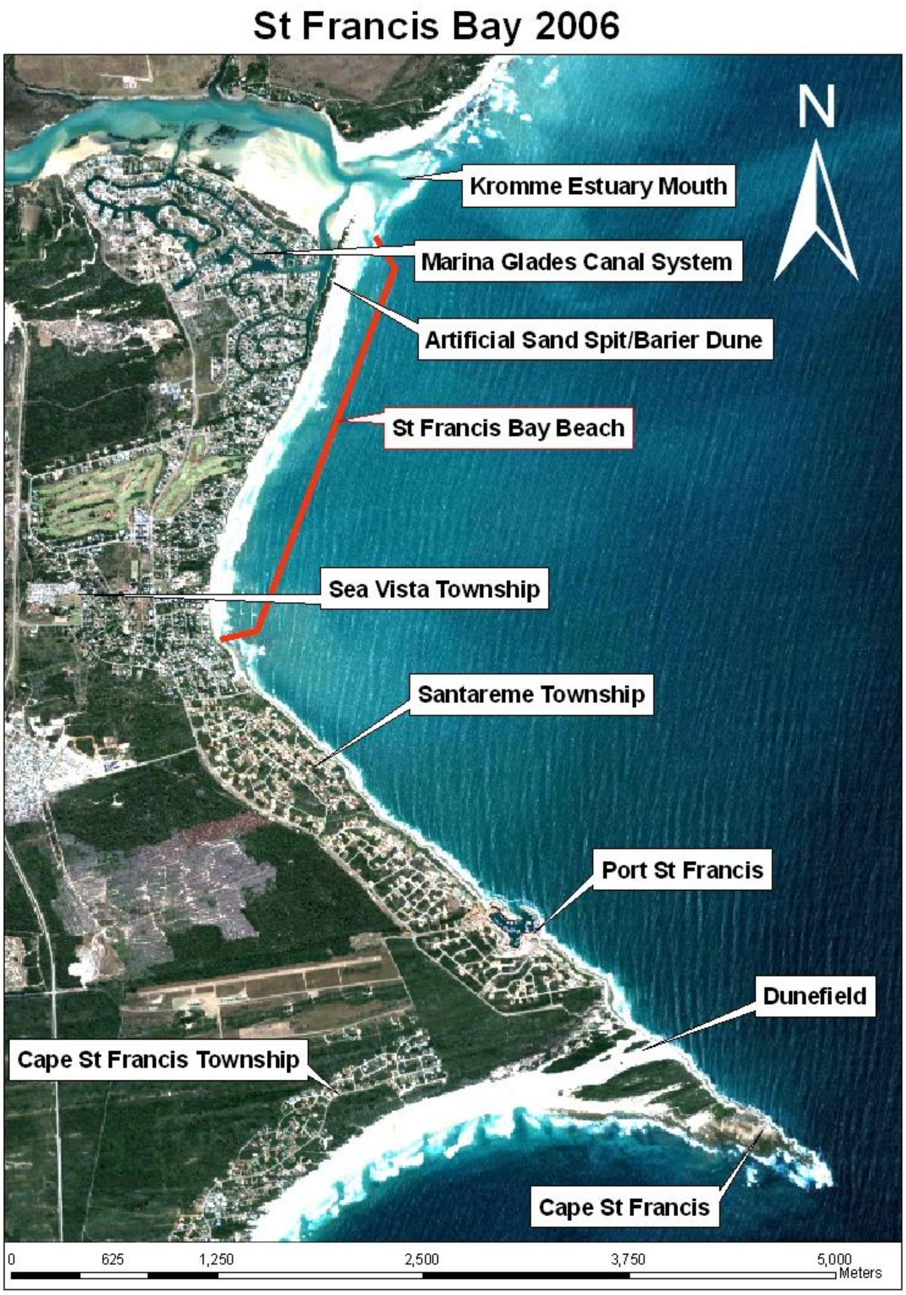

Figure 2.5 Google Earth Image from 2006, showing significant development including: Port St Francis, the Santareme township, Sea Vista and the Marina Glades canal system. Beachfront development extends up to St Francis Bay Beach; the site of significant chronic erosion is marked in red.

2.3.2 Kromme Estuary

At the southern end of the St Francis Bay Beach lies the highly variable but permanently open mouth of the flood tide dominated Kromme Estuary, which extends 14 km inland (Figure 2.6), with an average width of 80 m and an average depth of 2,5 m at low water ordinary spring tides. An artificial sand spit/barrier dune extends for about 500m from the southern bank; this was created with dredge spoil during canal excavation in the late 1960's. The tidal area of the Kromme Estuary is about 3 km^2 and the greatest width of the tidal zone is 175 m, inside the mouth behind the sand spit (Bickerton and Pierce, 1988). The Kromme Estuary exhibits a flood tide dominated flow regime, resulting in the accumulation of marine sediment and extensive flood tidal deltas in the lower 4.5 km. The main tributary flowing into the Kromme Estuary is the Geelhoutboom River which flows into the Kromme approximately 9 km upstream of the mouth. Other tributaries include: the Boskloof (5.2km upstream of the mouth), the Sand river (2km upstream from the mouth) and the Huisriver (1km upstream of the mouth) (Bickerton and Pierce, 1988)).

Figure 2.6 The full extent of the Kromme Estuary, including the main tributaries and Marina Glades canal system (Google Earth, 2006).

The estuary is completely saline due to almost absolute attenuation of fresh water as a result of the construction of two large dams within the Kromme River catchment area which drains a large part of the Langkloof (Wooldridge, 2007) (Figure 2.7). The Churchill Dam was completed in 1943, and is situated 50 km from the mouth with a capacity of 33, 3 x 10^6 m^3 and the Mpofu Dam formerly known as the CW Malan Dam was constructed in 1982, situated 4km from the tidal head of the Kromme Estuary and constructed with an earth and rock-fill structure with a clay core, with a storage capacity of 100 X 10^6 m^3 (Bickerton and Pierce, 1988); CSIR, 1992). The combined capacity of these two dams is greater than the mean annual runoff (MAR) for the catchment area of the Kromme River, thus greatly reducing the volume of freshwater reaching the Kromme Estuary. These dams supply drinking water to Port Elizabeth. In addition numerous small farm dams further reduce fresh water supply to the estuary (Bickerton and Pierce, 1988)).

Figure 2.7 Google Earth image (2008) showing the Kromme Estuary and the two large storage dams in the catchment of the Kromme River, The Mpofu and Churchill dams (Google Earth, 2008).

Development along the Estuary includes a marina which was initiated in 1969 on the southern side near the inlet and more recently extended in 2001, and a road bridge which was constructed across the estuary in 1976, roughly 3km from the inlet, neither of these developments appear to interfere with the tidal hydraulics of the system. Holiday homes with jetties are found along the banks of the lower Kromme near the road bridge. Farming is practiced on a limited scale on some parts of the estuary banks (Reddering and Esterhuysen, 1983).

2.4 Geology

2.4.1 Coastal

Cape St Francis is composed of resistant quartzites of the Table Mountain Group. St Francis Bay has formed in less resistant shale of the Bokkeveld Group (Illgner, 2008) Extensive volumes of loose sand of Quaternary origin extends across Cape St Francis as active or relic (stabilised) headland bypass dunefields, features described in more detail in section 2.7.7 and 2.8.1. The geology of the Cape St Francis region is shown in Figure 2.8 below.

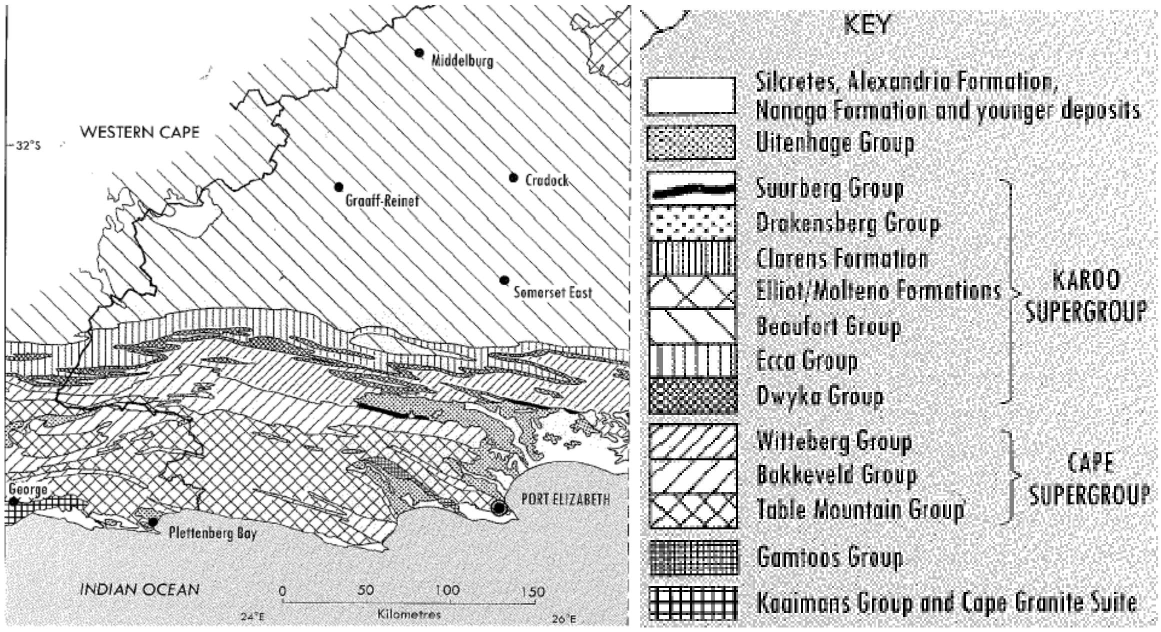

Figure 2.8 Geology of the Cape St Francis area (left), legend (right) (Maud, 2008).

2.2.1 Geology of the Kromme River and Estuary

The Kromme River catchment area drains part of the Langekloof which is a 75 km long east-west trending Bokkeveld slate syncline which stretches for 20km east of Joubertina to near the tidal head of the Kromme Estuary. Resistant quartzite of the Table Mountain Group forms the anticlinal ridges. These deformed rock suites form part of the Cape Fold Belt which extends across the entire southern Cape coastal Area (Reddering and Esterhuysen, 1983).

The tidal head of the estuary is a rapid across Bokkeveld sandstone. In the upper reaches the estuary is incised into bedrock but the relief flattens down-estuary. The straight upper section of the channel near the tidal head flows along a vertically folded contact between the Table Mountain and Bokkeveld Groups. The latter is readily eroded whereas the quartzite resists weathering. The geological substrate of the estuary consists of Bokkeveld slate. Weathered outcrops are common the entire length of the estuary, particularly along its northern bank. Weathered slate supplies a small volume of in situ sediment. The lower estuary near the inlet is characterised by sandy sediment and inter-tidal flats are well developed (200m wide). In the muddier upper estuary the inter-tidal areas are much narrower (20 m) (Reddering and Esterhuysen, 1983) (Figure 2.9)

The northern bank is composed of soft sandstones and shale of the Bokkeveld Group until just upstream of the mouth. The sand of the northern bank of the mouth of the estuary is classified as drift sand of the late Tertiary age. The southern bank is characterised by Bokkeveld Group shale, from the head of the estuary to its middle reaches. From here alluvium of the late Tertiary extends downstream to approximately 3km from the mouth. Between this point and the mouth, consolidated sand, also of the late Tertiary is found (Hecht, 1973 in Bickerton and Pierce, 1988)).

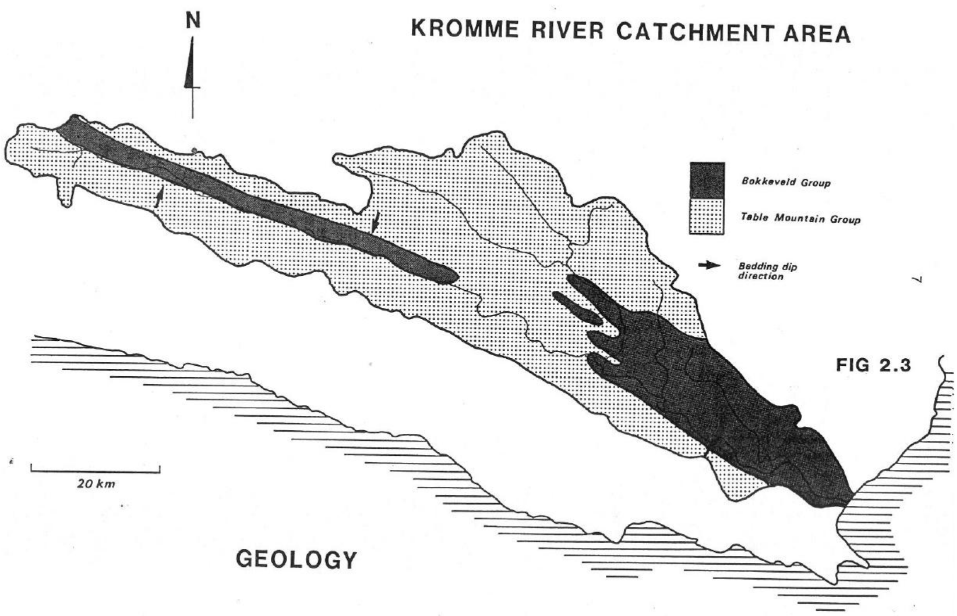

Figure 2.9 Geology of the Kromme River catchment from Reddering and Esterhuysen (1983).

2.5 Climate

2.5.1 Atmospheric Circulation Patterns

The major changes in configuration of the southern coasts expose the subcontinent to the contrasting influence of cold and warm ocean currents, circumpolar westerlies and subtropical high pressure anticyclones. The significance of the subcontinents position to these major fluid and atmospheric environments is that neither one predominates to the exclusion of the others (Lubke, 1985). An initial climatic asymmetry is imposed by the existence of the cold Benguela current flowing northwards along the west coast, which inhibits evaporation and rainfall and the warm Agulhas current flowing in a south westerly direction along the east and south coast (see section 2.6.1), which enhances convectional processes (Preston-Whyte and Tyson, 1996).

The weather regime is dominated by an alternating succession of east-moving cyclones from the circumpolar westerlies, interaction with subtropical high-pressure anticyclones which are centred over the South Atlantic seaward of the west coast, and over the eastern interior of Southern Africa and adjacent South Indian Ocean. The anticyclones are subsiding air masses of the sub-tropics and the low-pressure cyclones are ascending moist air masses originating as perturbations in the circumpolar westerlies. Both anticyclones and including the landward extension over the eastern interior of the South Indian Ocean High, fluctuate in position, ridging in south of the subcontinent where they cause a predominance of easterly winds along the coasts particularly in summer. In areas where the easterly blows offshore or with parallel trajectory, with the land on the right, moves inshore surface waters seawards and causes the upwelling of cold waters of Antarctic origin close to the coast (Heydorn and Tinley, 1980).

2.5.2 Winds

As discussed above South African weather is dominated by low pressure anticyclones and associated cold fronts which sweep from west to east across the mid latitudes. In autumn and winter this circumpolar westerly belt shifts north and weather is dominated by the regular passing of mid-latitude cyclones and associated westerly winds. In summer this westerly belt shifts south as the earth tilts on its axis and easterlies associated with the South Indian

Ocean High occur relatively more frequently along the South African coastline (Preston-Whyte and Tyson, 1996).

2.5.3 Rainfall and Temperature

The Rainfall distribution across South Africa is strongly influenced by the Contrasting warm Agulhas and cold Benguela currents on the east and west coasts respectively. High levels of evaporation over the warm waters of the Agulhas Current during the summer months, in conjunction with the weakening of the Mid-latitude High Pressure System, leads to higher levels of precipitation over the eastern seaboard and eastern interior during the summer months. The western half of South Africa is characterised by winter rainfall, relatively high levels of precipitation are experienced in the South West coastal areas and low precipitation levels are experienced in the North and central areas due to limited evaporation over the cold Benguela current (Preston Whyte and Tyson, 1996).

The Kouga coast falls roughly in the middle of the winter and summer rainfall regions, classified as warm-temperate, tending towards sub-tropical in the east. Rainfall occurring throughout the year, with lowest precipitation during summer (Bickerton and Pierce, 1988)), Table 2.1 below summarises weather for Port Elizabeth +/- 70 km north east of St Francis Bay.

Table 2.1 This climate information is the normal values and, according to World Meteorological Organization (WMO) averages for 1961 – 1990 (South African Weather Bureau, 2006)

Month	**Temperature (° C)**				**Precipitation**			
	Highest Recorded	**Average Daily Maximum**	**Average Daily Minimum**	**Lowest Recorded**	**Average Monthly (mm)**	**Average Number of days with >= 1mm**	**Highest 24 Hour Rainfall (mm)**	**Average Monthly (mm)**
January	39	25	18	10	36	9	68	36
February	38	25	18	11	40	9	121	40
March	41	25	17	8	54	10	224	54
April	39	23	14	4	58	9	105	58
May	35	22	12	2	59	9	76	59
June	32	20	9	-1	62	8	60	62
July	33	20	9	-1	47	8	99	47
August	34	20	10	2	64	10	77	64
September	39	20	11	2	62	9	429	62
October	39	21	13	3	59	11	46	59
November	36	22	15	6	49	11	52	49
December	36	24	16	9	34	9	95	34
Year	**41**	**22**	**14**	**-1**	**624**	**112**	**429**	**52**

2.6 Oceanography

2.6.1 Currents of Contrast

The oceanography around South Africa is characterised by two large contrasting currents on the east and west coasts, the warm *Agulhas* and cold *Benguela* currents respectively (Figure 2.10). The Agulhas Current is the western boundary current of the South Indian Ocean flowing pole wards down the east coast of Africa from 27°S to 40°S (Lutjerharms, 2001).

The Agulhas Current can be considered to consist of two distinct parts: the northern and the southern current. At Port Elizabeth, where the southern Agulhas Current starts, the maximum temperature is 25°C in January, with a minimum of 21°C in August. Surface salinities decrease from 35.5 PSU in the north to 35.3 PSU in the south. The southern part flows along the wide shelf expanse of the Agulhas Bank and by contrast meanders widely as it flows past the Agulhas Bank south of Africa (Figure 2.11). Wind-driven upwelling along the coastline, and particularly at prominent head-lands such as Cape St Francis, occurs during periods of strong and persistent easterly winds (Schumann *et al*., 1982). This brings colder water, already on the shelf, up from below the thermocline. During the past few decades it has been demonstrated that the greater Agulhas Current system has a marked influence on the climate variability over the southern African subcontinent. It has also been shown that this current is a key link in the exchanges of water between ocean basins and is believed to have a special role in the oceans' influence on global climate (Lutjeharms, 2001).

The *Benguela*, which shares its name with a town in Angola, is one of four major current systems situated at the eastern boundaries of the world oceans, and the oceanography of the region is in many respects similar to that of the Canary Current off north-west Africa, the California Current off the west coast of the USA, and the Humboldt Current off Peru and Chile (Shannon, 2001).

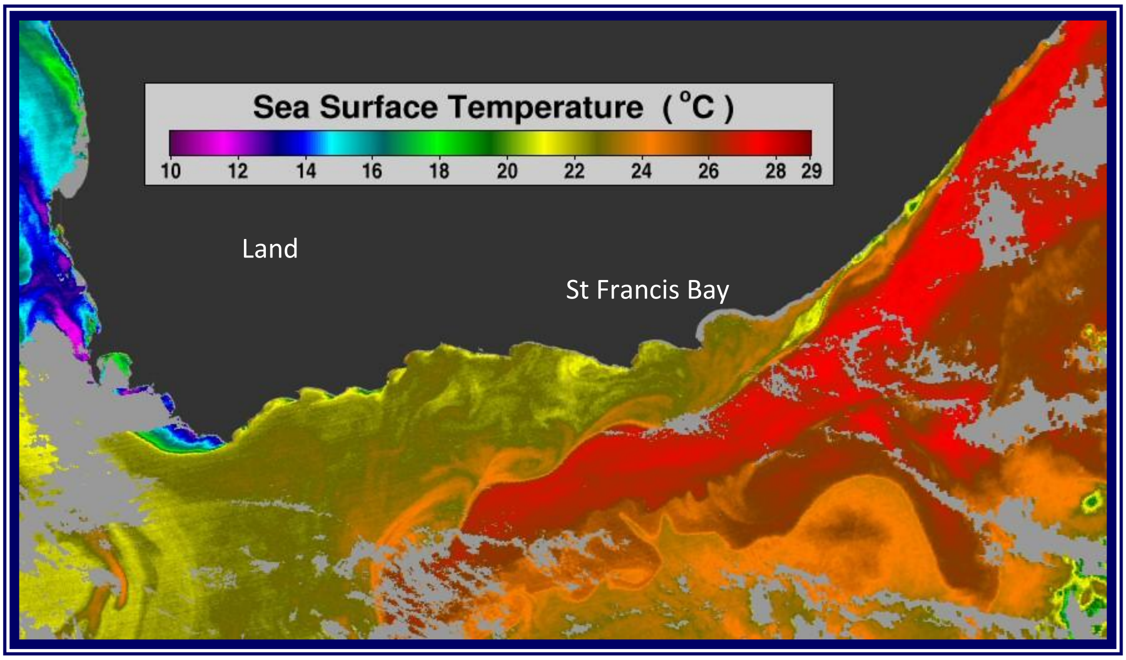

Figure 2.10 False colour RMAS Satellite image of sea surface temperature. The contrasting warm Agulhas and cold Benguela currents on the east and west coast respectively.

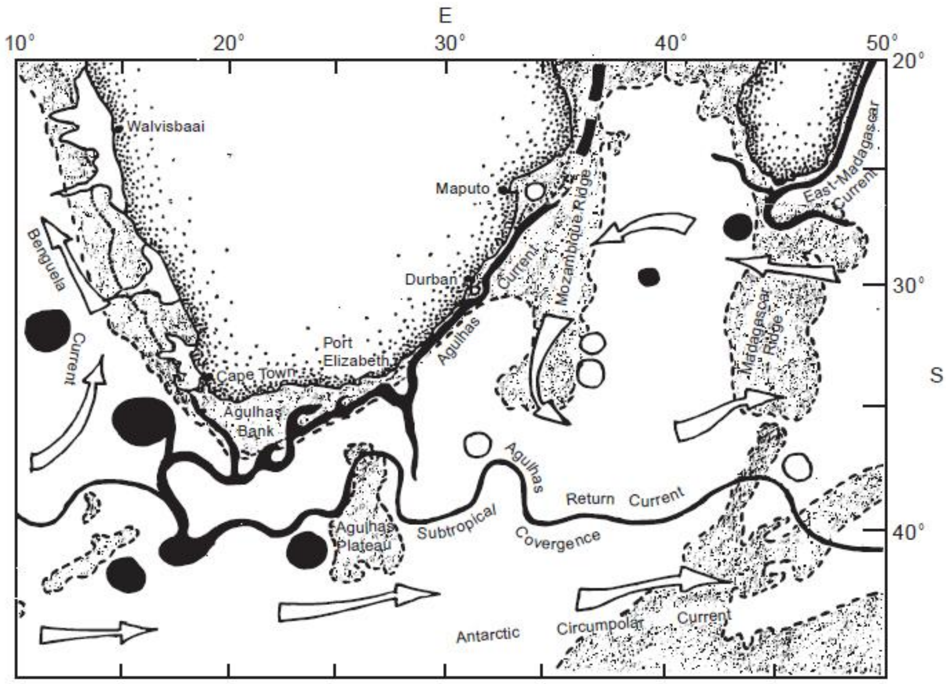

Figure 2.11 A conceptual portrayal of the Oceanography off South Africa, dominated by the Agulhas Current on the east and Benguela Current on the west. Ocean regions shallower than 3000m have been shaded. Intense currents are black, whereas the general background circulation is shown by open arrows. Cyclonic eddies are open; anticyclonic rings and eddies are black. (Lutjeharms, 2001).

2.6.2 Waves

Waves on the South African coastline are predominantly from the south westerly quarter, as the product of low pressure storms formed in the circumpolar westerly belt. These waves are often generated far offshore over great fetch and therefore swells reaching the South African coastline from this direction are generally well developed and long period (9-16 seconds). The largest waves originate from the south westerly quarter with greatest wave heights experienced further south and a reduction in wave height is experienced as one moves east along the East coast and north along the west coast (Roussow, 1989 in Entech, 2002a). Observations show that the wave direction pattern follows that of known weather patterns. During the passage of a cold front, wave directions swing from northwest to southwest along the southwest coast. Dominant directions are westerly to south-westerly along the Cape south and south-west coast. This transforms to south-westerly along the east coast. Figure 2.12 from Rossouw (1989 in Entech, 2002a), summarises the overall wave direction patterns along the South African Coast.

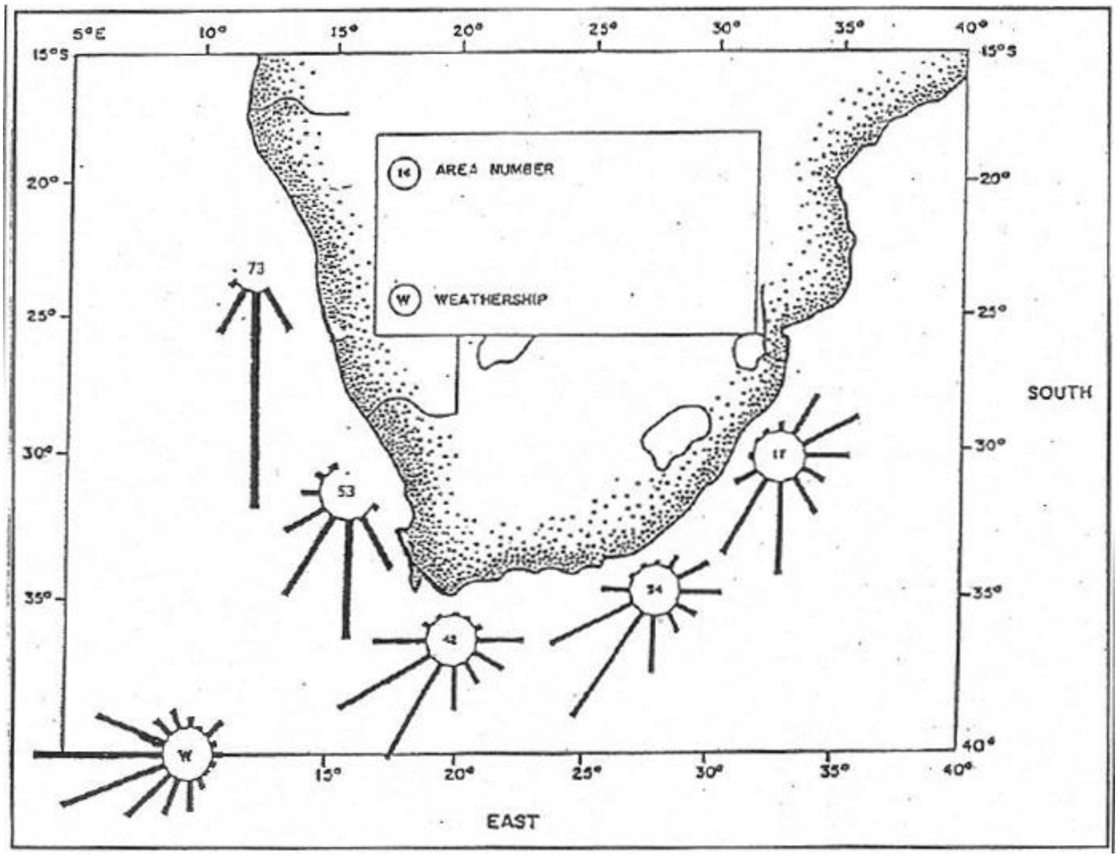

Figure 2.12 Wave direction distribution along the South African coast (Rossouw, 1989 in Entech, 2002a).

As described in the previous section, during spring and summer the circumpolar westerly belt moves south and local meteorological conditions are dominated by high pressure systems and associated easterly winds. These local easterly winds result in a higher prevalence of short period (5-8 sec) easterly waves along the southern and eastern coastline of South Africa (Tinley, 1985; Entech, 2002a).

Along the Southern Coast, the mean significant wave height is in the order of 2.7 m, which is relatively large. Extreme wave events can produce waves in excess of 10m, and Roussow (1989 in Entech, 2002a) gives the corresponding wave heights for three different return periods: 1year: 8m, 10 year: 10m and 100 year: 12m. Similar return period wave heights were calculated by Mead *et al.* (2006), shown in Figure 2.13 below.

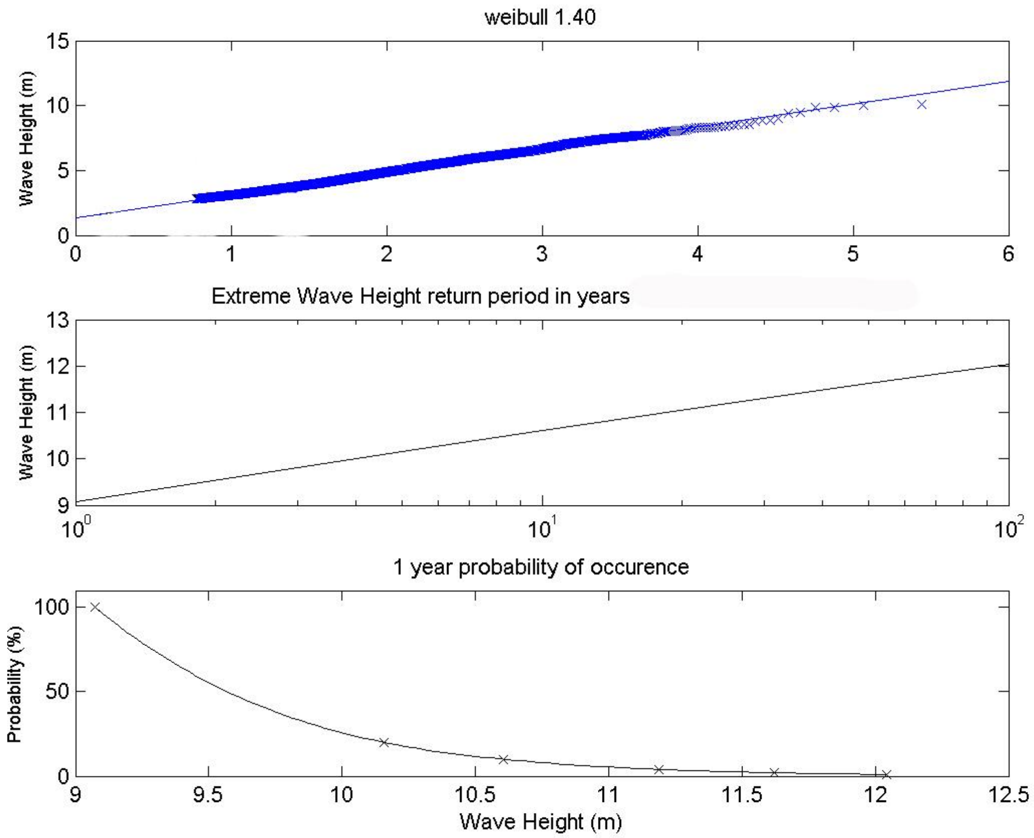

Figure 2.13 Results of extreme wave height return periods calculated from wave data from 1 January 1997 to 30 April 2006 (Mead *et al*., 2006).

Due to the orientation of St Francis Bay and the protection offered by the large headland of Cape St Francis, swell conditions within the bay differ from the open coastline. Although waves from the south westerly quarter occur for more that 60% of the year, within the bay waves from this direction are much reduced in height due to the large degree of refraction and diffraction around the Cape St Francis headland. While short period waves generated by local Easterly winds may be of secondary significance on the open coast, waves from this direction are allowed direct approach and therefore account for major wave events within the bay (Entech, 2002a; Mead *et al.*, 2006). In addition although fairly infrequent, longer period waves from a southerly to south easterly direction have led to severe cross shore erosion at St Francis Bay Beach, such as the event of 30 August to 3 September 1978 detailed by Shillington and Britten-Jones (1979). A more recent event in March 2007 is detailed in chapter 0. Nearshore wave height estimates are given as 4.4 m for once-per-year significant wave height (Hs), and 2.2 m for the more dominant Hs20% exeedence wave height, that is the significant wave height exceeded, on average, 20% of the time (CSIR, 1992).

2.6.3 Tides

Tides along the South African coast are diurnal with a fairly consistent average tidal range of 1.6m, falling within the micro-tidal class. In St Francis Bay the average tidal range is 1.08 m, with an average spring tidal range of 1.65 m, and average neap tidal range of 0.5 m (SAN, 2002). Tidal levels are recorded by the South African Hydrographic Office (SANHO) at a location within the Harbour at Port Elizabeth in Algoa bay, 70 km to the north east of St Francis Bay, summarized in Table 2.2 below.

Table 2.2 Tidal Levels at Port Elizabeth relative to Chart Datum (CD) (South African Navy Hydrographer, 2006).

Tide	Level(m)
Highest Astronomical Tide (HAT)	2.12
Mean High Water Springs (MHWS)	1.86
Mean High Water Neaps (MHWN)	1.29
Mean Level (ML)	1.04
Mean Low Water Neaps (MLWN)	0.79
Mean Low Water Springs (MLWS)	0.21
Lowest Astronomical Tide (LAT)	0

Local water levels can be affected by wind, atmospheric pressure and wave set-up. Research has shown that the occurrence of long period infra-gravity waves known as coastal-trapped waves (CTW's) which propagate in a anti-clockwise direction at a peak period of 10 days along the coast of South Africa can have a marked influence on water levels (Schumann and Brink, 1990). In addition water levels at the coast can be affected by strong onshore winds which blow the ocean water up against the coastline; this phenomenon is known as 'storm surge'. Storm surge destructiveness varies depending on the magnitude and duration of winds, magnitude of the low pressure system, the associated wind driven waves, ocean bathymetry and the coincidence with astronomical tides. (Dean and Dalrymple, 2002). CTW's and storm surges can increase sea levels on the South Coast of South Africa by more than 0.5 m (Schumann and Brink, 1990).

2.7 Relevant Coast Processes

2.7.1 Defining the Beach Environment

Before introducing the relevant coastal processes, it is important to review the commonly accepted nomenclature. Although beach morphology varies depending on sediment composition and the physical processes of waves, currents and sediment transport, the *beach* is commonly defined as an accumulation of unconsolidated sediment (sand, gravel, cobbles and boulders) extending from mean low tide to some physiographic change such as a sea cliff or dunefield or a point where permanent vegetation is established. This definition may satisfy the average recreational beach user, as it focuses on the dry portion of this environment, but this is highly unsatisfactory from the coastal scientist's perspective, since this limited view of the beach does not include the sub-aerial portion of the beach (Komar, 1998).

The significant processes responsible for beach morphology, wave breaking and sediment transport, occur in this sub-aerial portion of the beach. The term *littoral* is used to denote the entire environment, the zone extending across the exposed beach into the water to a depth at which the sediment is less actively transported by surface waves. This is a rather imprecise definition because waves can transport sediments at considerable water depths, but in general 10 to 20m water depth is a reasonable depth limit for the littoral zone. In practice the term beach is often used to refer to the whole littoral zone. The term *coastal* is even more inclusive, extending inland to include sea cliffs, dunefields and estuaries. The *nearshore zone* extends seaward from the shoreline to just beyond the region in which the waves break. This term is particularly important when discussing waves, currents and other significant physical processes within this environment. Figure 2.14 below depicts the commonly accepted terminology used to describe the distinct zones of wave and current action in the nearshore, which are closely related to the beach profile zones (Komar, 1998).

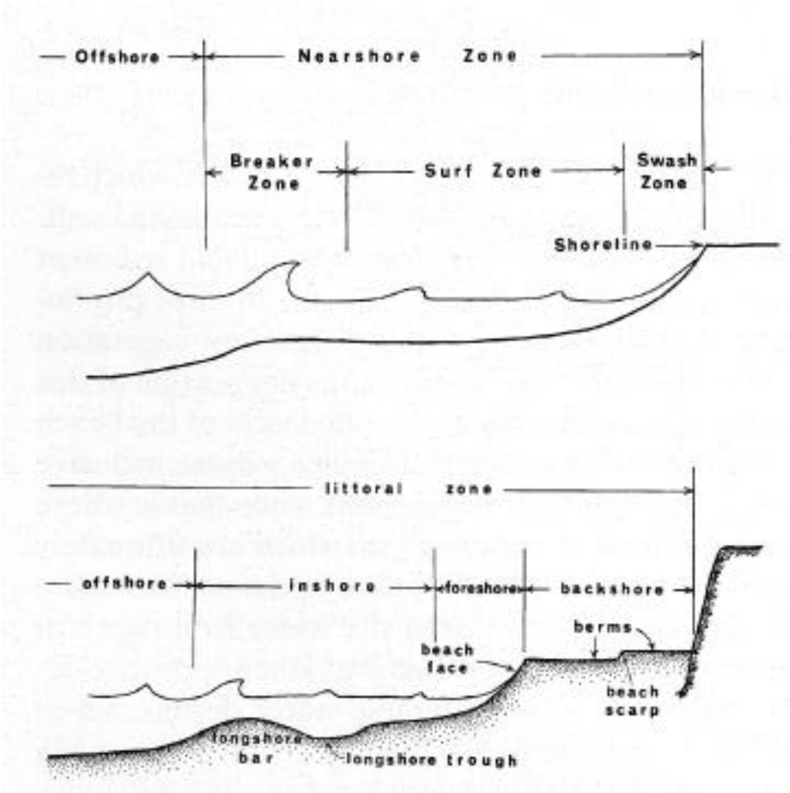

Figure 2.14 Terminology used to describe processes of waves and currents in the nearshore (above) and the terminology used to describe the beach profile (below) (Komar, 1998).

The width of the surf zone is dependant on beach slope and tidal level. Beaches of low slope, normally composed of fine sand, are characterised by wide surf zones. Conversely, the surf zone is often absent from steep gravel and cobble beaches, where the waves break close inshore as a swash that runs up and down the beach face. Moderately sloping beaches commonly lack a surf zone at high tide, as waves break close to shore over steeper beach face, developing a surf zone at low tide when waves break over the flatter portion of the beach profile. This variation in beach morphology has led to the development of a comprehensive classification scheme (Wright and Short, 1983 in Komar, 1998).

Beaches are classified into three main morphological types: *dissipative; intermediate* and *reflective* (Figure 2.15).

The *dissipative beach* is characterised by a low sloping profile, where waves break far offshore and continually lose energy as they travel as breaking bores across the wide surf zone. When the wave heights increase during a storm, the waves break further offshore, with minimal increase in wave energy at the shore. The morphology of the dissipative beach, as the name suggests, acts to dissipate the energy of the wind-generated waves. The opposite occurs on a *reflective beach,* where the waves break close to the shore with little prior loss of energy. The *intermediate beach* includes several morphological types characterised by greater three dimensional morphology involving complex current circulation patterns and bar-trough systems (Wright and Short, 1983 in Komar, 1998).

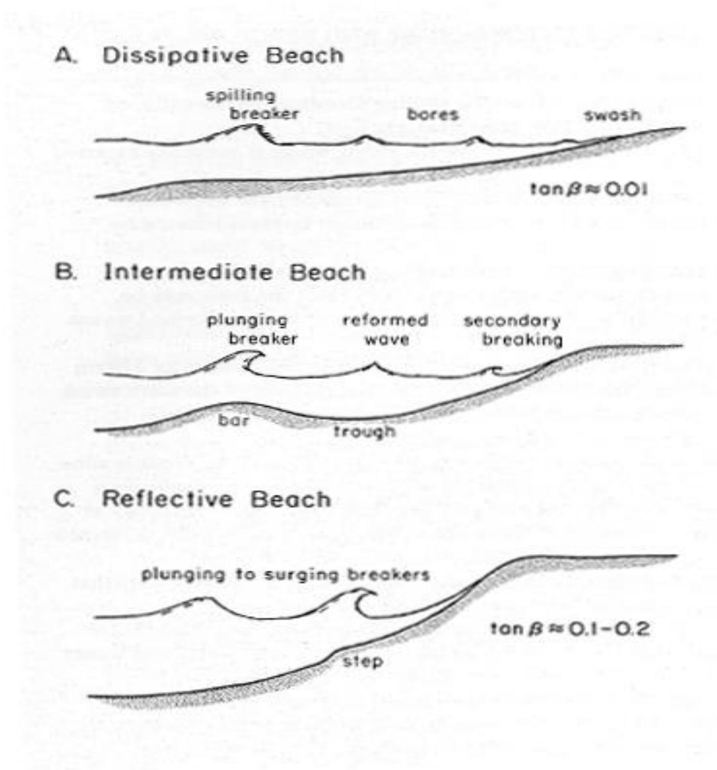

Figure 2.15 A. Dissipative, B. intermediate and C. reflective beach classification developed by Wright and Short (1983) describing beach morphologies and associated patterns of nearshore waves and currents. The classification depends on the angle of beach slope β and the wave conditions (Komar, 1998).

2.7.2 Wave Generation, Refraction and Attenuation

Several types of waves occur in the ocean, some of long periods of minutes and hours, such as astronomical tides, tsunamis, edge waves and coastal-trapped waves. However the most important type of waves in terms of beach erosion and accretion, are those of shorter periods up to 20 seconds, and these are usually wind driven wave waves also know as gravity waves (Komar, 1998).

These waves are created when wind blows over the sea surface imparting energy on the sea surface. The empirical relationships governing Wave height and period are wind velocity, duration and fetch (distance over which wind blows) (Figure 2.16). Typically a full spectrum of waves (wide range of wave height and period) exist in the area of generation. The rate of movement across the sea is dependant on the wave period, as longer period waves travel faster than short period waves. Once waves leave the area of generation they are no longer under the influence of wind and wave groups begin to sort themselves out due to this process known as wave dispersion Figure 2.17 (Komar, 1998).

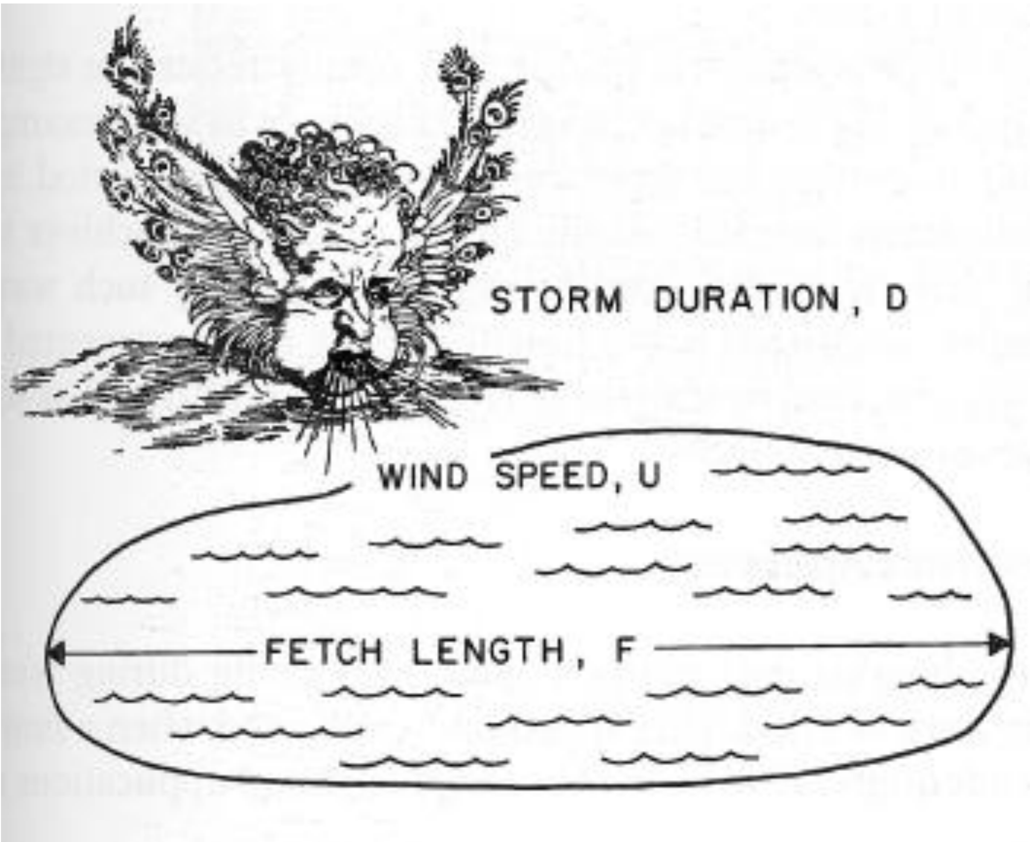

Figure 2.16 Main storm factors involved in wave generation (Komar, 1998)

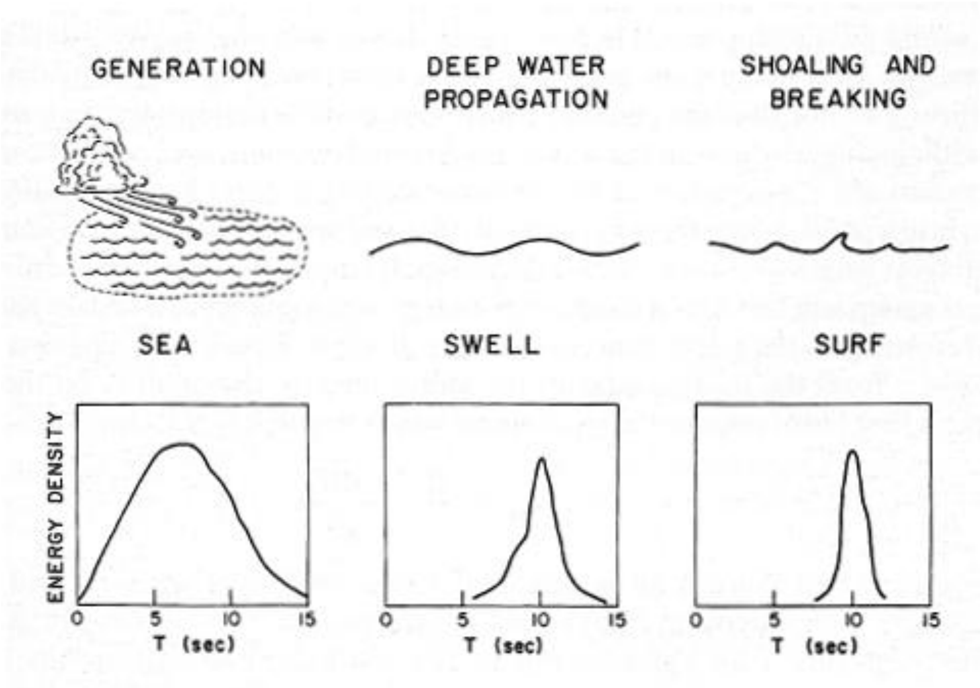

Figure 2.17 The change in wave spectra form the storm area of wave generation where the spectrum is wide, to a spectrum of swell waves narrowed by processes of wave dispersion and dissipation (Komar, 1998).

Deep water waves can travel thousands of kilometres with very little loss of energy, however great changes occur when waves reach shallow water where waves begin to feel the bottom and the processes of refraction, diffraction, shoaling and finally breaking occur. The relationship between wave speed and water depth is responsible for "wave refraction", the process of rotation or bending of waves as they pass over varied bathymetry. The portion of the wave crest in deeper water will travel at a greater velocity; therefore waves arriving at an oblique angle to the coastline will tend to rotate in order to become more nearly parallel to the bathymetry. This refraction can be described by *Snell's Law* from Komar, (1998):

$$\text{Sin}\alpha/C = \text{constant} \qquad \text{Equation 2.1}$$

Where α is the angle between the wave crests and bathymetry contours and C is the wave velocity, equation 2.1 is modified to

$$P = (ECn)\cos\alpha \approx \text{constant} \qquad \text{Equation 2.2}$$

With more complex bathymetry, wave refraction becomes more complex with focussing and defocusing of wave energy (Figure 2.18). For example wave refraction has the effect of concentrating wave energy at headlands, a modern interpretation of the old sailors expression, “the point draws the waves” (Bascom, 1964).

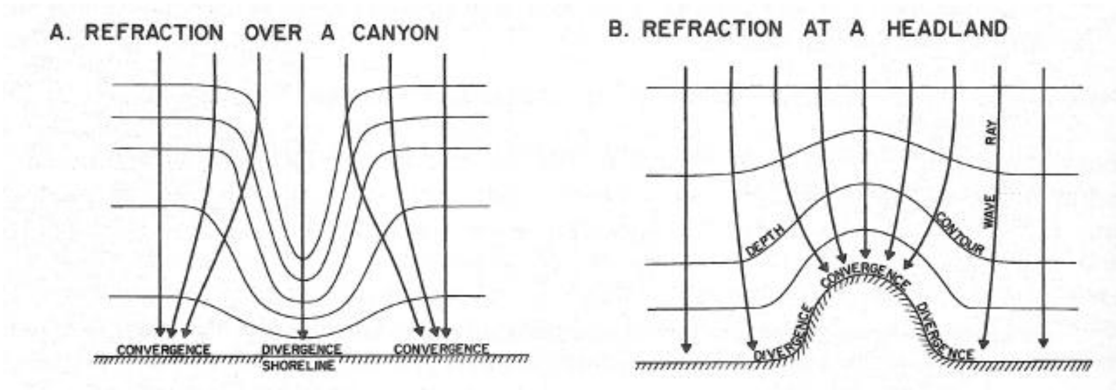

Figure 2.18 Convergence and divergence of wave rays over a submarine canyon and at a headland, due to the process of wave refraction (Komar, 1998).

As waves approach the shore the frictional effect of the bottom also causes energy loss decreasing wavelength and speed, but the wave period remains constant.

$$L=CT \qquad \text{Equation 2.3}$$

Due to the decrease in L and increase in height, H the wave steepness H/L increases progressively as the waves approach the shoreline. This results in the wave crests becoming narrower and peaked, the troughs becoming wide and flat. Eventually the waves over-steepen, become unstable and break, with the nature of wave breaking dependant on the initial steepness and on the slope of the beach (Komar, 1998).

Wave breaking is depth limited and dependant on height and wavelength and breaking occurs at a ratio of wave height to water depth of 0.8 to 2.0. Breaking waves can be classified into three main types according to wave steepness (Hb/L) and a single value of beach slope, β. Dally (1989) defines the Irribarren number as

$$\xi_h = \frac{\beta}{\sqrt{H_b / L}} \qquad \text{Equation 2.4}$$

where β is the beach slope, ξ_b is calculated and subsequently used to classify the breaker type as follows from Battjes (1982 in Komar, 1998) in Table 2.3 below:

Table 2.3 Breaker type classification according to Irribarren number.

Irribarren Number	**Type of Breaker**
$\xi_b > 0.4$	Spilling
$0.4 < \xi_b < 2.4$	Plunging
$\xi_b > 2$	Collapsing

The description of the three breaker types from Komar (1988) is as follows:

If the beach slope is low and/or the incident wave steepness is high, the onset of breaking occurs at a great distance offshore. Breaking is characterised by the presence of foam draping the forward side of the crest, the trough in front is not visibly disturbed: this is classified as a *spilling breaker* and dissipation takes place as the wave crest becomes unstable and flows down the face, producing an irregular, foamy water surface that eventually forms a bore. When the beach slope increases and/or the incident wave steepness decreases, the crest becomes forward leaning as it approaches the shore, its amplitude grows so that the profile is quite asymmetric, the crest ultimately curls forward and forms a jet, plunging into the trough ahead: this type of breaker is therefore classified as a *plunging breaker*. Due to the air tunnel formed as the crest plunges onto the trough, the breaking wave is accompanied by much noise and turbulence. Shortly after the collapse of the tunnel, a travelling bore is formed which dissipates as it travels shoreward. The third breaker type the *collapsing breaker* occurs when the beach slope is large and/or the wave steepness is low. Minimal breaking occurs only at the instantaneous shoreline as the lower part of the face steepens and falls, forming an irregular turbulent water surface that moves up the beach without forming a bore. Dissipation is low and almost all the wave energy is reflected. It is important to note that the transition from one type to another is always gradual so that the numerical values marking the border lines are not precise (Mei, 1983). Figure 2.19 below illustrates the different breaker types from physical modelling analysis.

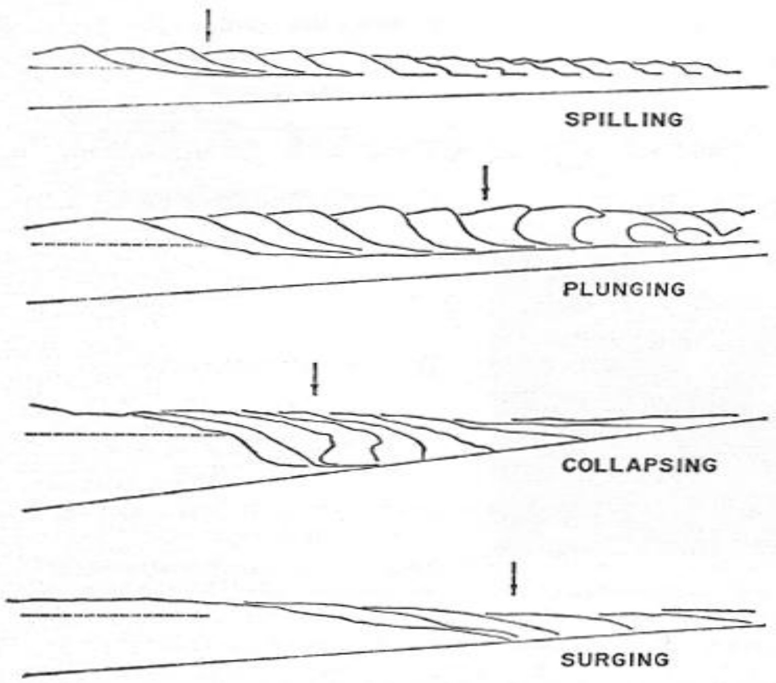

Figure 2.19 waves breaking on a beach, profiles traced form high speed moving pictures obtained in a laboratory channel, arrows point to initial breaking position American Geophysical Union, 1968 in Komar, 1998).

2.7.3 Long shore sediment transport

Waves breaking in the nearshore combine with various horizontal and vertical patterns of nearshore currents to transport beach sediments. On a smaller scale this transport leads to the local rearrangement of sand into bars and troughs, or into a series of rhythmic embayments. On a larger scale these processes lead to extensive longshore displacement of sediment. Waves breaking obliquely to the coast lead to longshore currents and associated longshore sediment transport which occurs primarily within the surf zone, directly parallel to the coast and can vary in direction depending on incident wave angles (USACE, 2006) (Figure 2.20). This current system is fairly simple and has been well described through mathematical analysis and field measurement programs. Therefore coastal scientists and engineers have a good understanding of its generation and a reasonable ability to predict velocities and sediment transport rates (Komar, 1998). The resulting movement of beach sediment along the coast is referred to as *littoral transport* or *longshore sediment transport*, while the actual volumes of sand transported are termed the *littoral drift*. Littoral transport can also occur due to currents generated by alongshore gradients in breaking wave height (Komar, 1998; USACE, 2006).

Several modes of longshore sediment transport exist: *bedload transport*, which can be in the form of sheet flow or *saltation*; *suspended load*, when sediment is carried up within the fluid column and moved by currents; *swash load*, which is moved on the beach face by the swash. It is not entirely clear which of these motions predominates for various wave conditions, sediment types and conditions on the profile or even whether it is important to distinguish the different mechanisms (Dean and Dalrymple, 2002). However it is clear that longshore sediment transport is one of the most important nearshore processes controlling beach morphology, determining to a large degree whether shores erode, accrete or remain stable (USACE, 2006).

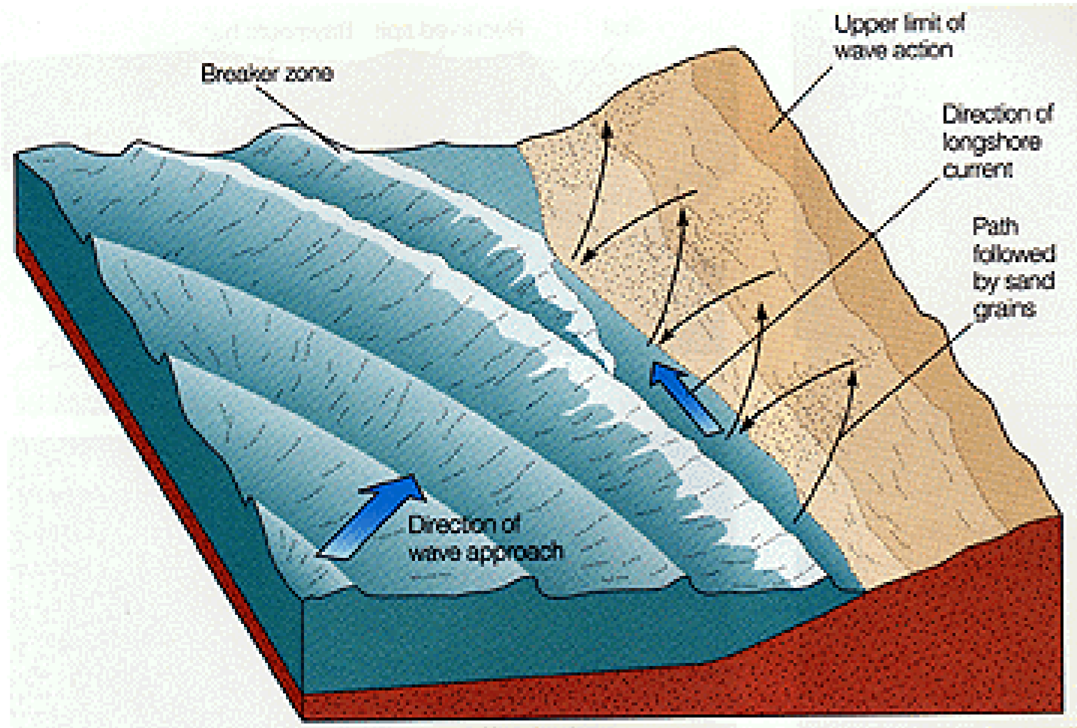

Figure 2.20 Longshore currents and longshore sediment transport occurs when waves break on a beach at an oblique angle, inducing sand transport through longshore current in the surf zone and a zigzagging of sand up and down the beach in the swash zone up until the upper limit of wave action.

2.7.4 Cross Shore Sediment Transport

Cross-shore sediment transport involves offshore and onshore sediment transport occurring in response to storms and low wave activity respectively. These two directions of transport occur in distinct modes with distinctly different temporal scales. Offshore transport is the simpler of the two, tending to occur over short time scales, in the order of hours to days and as a regular process with transport more or less in phase over the entire active profile.

During storm conditions the ratio of wave height to wave length is usually relatively high and the waves are said to be *steep*. Steep waves transport sand in the offshore direction, carrying sand from the shallow water region of the beach and depositing it in deeper water in an offshore bar in the vicinity of the breaker line. Onshore sediment transport within the region delineated by the offshore bar often occurs in 'wave–like' motions referred to as *ridge-and-runnel* systems in which individual packets of sand move toward, merge onto and widen the dry beach. The role of both *bed* and *suspended load* transport complicates the understanding of cross-shore sediment transport. The relative contribution of these two components depends in an unknown way on grain size, local wave energy and other variables (USACE, 2006). Figure 2.21 below summarises the longshore and cross-shore sediment transport components.

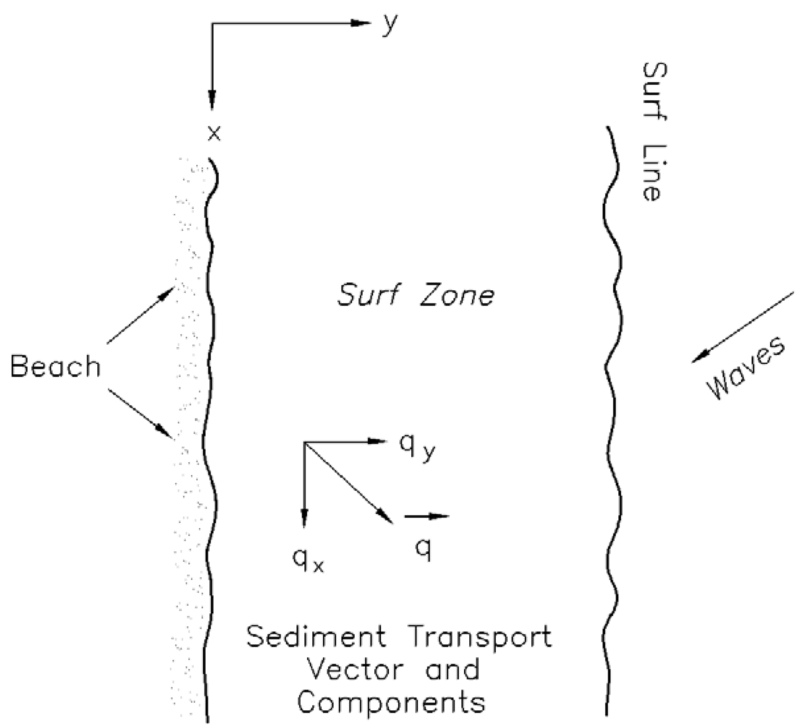

Figure 2.21 Longshore (*qx*) and cross-shore (*qy*) sediment transport components (USACE, 2006).

2.7.5 Rip Currents

Rip currents are strong, narrow, seaward directed flows that begin close to the shore and extend seaward through the surf zone and beyond. These features occur on a wide range of beaches, but are most common on beaches with pronounced bar and trough morphology. Rip currents are often comprised of three interconnected components: (1) longshore feeder currents that convey water into (2) a narrow rip-neck that flows through the surf zone, eventually decelerating and expanding into (3) a rip-head seaward of the breakers. This circulation is driven by longshore pressure gradients and enhanced by morphology, with more intense wave energy dissipation and set-up occurring across barred areas compared to the rip channels. Rip channels are important mechanisms for offshore transport of water, sediments, pollutants and pose great risk to swimmers (Brander, 1999). Rip currents are common along St Francis bay beach as seen in Figure 2.22 below.

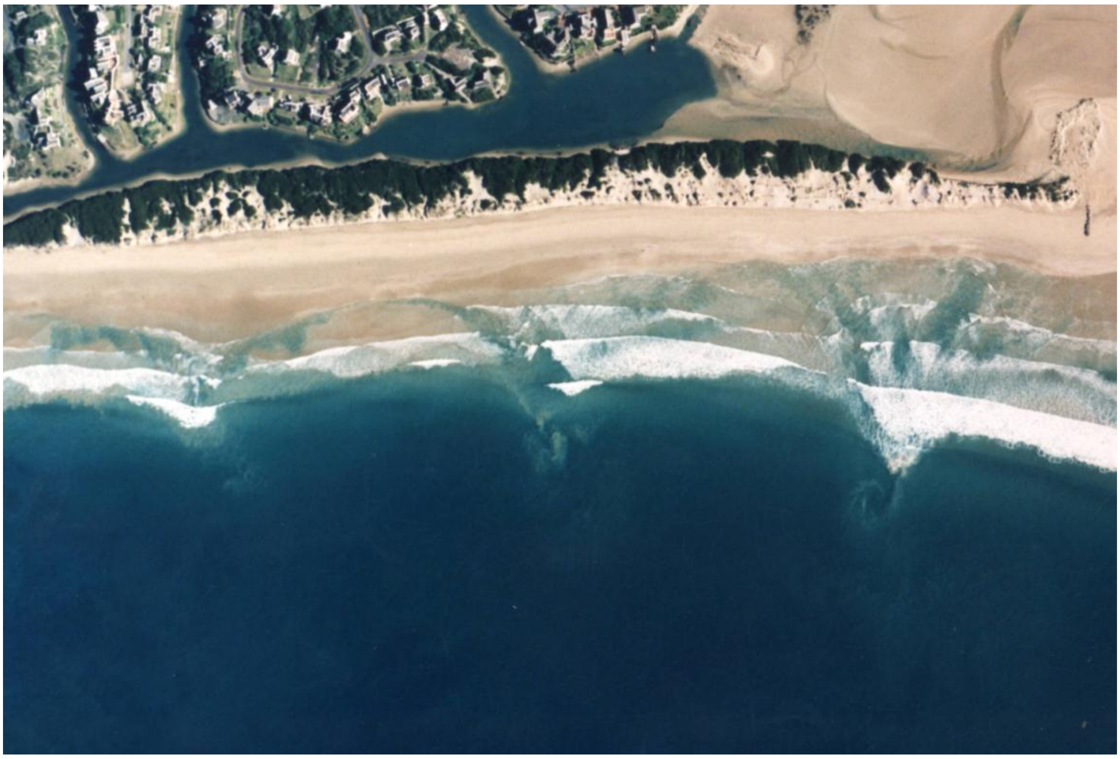

Figure 2.22 Aerial photograph of the northern end of St Francis Bay beach along the artificial sand spit/barrier dune, taken in July 1994. Several rip currents are clearly visible actively transporting suspended sediment offshore.

2.7.6 Infragravity Waves

Low frequency oscillations at the shoreline are often measured by wave staffs and current meters place in the surf zone. However offshore these low-frequency motions are either non-existent or constitute a very small portion of the total wave field. These low-frequency waves are *surf beat, edge waves* and *shear waves,* can be of great significance in beach dynamics (Dean and Dalrymple, 2002).

Waves travelling towards a shore are often modulated into groups leading to the generation of mean water level changes, a phenomenon known as *surf beat*. Groups of large waves lead to lower water levels (set-down) and smaller waves lead to raised water levels. When the wave groups enter the surf zone, the low-frequency forced water level variations are released, reflect from the beach and travel offshore as free waves. This mechanism can be combined with the more likely mechanism that the large waves within the wave groups generate a larger set-up on the beach, which must then decrease when the smaller waves of the group come ashore, resulting in an offshore radiation of low-frequency motion at the frequency associated with the wave group (Dean and Dalrymple, 2002).

Edge waves are motions that only exist near the shoreline and propagate in an alongshore direction. Various explanations for the mechanisms of generation of edge waves have been proposed. Recent findings indicates that edge waves generated by spatially and temporally varying radiation stresses of the incident waves is responsible for most of the low-frequency motion in the surf zone (Dean and Dalrymple, 2002). Edge waves form when reflected energy is trapped inshore by refraction, as the reflected wave propagates into deep water, the refraction process acts in reverse and the reflected wave direction of propagation becomes more oblique to bottom contours. If the reflected wave rays (orthogonals) become parallel to bottom contours before the wave reaches deep water, whey will refract back to the shore, thereby becoming trapped and producing edge waves (Wright, 1995).

Shear waves, were discovered more recently. In 1986 a field experiment at Duck in North Carolina revealed the surprising behaviour of the longshore current. A very large longshore current formed by very large waves began to oscillate with a low frequency. This wave motion occurs in the horizontal plan and moves with a speed slower than the longshore current, causing the longshore current to move back and forth across the surf zone. This phenomenon is presently one of considerable interest in the field of nearshore hydrodynamics (Dean and Dalrymple, 2002).

2.7.7 Coastal Dunes

Coastal dunes occur on much of the world coastlines, exhibiting a great deal of variety in form depending on factors such as: sediment composition, sediment supply, wind strength, wind direction, climatic setting and vegetation. (Bird, 1990 in Labuz, 2005). Coastal dune ridges are structures built by sand blowing along or across the beach. The morphodynamics of coastal dunes are governed by a complex interaction of the above factors. Shore parallel dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation are termed f*oredunes*. Foredunes range from relatively flat terraces to distinctly convex ridges. Actively accreting foredunes are situated on the foremost seaward position in a dune system; however on eroding coasts or coasts where foredunes are unable to form, other dune types may occupy the foremost position. Although a more detailed classification has been developed, typically foredunes can be classified in two main classes, incipient and established, each incorporating a wide degree of morphological and ecological variation (Hesp, 2002).

Foredunes can form on any sandy shore in almost any climate from tropical to arctic. Incipient and established foredunes have been called a variety of other names including embryo dunes, frontal dunes, retention ridges, beach ridges, parallel dune ridges and transverse dunes. *Incipient foredunes* may be seasonal when formed around annual plants or permanent where formed around perennial plant species. Morphological development is primarily dependant on plant density, distribution, height and cover, wind velocity and rates of sand transport. Additional secondary factors include: the rate and occurrence of swash inundation, storm wave erosion, overwash incidence and wind direction (Hesp, 2002).

Established foredunes develop from incipient foredunes and are generally characterized by the growth of intermediate, often woody plant species and greater morphological complexity, height, width, age and geographical position. In certain instances, the species responsible for initiating the incipient foredune, also dominates the established foredune. In such instances the remaining factors distinguish the established dune form the foredune (Hesp, 2002).

Foredunes range from very low scattered dunes of less than one meter in height to large dune complexes with heights in the order of 30-35m. Beach width, sediment supply and wind velocity are three important factors influencing foredune development. The first two factors are directly related to surf zone-beach type, particularly where sediment supply is not a limiting factor. All other factors being equal, larger foredunes occur on dissipative beaches (widest beaches and maximum potential sediment supply) and the smallest dunes occur on reflective beaches (narrowest beaches and minimum potential sediment supply). Vegetation succession trends and species richness on foredunes can also be strongly related to surf zone-beach type and vegetation characteristics influence foredune morphology (Hesp, 2002).

The combination of mode and frequency of beach/dune erosion, rates of aeolian sand transport, and foredune volume and morphology provide an explanation of the nature and morphology of landward-occurring, large-scale dune systems. Dissipative beaches are frequently characterised by large-scale transgressive dune sheets; intermediate, by a trend from large-scale parabolic dune systems (high-wave energy) to small-scale blowouts (low-wave energy); and reflective beaches by minimal dune development (Short, 1982 in Short, 2001).

Foredunes are a critical part of the natural coastal defence of many sandy coastlines, acting as a barrier between the sea and land, supplying sand to the beach when needed and storing sand when it is abundant. During storms, the foredunes and beach are eroded by waves and sand is deposited in longshore bars at the outer limit of the breaker zone. During calm periods waves return the sand to the beach and in the presence of favourable winds this sand is transported back into the foredunes. Here the presence of native sand binding species induces the sand deposition and dune recovery/building (Figure 2.23). In this way sandy foredunes act as a natural seawall which carries out its own nourishment (French, 2001).

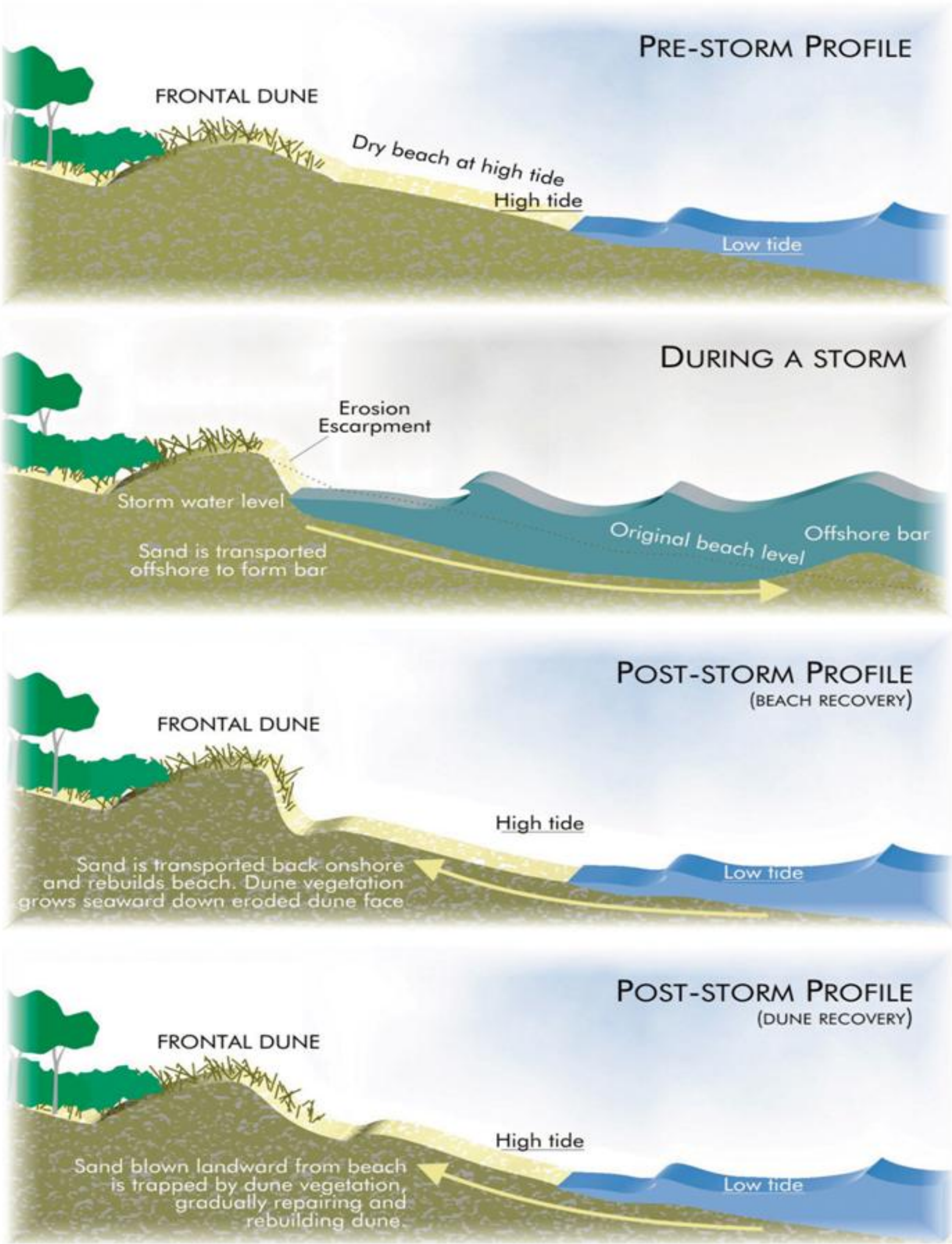

Figure 2.23 The natural cycle of beach and foredune erosion and recovery, during periods of high and low waves respectively (Environment Waikato, 2001in Jenks, 2001).

When the sediment supply is reduced this will lead to the retreat of the beach and under natural circumstances the dunes will retreat. However when development has taken place on dunes all available sand below the said infrastructure is effectively sealed and this natural store of sand is no longer available. This inevitably leads to a sediment deficit, coastal erosion and expensive coastal protection works (French, 2001).

In the case of St Francis Bay the beach erosion has led to the entire loss of the natural functioning dune system, with rock revetments constructed along much of the beach to protect the property and infrastructure behind. In unprotected areas the established dune is being eroded and the overall erosion trend and sediment starved nature of this environment means that no natural dune system is present along St Francis Bay Beach (Klages *et al*., 2002).

Coastal dune rehabilitation is a major preoccupation today on many populated dune-bound coasts, because of the vital role dunes play as a buffer against storms and in balancing beach sediment budgets (discussed above), (Carter, 1988 in Anthony *et al*., 2007). The dune front is a particularly critical zone in these functions because it can occur very rapidly under the influence of winds and especially of storm waves and storm surges (Anthony *et al*., 2007).

A second dune type critical to the region is the *Transgressive dunefield.* These features form in situations of abundant sediment supply and dominant onshore, alongshore oblique or across-shore movement of aeolian sand. These dunefields can vary in size from fairly small to extensive (several km^2) and they may be fully vegetated, partially vegetated or fully vegetated (relict) (Hesp and Martinez, 2008).

In most cases these dunefields move inland and the sand is lost from the beach system (French, 2001). However, if coastal configuration and sediment availability allow the development of sandy beaches up-drift of a headland, under favourable wind conditions sand can be blown inland of these beaches in corridors of dunes, migrating across the headland and intermittently supplying sand to the shores of the downwind side of the headland (Tinley, 1985; McLachlan *et al*., 1994) This type of transgressive dunefield, classified as *headland bypass dunefields* by Tinley (1985), (Figure 2.24) , occur at several locations along the South African coastline notably: Cape Recife, Cape St Francis and Struis Point (Figure 2.25) (McLachlan et al., 1994). These headland bypass dunefields act as an important component of the sediment budget, maintaining sand movement along the coast. In all above mentioned sites headland-bypass systems were artificially vegetated in ignorance of the interdependence of beach and dune systems in coastal sediment transport processes, leading to coastal erosion in down-transport areas (McLachlan *et al*., 1994).

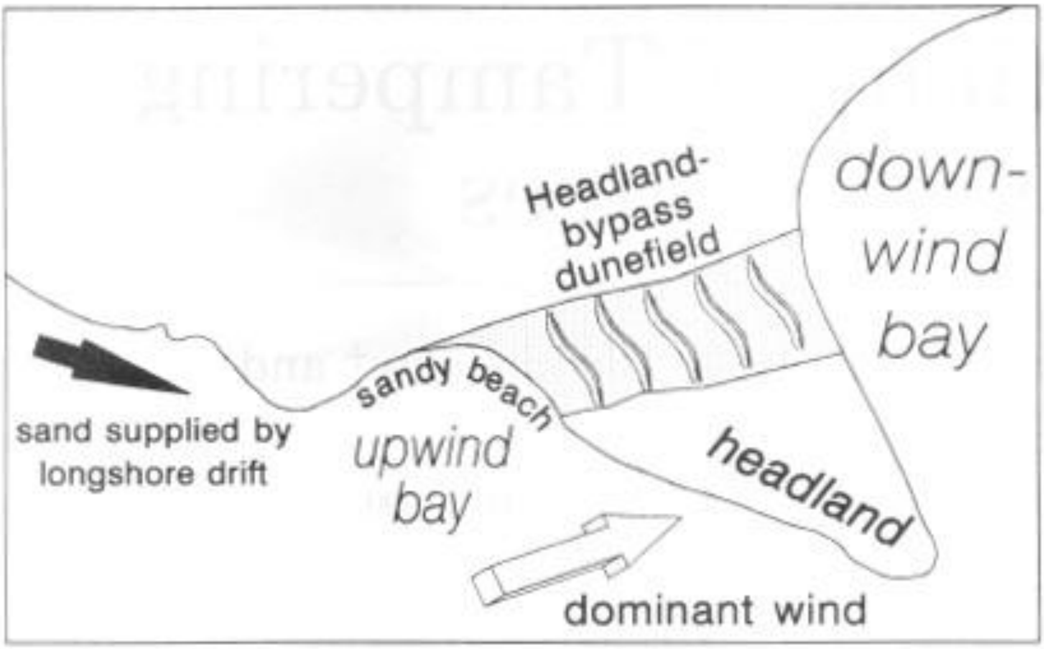

Figure 2.24 Conceptual model of a headland-bypass dunefield, typically 200-2,000 m across (McLachlan *et al*., 1994).

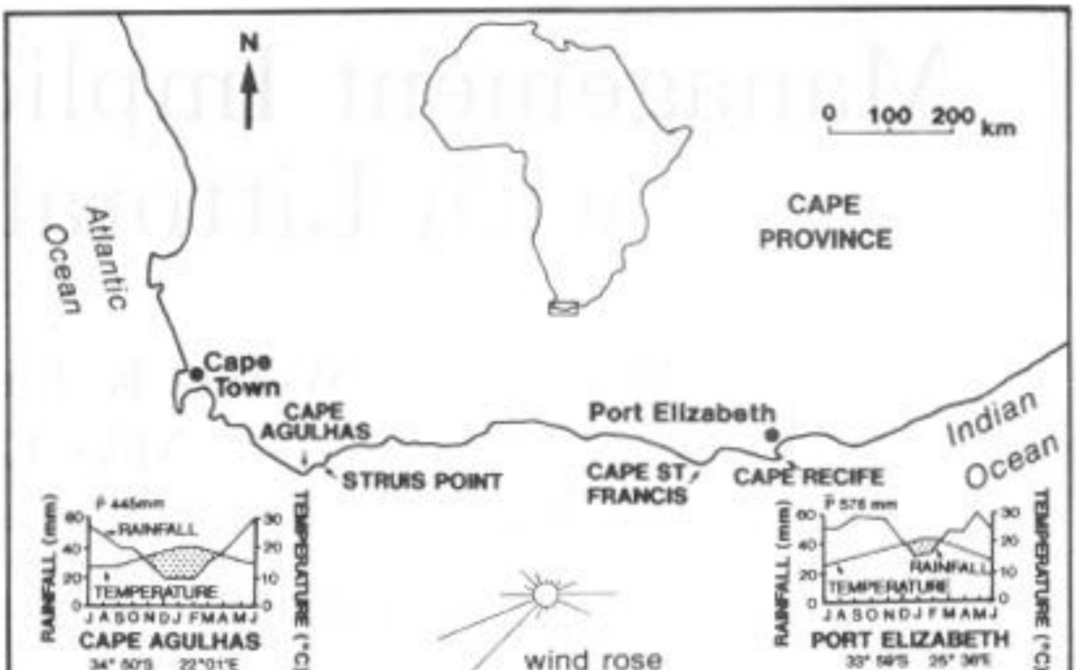

Figure 2.25 The south coast of South Africa locating the dunefields described. Climographs (dry seasons shaded) are for Port Elizabeth and Cape Agulhas. The wind rose is representative of the southeast coast. Rose arms are plotted in the upwind direction (McLachlan *et al*., 1994).

Calculation of current dune movement rates indicates the dunes in larger dunefields (15 to 20 km in length) would take 2 000 years and longer to cross headlands at present aeolian sand transport rates. Historical evidence suggests these dunefields periodically reach the eastern shores of the headland, dispensing large volumes of sediment into the downwind bay. However the presence of long vegetated longitudinal dunes of Holocene and Pleistocene age (2million years), suggests that these dunes have experienced various natural cycles of activation and stabilization during the present interglacial and earlier interglacials (McLachlan *et al*., 1994).

Because of the high-energy wind environment, headland–bypass dune systems tend to be non-accretionary in the long term and provide an important function in maintaining the sediment budget by transporting sand between bays. Where coastal alignment or topography is not suitable for the transport of sediment via headland bypass dune systems, this sand may accumulate in offshore submarine spit bars (Martin and Flemming, 1986) or in an accretionary transgressive dunefield such as the Alexandria coastal dunefield on the northern shore of Algoa Bay, which acts as a sand sink (Illenberger and Rust, 1988).

2.7.8 Beach Morphology Classification

Beach systems can be classified into three types according to Short (2001): wave-dominated, tide-modified and tide-dominated. Wave-dominated beaches are a product of relatively high waves compared to tidal range, which can be defined quantitatively by the relative tide range (RTR):

$RTR = TR/Hb$ Equation 2.5

Where TR is the spring tide range and Hb is the average breaker height. For St Francis Bay TR=1.65m (SAN, 2006), Hb=0.89m (Mead *et al*., 2006). Therefore RTR= 1.85, which falls in the wave dominated range, RTR<3 (Short, 2001).

Furthermore Beach morphology type can be defined using the dimensionless "fall velocity" Ω:

$\Omega = Hb/TWs$ Equation 2.6

Where Hb is significant breaker height, Ws is sediment fall velocity and T is the wave period (Short, 1999). For the St Francis Bay beach Hb= 0.9 m, Ws = 0.026 m/s for a mean sand size of 0.22 mm, and T=10.5 s. Therefore Ω = 3.3; which falls in the Intermediate class, $1<\Omega<6$ according to Short (1999 in Short, 2001).

Intermediate beaches form under moderate (Hb > 0.5m) to high waves, on swell and sea coasts, in fine to medium sand. Intermediate beaches are characterized by the existence of a surf zone, rip cell circulation and rhythmic beach topography. Occurring across a wide range of wave conditions, they consist of four beach states ranging from the lower energy low tide terrace to the high energy longshore bar and trough (Figure 2.26).

Intermediate beaches are controlled by processes related to wave dissipation across the surf zone which transfers energy from incident gravity waves with periods of 2-20 s, to longer infragravity waves with periods >30 s. Incoming long waves associated with wave groupinesss, increase in energy and amplitude across the surf zone and are manifest at the shoreline as wave set up (crest) and set down (trough). They then reflect off the beach leading to an interaction between the incoming and outgoing waves to produce a standing wave across the surf zone.

It is believed that standing edge waves trapped in the surf zone are responsible for the cellular circulation that develops in to rip current circulation, which in turn is responsible for the high degree of spatial and temporal variability in intermediate beach morphodynamics (Short, 2001)

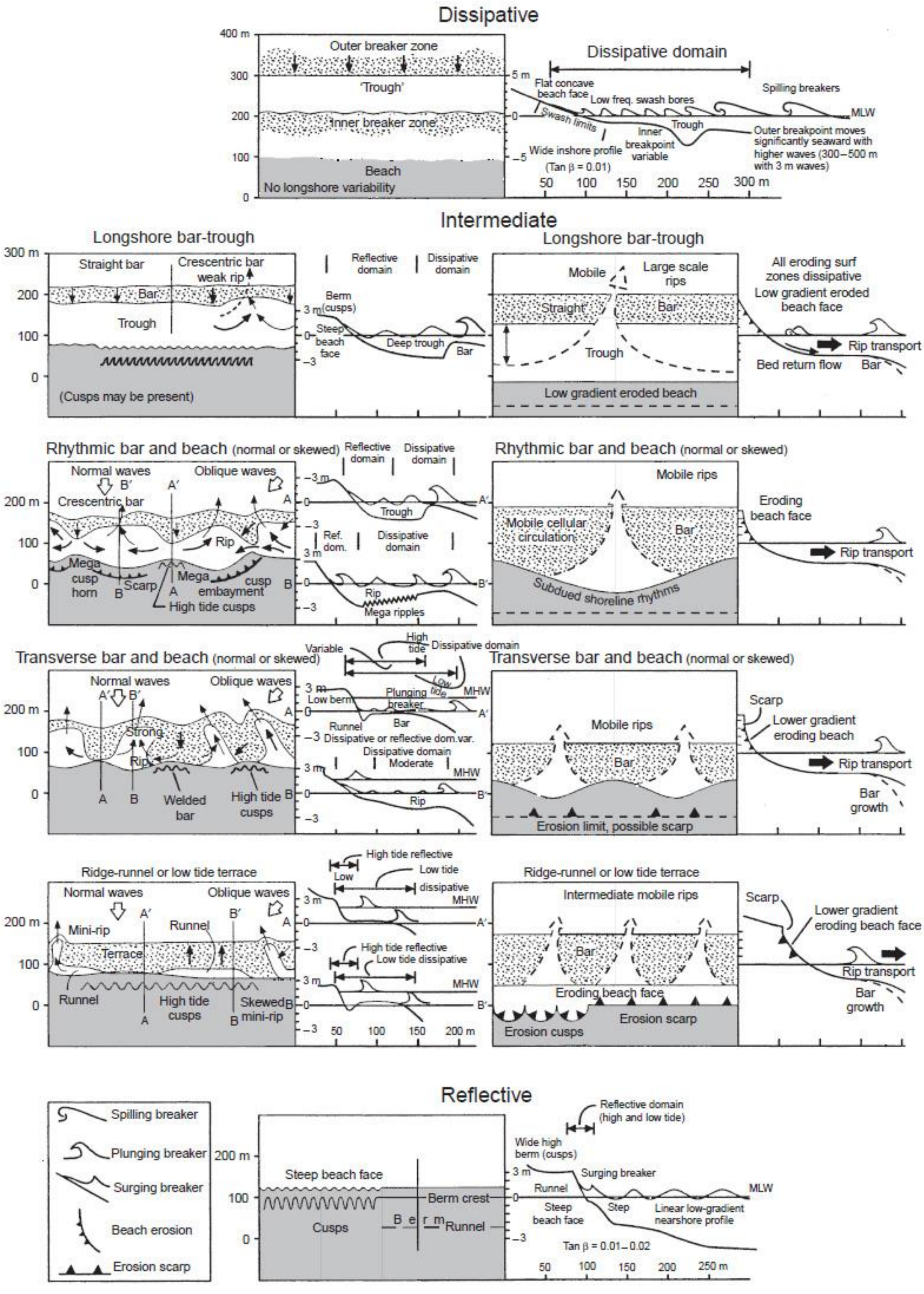

Figure 2.26 Three-dimensional sequence of wave-dominated beach changes for accretionary (left) and erosional (right) wave conditions. The sequence ranges from dissipative (top), through intermediate, to reflective (lower). (Reproduced from Short, 1999 in Short, 2001)

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2.8 Sediment Transport and Budget

2.8.1 Cape St Francis Headland

Cape St Francis is one of several prominent headlands along the South Coast of South Africa. Due to the predominant south westerly deep sea swell direction wave driven longshore sediment transport is generally from west to east along this coast.

Headlands such as Cape St Francis act as a non return for sediment transported along this coast. The oblique angle of orientation of Cape St Francis headland means that most of the sand transported along the coast in this manner is deposited in deep water forming a large "submarine spit bar" extending beyond to the east of the cape from where sand cannot return to the coast (Martin and Flemming, 1986). The existence of a large submerged sand spit east of Cape St Francis (Figure 2.27) indicates that little sand is transported around the headland by wave driven currents. Therefore it is clear that the headland bypass dunefields were critical to the sediment budget of the protected eastern shores of Cape St Francis (McLachlan *et al.*, 1994).

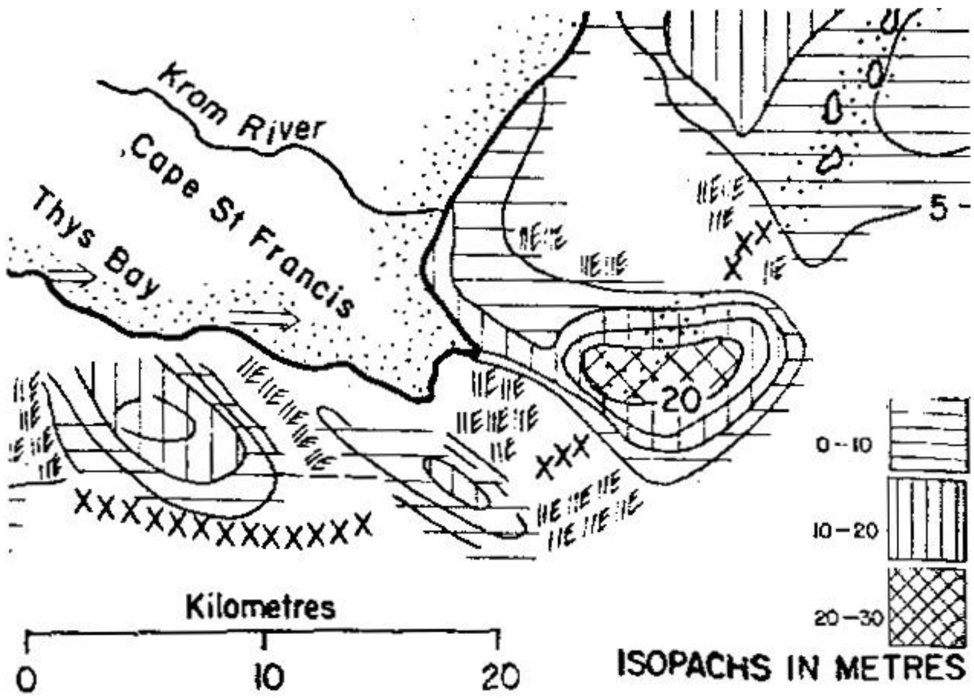


Figure 2.27 Sediment thickness around Cape St Francis, the sand transported from west to east past Cape St Francis is deposited in deep water to the east in a submarine spit bar (Martin and Flemming, 1984).

Several dunefields were active at the time of the first developments in St Francis Bay in the 1960's (
Figure 2.28), The two major corridors of active transverse dunes were fed by sandy beaches at Oyster Bay and Thys Bay, transgressing the headland within a suite of vegetated longitudinal ridges, indicative of past dunefield activity. The active dunes formed a thin veneer of sediment over the headland, with average dune heights of 10m and dune spacing in the order of 200-250m. A high water table leads to the formation of substantial pans in the interdune areas during rainy months. This water is drained from the eastern section of the dunefield by the Sand River, a small tributary of the Kromme River. Late Stone Age middens and Early and Middle Stone Age implements have been found on fossil dunes in both dune systems McLachlan *et al*., 1994).

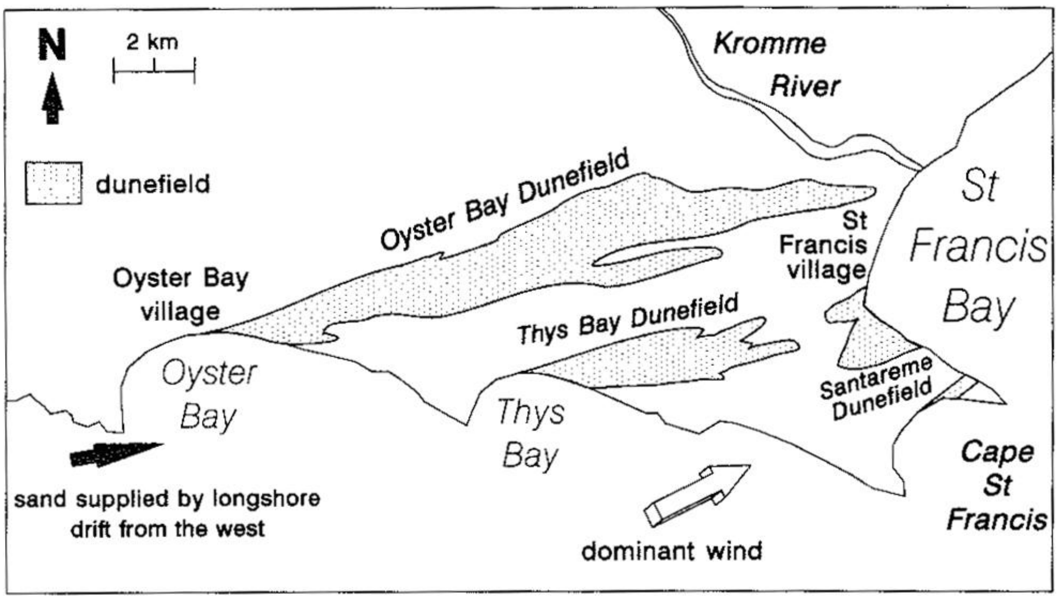


Figure 2.28 Cape St Francis Headland in 1942 with several headland-bypass dunefields present. The Santareme dunefield, the eastern tip of the Oyster Bay dunefield and the dunefield feeder zones (i.e., the dunefield portions immediately adjacent to Oyster Bay and Thys Bay) have subsequently been artificially vegetated (McLachlan *et al*., 1994).

Both dune systems have been cut off from their respective sand sources. Development of the village of Oyster Bay precludes any further input from the sandy beach into the Oyster Bay dunefield. The leading nose of this dunefield had not reached the St Francis Bay shore in 1942, and was approaching the shore of St Francis Bay by 1961. The Santareme dunefield, the leading edge of the Thys Bay headland bypass dune system, was discharging sand into St Francis Bay over a coastal length of 2.4 km in 1942. The distribution of the active dunefields suggest that sand has been moving across the headland in pulses. Prior to development and stabilization of the Santareme dunefield, the average dune migration rate was calculated at 18 $m.yr^{-1}$ with average sand transport rate of 38 $m^3.m^{-1}.yr^{-1}$ resulting in conservative estimates that this system was actively discharging +/- 90 000 m^3 of sand per year into the southern corner of St Francis Bay (McLachlan *et al*., 1994).

The angle of wave incidence along this stretch of coast between Cape St Francis and the St Francis Bay beach results in strong longshore currents (CSIR, 1992), which would have transported this large supply of sediment towards the southern end of St Francis Bay beach. From here varying longshore currents and cross shore sediment transport processes would have spread this sediment along the beach (CSIR, 1992). This large supply of sand resulted in a wide sandy beach with an average beach width of +/- 90m at the time of initial development in the area in the 1960's.

The foredunes behind the beach, the downwind nose of the Oyster Bay dune system and the northern flank of the Santareme dunefield have been stabilized since 1964 due to the development of now prestigious holiday township of St Francis Bay. In the 1970's despite signs of beach erosion and warnings from prominent ecologists (Lubke, 1985), the larger southern flank of the Santareme dunefield was stabilized, initially using plant cuttings, followed by extensive housing development which resulted in the irreversible stabilization of the Santareme dunefields by 1987 (Figure 2.29)(CSIR, 1992).

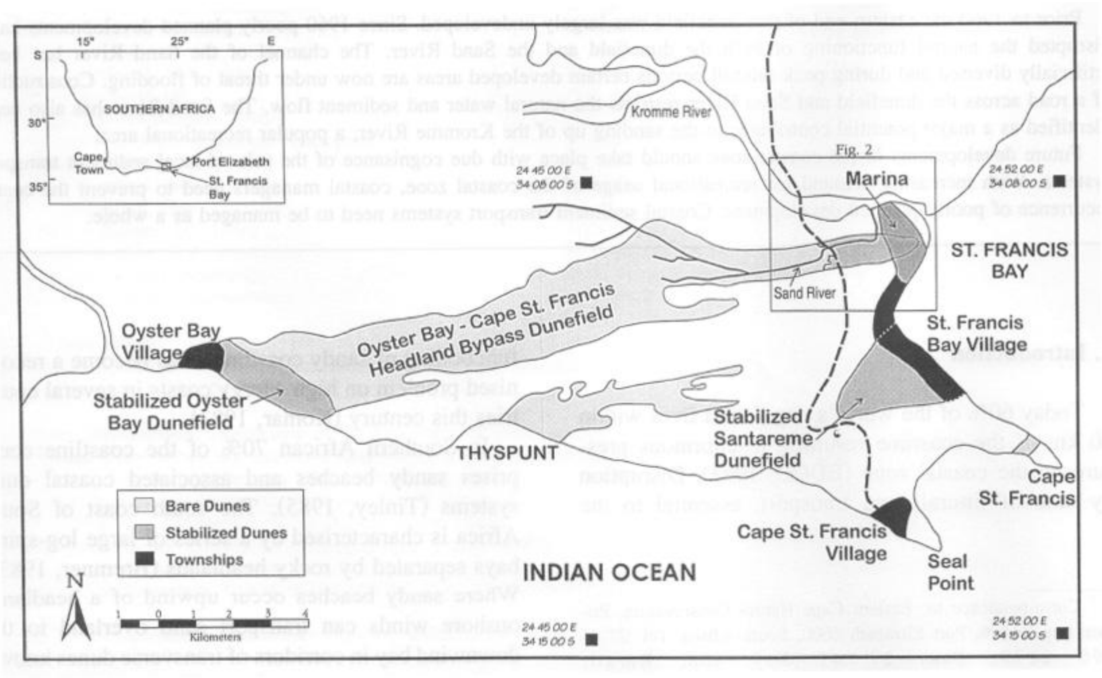


Figure 2.29 Development and stabilisation of the Cape St Francis headland bypass dunefield. (La Cock and Burkinshaw., 1996).

Although a small (200m wide and 700-800m long) dune corridor is still active and calculated to be supplying +/- 10 000 m^3 sand to St Francis Bay from Cape St Francis Beach this is only 10 % of what was previously supplied to St Francis Bay from the Santareme dunefields via Aeolian (wind driven) transport (McLachlan *et al*., 1994). Dredge operations remove roughly 20 000 m^3 of sediment from the mouth of the port per year (Port St Francis Port Captain, pers. comm., 2006) Therefore the sediment supply around the point via wave driven currents must be in the order of 10 000m^3 per year, although WPR (1993) propose that this supply may be cyclical. In summary, roughly +/- 20 000 m^3 per year is currently supplied to the bay as opposed to +/- 110 000 m^3 prior to stabilization (McLachlan *et al*., 1994; La Cock and Burkinshaw., 1996), Figure 2.30 below gives details of the sediment budget around Cape St Francis.

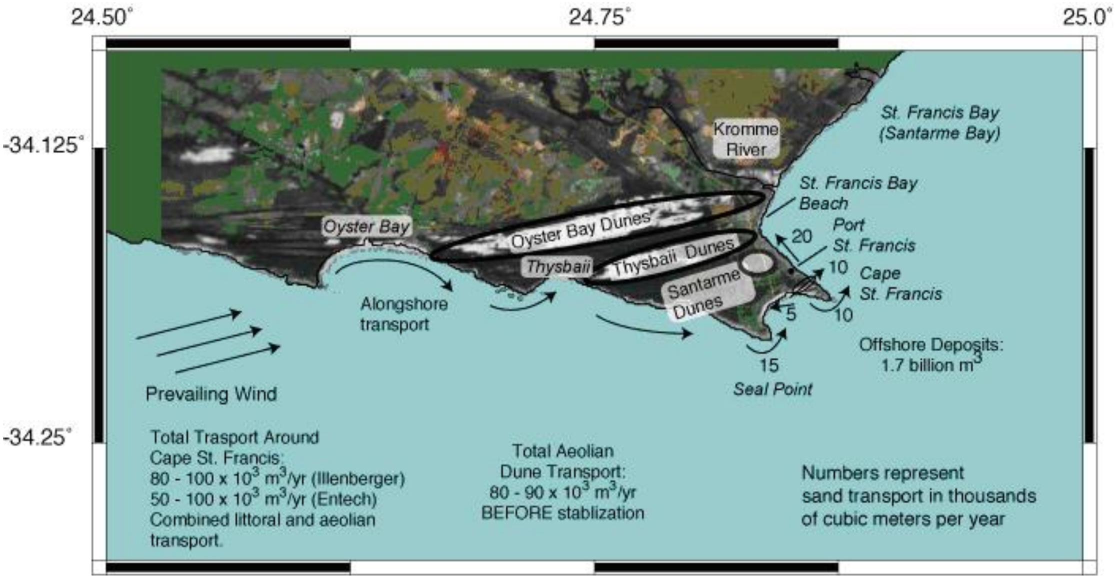


Figure 2.30 Summary of sediment transport routes and dynamics before and after dune stabilisation (Illenberger and Burkinshaw, 1997).

2.8.2 Kromme Estuary

The fluvial sediment yield of the Kromme is small and consists mainly of mud weathered from Bokkeveld slates. The sand input is also small because its quartzitic source resists weathering and erosion. Furthermore the Churchill and Mpofu dams stop most of the fluvial sediment input into the estuary, although some mud and to a lesser extent sand still enters from the Geelhoutboom River. The Sand River drains the eastern portion of the Oyster Bay dunefield, flowing episodically during flood events; it transports a minor amount of sand into the Kromme estuary at the confluence 2km from the mouth (Figure 2.31).

The Kromme Estuary exhibits a flood tide dominant flow regime, similar to most estuaries in the South Eastern Cape (Reddering and Esterhuysen, 1987), extensive accumulation of marine sediment occurs within the lower reaches, up until 4.5km from the mouth (Reddering and Esterhuysen, 1983; Bickerton and Pierce, 1988; CSIR, 1992; Entech, 2002a, Entech, 2002b, Entech, 2002c). During periods of flooding the sand river transports sand from the eastern extent of the Oyster Bay dunefield and is estimated to deposit 5 000 - 10 000 m^3 of sand into the Kromme Estuary at its confluence on the southern bank 2km from the mouth (Entech, 2002c), from here this sand is transported up and down the estuary by flood and ebb currents respectively. The two large storage dams now trap all terrestrial sediment from the Kromme river catchment area, greatly reducing the input of terrestrial sediment into the Kromme estuary. A small volume of finer sand of terrestrial origin in the silt and clay class still enters the estuary from the Geelhoutboom River. This fluvial sediment is finer gained than the marine sediment entering at the inlet. Under conditions of low tidal current velocity in the upper estuary, the clastic mud settles from suspension, probably aided by saltwater induced flocculation (Reddering and Esterhuysen, 1983).

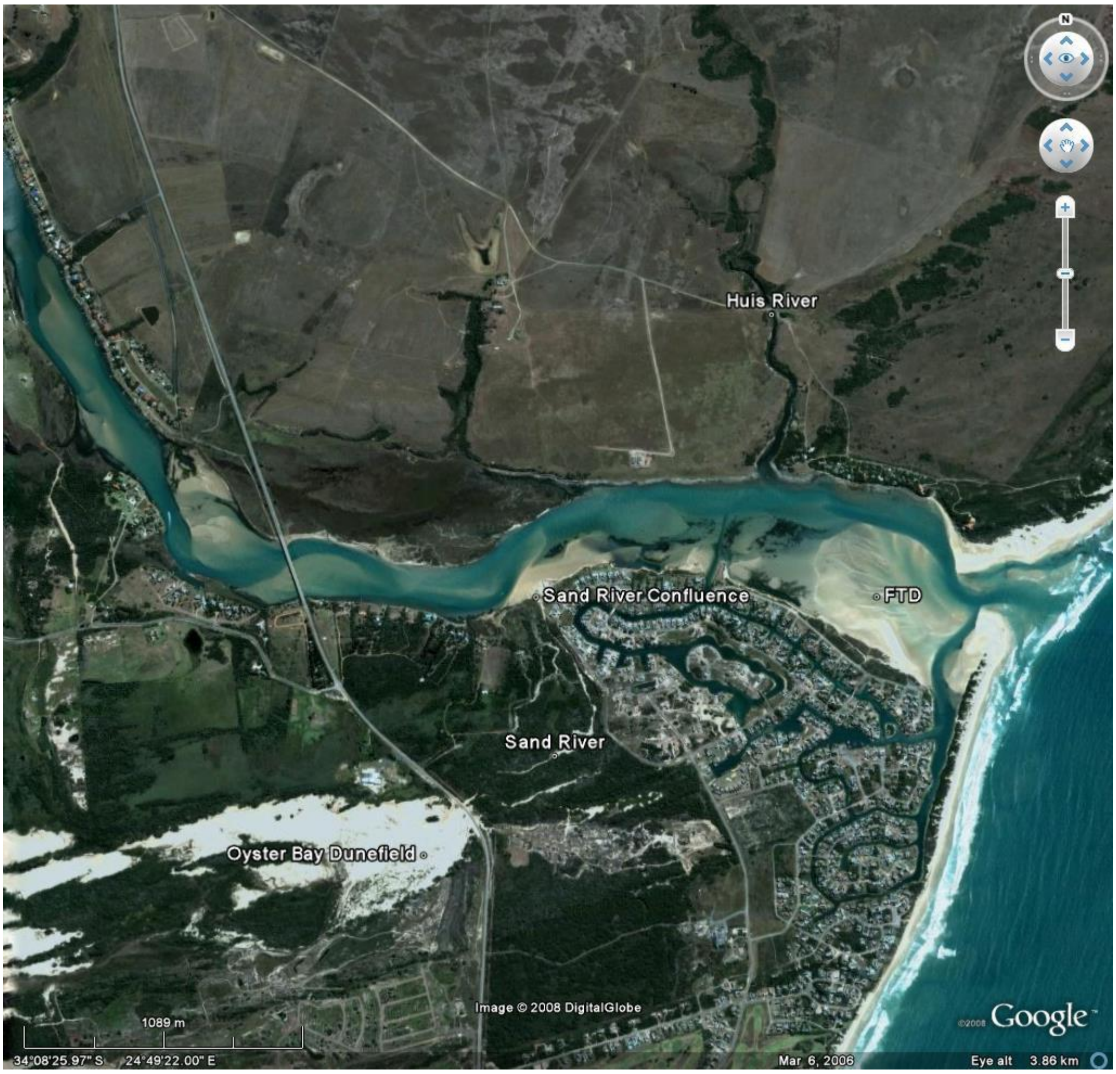


Figure 2.31 Extensive accumulation of sediment is evident in the lower reaches of the Kromme Estuary, marine sand enters through the mouth under strong flood tidal currents where a majority is deposited in the large Flood Tidal Delta (FTD), during floods the sand river deposits sand into the Kromme Estuary 2 km from the mouth on the southern bank from here it is spread up and down the estuary by ebb and flood tidal currents.

Analysis of sediment distribution in the Kromme shows a gradation in substrate particle size from medium sand in the lowest 4.5 km to more angular fluvial sand particles, with smaller grain sizes and higher organic content upstream of 5km from the mouth (Figure 2.32). This sediment distribution demonstrates the flood tide dominated character of the Kromme Estuary, resulting form the normal up-estuary decrease in tidal current velocity and from sediment availability. This is characterised by flood tidal deltas deposited in the lower estuary by flood-tidal currents. These features are characteristic of wave-dominated micro-tidal coasts (Reddering and Esterhuysen, 1983).

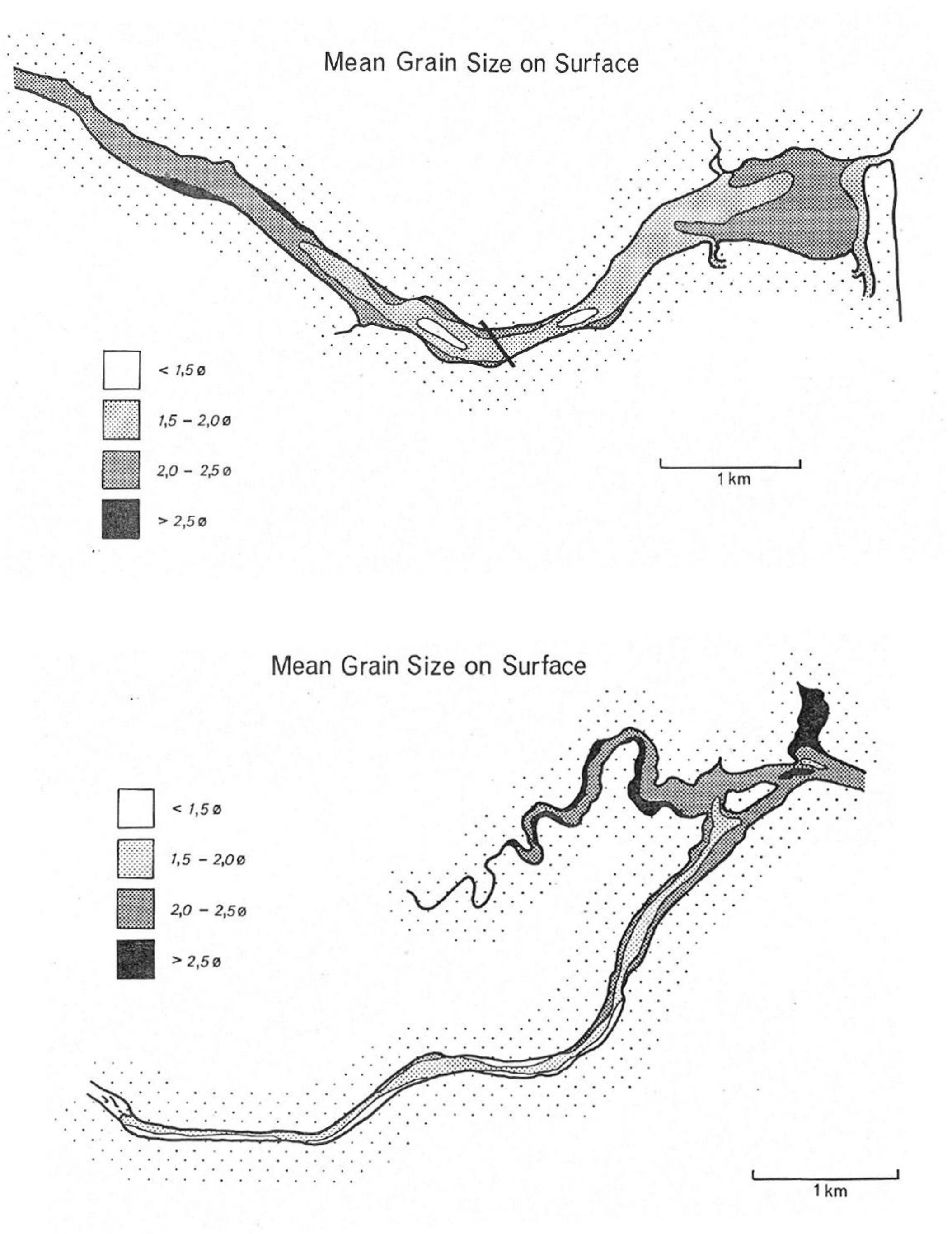


Figure 2.32 Lower (above) and upper (below) Kromme Estuary surface sediment grain size distribution from Reddering and Esterhuysen (1983).

Prior to river impoundment large floods would have scoured significant volumes of sediment from the lower reaches of the estuary, supplying sand to the beaches and forming a large submarine delta offshore, a process common to many estuaries in the area (Reddering and Esterhuysen, 1987). This delta would have acted as a barrier to longshore transport like a submerged "groyne" and possibly maintained sediment on the beach at St Francis Bay. However river impoundment has also effectively completely eliminated the ability of large floods to scour sediment accumulated in the lower estuary (Reddering and Esterhuysen, 1983; Bickerton and Pierce, 1988; CSIR, 1992).

The CSIR (1992) conducted 1-D hydrodynamic modelling to simulate flows during 2, 5, 10, 20 and 50 year return period flood events. For each flood event hydrographic simulations were carried out for the presence and absence of dams and sediment transport was calculated. The volume scoured by a design 50 year return period flood (maximum flow rate of 2 100 m^3m^{-1}) with no dams was calculated to be +/- 150 000 m^3. Therefore if all other influences remain constant, such as tides and waves, the average increase in bed elevation due to elimination of the 1:50 year flood by the dams is in the order of 100 mm in 50 years or 2 mm per year. Although higher frequency floods and other influences are excluded, this provides a crude idea of the order of magnitude of the rate of sedimentation resulting from the dams. Bickerton and Pierce (1988) estimate that 73% of the sand at the mouth is moved away to the north by longshore transport, leaving 27% available for transport into the estuary. The entry of sand into the estuary is considered to be quite non-linear and dependent on combinations of favourable wave and tide conditions and sand bank configurations within the mouth of the Kromme Estuary. Nevertheless with an estimated longshore sediment transport of 50 000 – 100 000 $m^3.yr^{-1}$ marine sediment supply is predicted to be in the order of 13 000 -27 000 $m^3.yr^{-1}$ (Entech, 2002c). Therefore it is estimated that the total net sediment influx into the lower Kromme Estuary from the Oyster Bay dunefields via the Sand River and from the sea via the Kromme Estuary mouth is in the order of 20 000 – 40 000 $m^3.yr^{-1}$

2.9 Beach Erosion at St Francis Bay

2.9.1 History, Data and Evidence

In the early 1960's a small fishing village was built at St Francis Bay, providing facilities for holidaymakers. During the 1960's the holiday village began to grow and in 1969 dredging began on the southern banks inside the mouth of the Kromme Estuary for early construction of the canal system. At this time the Santareme dunefield was actively discharging +/- 90 000 m^3 of sand per year along a 2.4 km stretch of Cape St Francis Headland into St Francis Bay (as previously discussed). As the area grew in popularity so development continued. Firstly the foredunes at the back of the beach, the leading nose of the Oyster Bay dunefield and the northern flank of the Santareme dunefield were stabilised due to the development of the St Francis Bay holiday township. Despite signs of beach erosion and warnings from prominent ecologists, development continued. First the larger southern flank of the Santareme dunefield was stabilised by the early 1970's, initially this section of dunes was vegetated using plant cuttings and finally irreversibly stabilised by the Santareme housing development (McLachlan *et al.*, et al., 1994; La Cock and Burkinshaw., 1996).

The plight of St Francis Bay beach became most evident when acute beach erosion of St Francis Bay beach was experienced due to a significant southerly storm wave event in September 1978 (Shillington and Britten-Jones, 1979), but after this event some evidence of accretion was observed. However this was to be short lived and Lubke (1985) measured a retreat of 9m between 1975 and 1982. Subsequent analysis of aerial photographs (WPR 1993; Illenberger and Burkinshaw, 1997) concluded that the retreat of the shoreline coincided with the reduction in supply from the Santareme dunefield, thus suggesting that the dune stabilisation is the primary cause of beach erosion.

WPR, (1993) conducted extensive analysis of aerial photographs from 1942 to 1987, for each set of photographs the position of the growth edge line (position of the most seaward extent of dune vegetation cover) and beach crest line/high water line (the point of maximum wave run-up) was extracted.

Further analysis of the beach cross section opposite erf 72 on Ralph road (Figure 2.33) was examined and the change in beach width defined by the two above mentioned lines was plotted as a function of time (see Figure 2.34 below). This Figure also shows significant narrowing of the reserve storage between the beach crest line and growth edge line from 1980 to 1987 as compared to the period prior to 1975. Other significant events also included in this diagram are:

- The extreme southerly wave event responsible for significant beach erosion in September 1978 (Shillington and Britton-Jones, 1979)
- The rate of vegetation cover on the Santareme dunefield.
- The Construction of the Mpofu dam (previously called the C.W. Malan dam).
- A marked shift in wind direction in 1982/83 (Schumann, 1992).
- The last significant river flood to affect the lower reaches of the Kromme Estuary during August 1979.

The position of the growth line and beach crest line from 1942 to 1989 including the erf boundaries of the beach front properties were plotted in Figure. The rate of dune stabilisation is shown in Figure 2.35. In addition Figure 2.36 included further data after the aerial photographic analysis period, showing a retreat of both the growth line and beach crest line from +/- 1990.

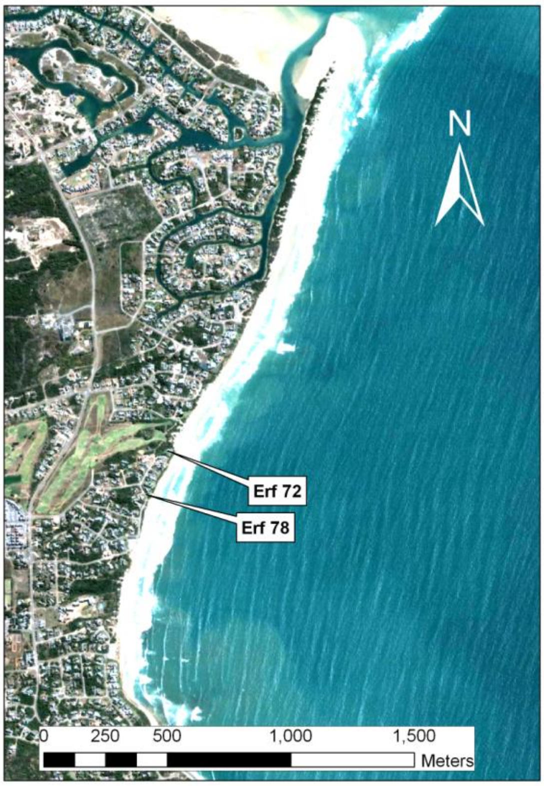


Figure 2.33 Google image from 2008 showing location of Erf 72 and Erf 78 used by WPR (1993) for detailed analysis of erosion from 1942 to 1987.

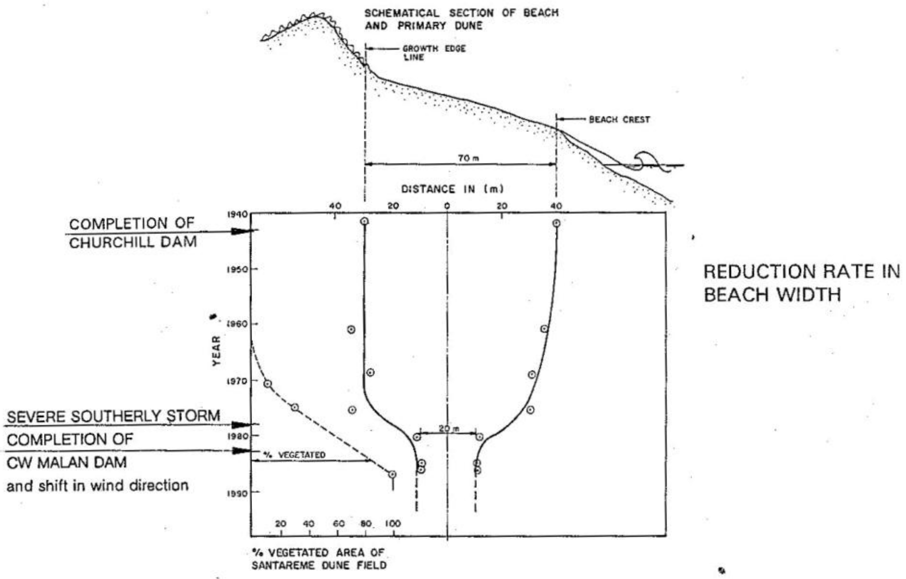


Figure 2.34 Rate of reduction in width between beach crest and growth line opposite erf 72 to 78, also included: construction of Churchill Dam (1943), severe southerly storm (1978), construction of Mpofu Dam (CW Malan) (1983), shift in wind direction (1982), % vegetated area of Santareme dunefield over time (WPR, 1993).

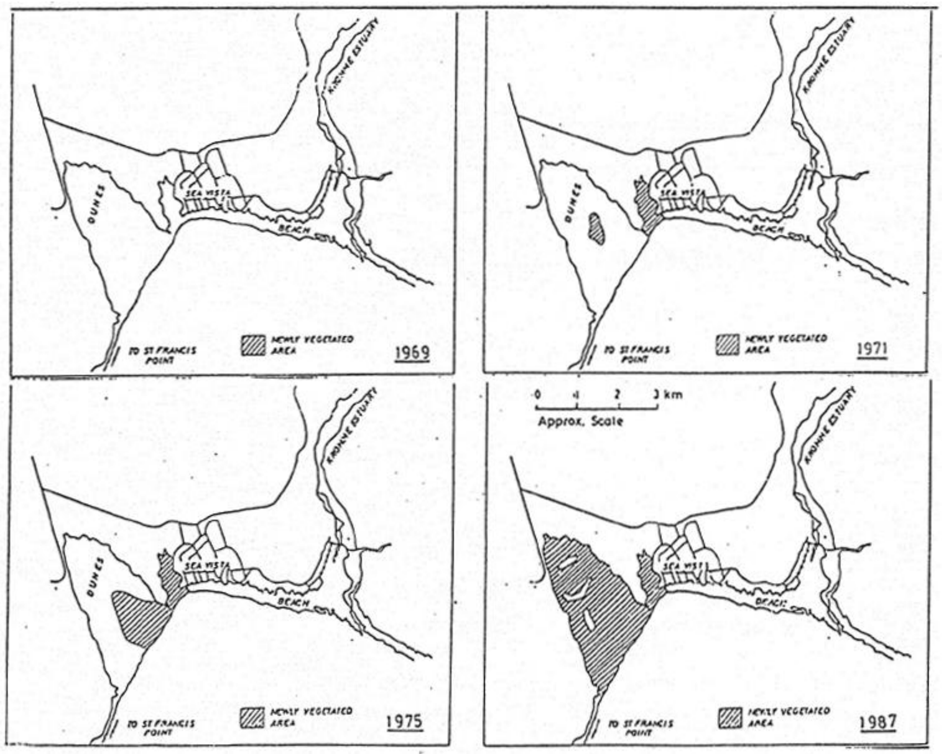


Figure 2.35 Rate of vegetation of the Santareme dunefield from 1967 to 1987 (WPR, 1993).

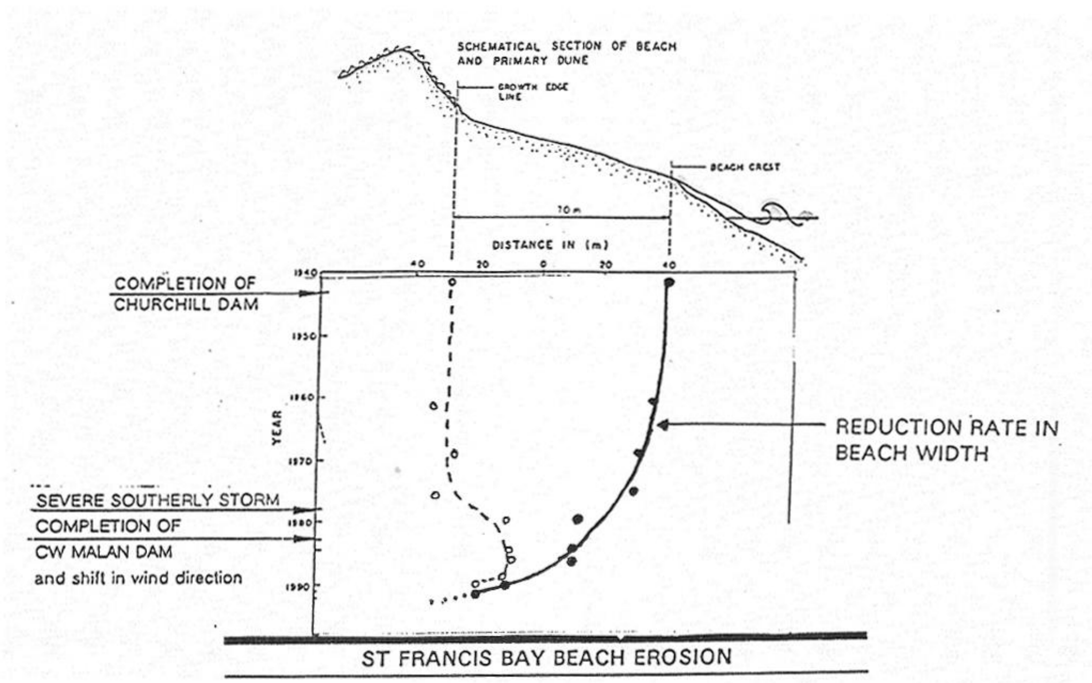


Figure 2.36 Reduction in beach width between beach crest and growth line opposite erf 72 to 78 the last two data points represent the erf boundaries of the beach front properties for 1990 and 1992 (WPR, 1993).

According to the analysis of aerial photographs by WPR (1993) recession and advance of the beach line had generally occurred over the full length of the beach. Over the central part of the beach the beach crest line retreated landward and the growth line moved seaward. A marked decrease in beach width was found from 1975 onwards. In the southern section of the beach both the beach crest line and growth line moved landward corresponding to the area significant damage to the dunes at the back o the beach were observed in 1989. Although outside of the aerial photographic analysis period, it was noted that during storms of September/October 1992 more damage was evident in the central region of the beach. This was interpreted as a slight shift in alignment of the beach under different storm wave directions (WPR, 1993).

Illenberger and Burkinshaw (1997) challenged previous aerial photographic analysis methods as discussed above, proposing that the beach crest line/high water mark was not a reliable indicator of shoreline erosion and that the "storm line" the highest part of the beach that is affected by storm waves, is a more reliable indicator of shoreline position. Using this storm line as a marker, aerial photographic analysis revealed that erosion of the dune ridge started after 1975, and by 1993 the southern portion of the ridge (Nevil Rd – Anne Ave – Ralph Rd) had been eroded by 40-60 m (Figure 2.37). This represents an average rate of 2 -

3 m/yr. Along the central and northern portion of the ridge (Poivre Crescent–Praslin Reach–Shore Rd) little or no erosion was evident. Additionally their results suggest widening of the beach from 1942 to 1969, thereafter progressive narrowing was observed.

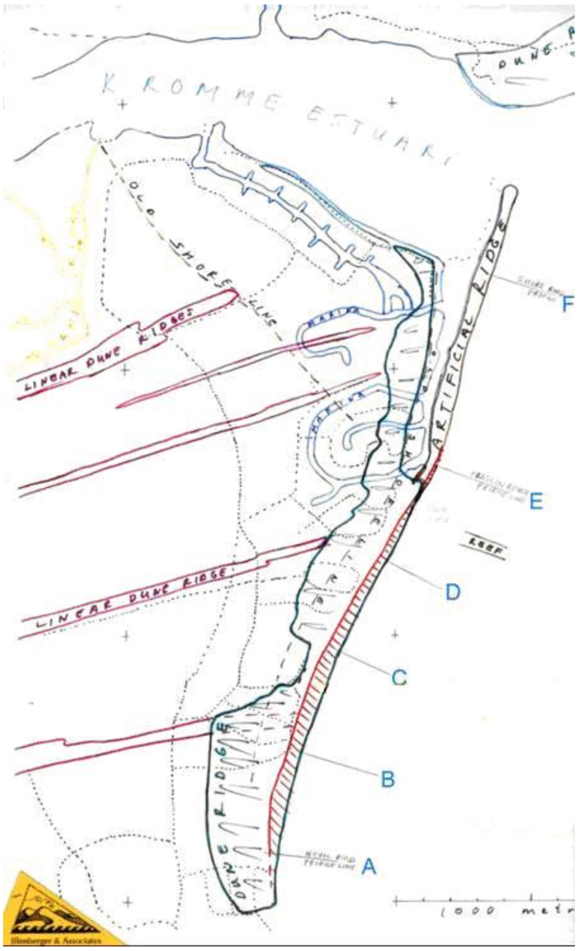


Figure 2.37 Results of aerial photograph analysis by Illenberger and Burkinshaw (1997) showing greatest erosion (hatched red) on the southern half of St Francis Bay beach.

Other findings were that prior to development the dune ridge was only semi-vegetated. Parabolic dunes extended up to 250 m from the beach across the ridge, in a similar way to the dunes that still exist on the dune ridge to the north of the Kromme River mouth. The ridge is now mostly vegetated, probably partly due to artificial planting, and partly due to natural spreading of the Australian acacia, rooikrans (Illenberger and Burkinshaw, 1997).

The placing of rock revetments began in 1993 after a significant erosion event in 1992 and has continued to take place ever since. Where properly maintained these revetments have proved effective in protecting the land and property immediately behind. However revetments offer no protection to the beach and have been shown to increase erosion of the beach by increasing turbulence and reflection of waves (Silvester and Hsu, 1999; Dean and Dalrymple, 2002).

Beach profiling was initiated in 1991 by the Municipality and carried out by the University of Port Elizabeth (UPE): at first 3 transects were measured every four months, in 1995 another 3 transects were added (Figure 2.38). Fixed markers were placed several metres above MSL at each site and surveys were conducted at Spring Low Tide, using a theodolite and staff. Measurements were recorded until generally 0.5 m below MSL, depending on wave conditions.

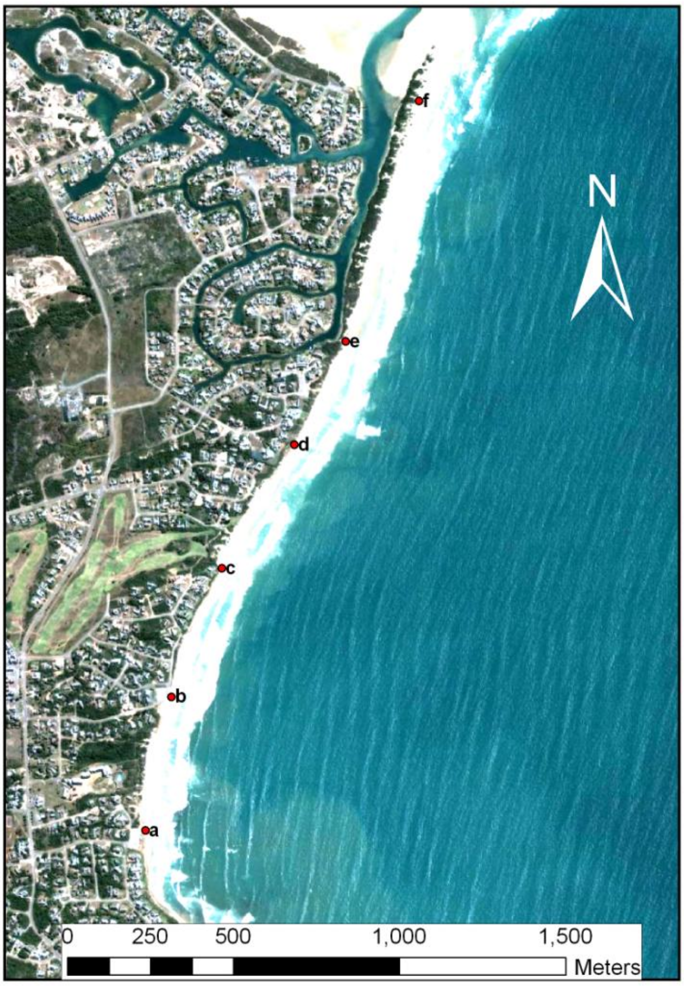


Figure 2.38 Beach profile locations a-f along St Francis Bay Beach: a) Nevil road; b) Anne Avenue; c) Ralph Road; d) Poivre Crescent; e) Praslin Reach and f) Shore Road.

Beach profiling was carried out in such a manner until 2006, with some gaps in data. Analysis of beach profile data shows a large degree of seasonal variation and an underlying long term chronic erosion rate of +/- 0.5 m/yr (**Error! Reference source not found.**), considering that the monitoring was only initiated fairly late, these results correspond well to aerial photographic analysis results and indicate a slight reduction in rate of retreat over the beach profiling period when compared to the aerial photographic analysis period.

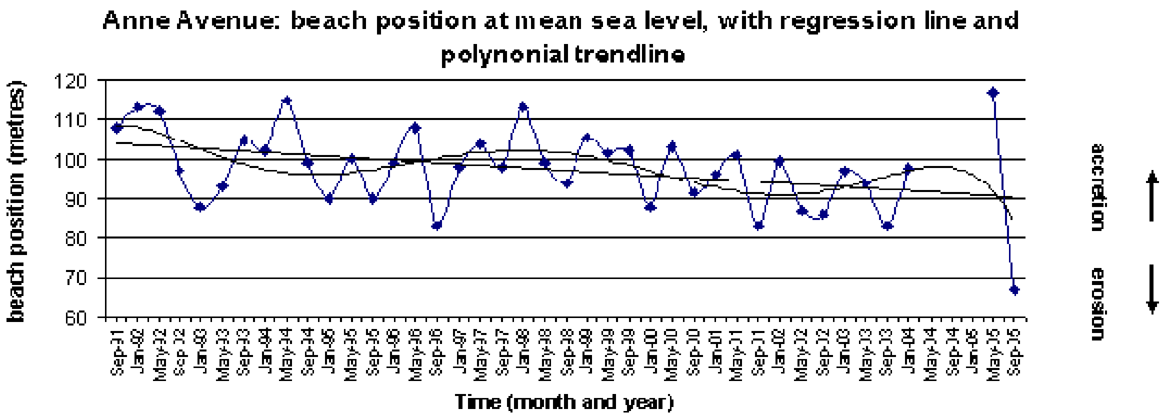


Figure 2.39 Anne Avenue beach profile B, beach position at mean sea level, with regression and polynomial trend line (Mead *et al*., 2006)

Erosion over the last few years has resulted in damage to property. Storm events between September 2005 and September 2006 caused erosion which resulted in the complete undermining and collapse of the public toilets at Anne Avenue (Figure 2.40)

Figure 2.40 Erosion in November 2005 began undermining the public toilets at Anne Avenue and the storm waves in August and September 2006 resulted in the total collapse of this structure (picture by Illenberger).

2.9.2 Studies of Beach Processes

“When working with the complex and continually varying nearshore environment one can never explain a system entirely, rather through the process of calculation and modelling with validation from actual measurements in the field can one come to a better understanding of the mechanisms of a system “(Dean and Dalrymple, 2002)

Although many studies have been conducted and reports have been written about the erosion problem at St Francis Bay (CSIR, 1992, WPR, 1993, Entech, 2002a&c; Otay and Samanci, 2003) very little actual fieldwork and data collection has been conducted. Therefore the results of much of this previous work should be regarded in a conservative manner.

According to a computation of the longshore current energy spectra (Schoonees, 1986 in Bickerton and Pierce, 1988)), using Voluntary Observing Ship (VOS) wave data and an analytical computer method, the net longshore transport at nine sites (Figure 2.41) along the coast of the greater St Francis Bay was calculated to be with one exception, north-going. Site 3 north of the Kromme Estuary mouth was the exception but only marginally. Cross shore processes were proposed as being significant in the sediment dynamics of St Francis Bay beach.

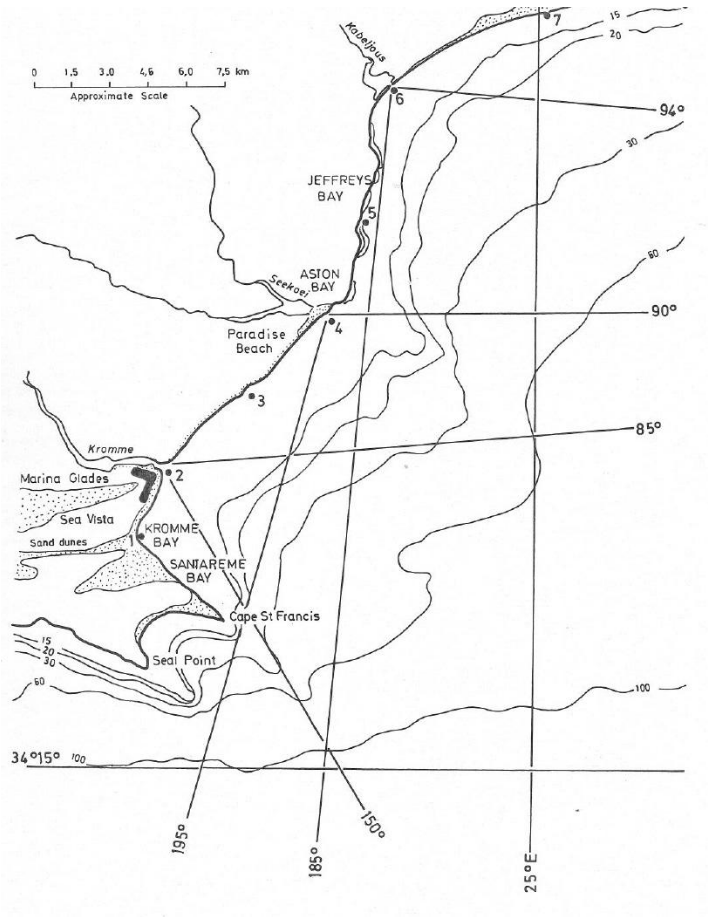


Figure 2.41 St Francis Bay, wave incidence and sites of longshore transport computation, including bathymetric contours (Fromme and Badenhorst, 1987 in Bickerton and Pierce, 1988)).

In 1992 the CSIR and KAP assessed the coastal processes and sediment dynamics in more detail as part of a study of sedimentation in the Kromme Estuary. This investigation used offshore wave data from Soekor Platform offshore of Mossel Bay. Mathematical refraction techniques were utilised to determine inshore wave conditions along the St Francis Bay coastline, from Seal Point to Seekoei Point represented in Table 2.4 and Figure 2.42 below. Results showed that waves approach the beach from variable direction, indicating a potential for littoral transport up and down the coast. However it was also concluded that the average direction of approach is close to normal to the beach, resulting in a small potential for net longshore transport. The only exception to this is Santareme Bay AA1, the section of coast along Cape St Francis, where in spite of low wave energy a high potential for net transport is estimated due to the oblique angle of incidence. Although the results of longshore sediment transport calculations (Table 2.5) were not representative of actual volume but rather indicative of the overall trends it is interesting to note that a net north to south potential longshore transport in the order of 60 000 $m^3.yr^{-1}$ was calculated for a point in the central part of St Francis Bay Beach (KK3) and a net south to north potential transport in the order 55 000 $m^3.yr^{-1}$ was calculated for the Kromme River mouth area (KK1) (CSIR, 1992). The majority of longshore sediment transport was calculated to occur in less than 6m water depth with the greatest transport in 2-4m water depth, see figure 2.3 offshore distribution of longshore transport at KK1 in the Kromme River Mouth.

Table 2.4 Summary of wave conditions on the study coastline (CSIR, 1992)

POSITION	WAVE CONDITIONS		EQUIVALENT ENERGY	
	(Hs) 20% (m)	(Hs) 1yr (m)	Magnitude (GJ/yr/m crest)	Wave Direction (degrees true)
Deep Sea	3,5	8,1	1 390	
TP1	3,7	8,0	1 147	205
DH1	3,6	7,3	1 047	202
DH4	3.6	7,8	1 070	209
KK1	2.2	4.4	308	129
KK2	3,0	6,8	706	135
KK3	2,6		446	112
KK4	2,6		511	128

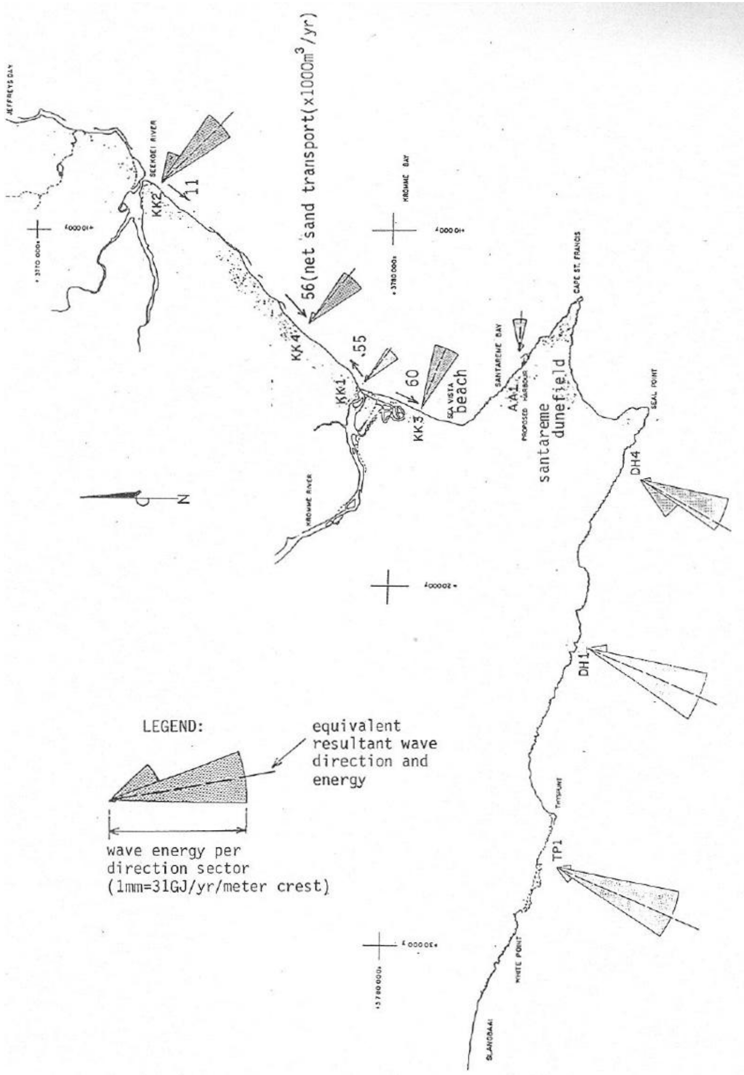


Figure 2.42 wave energy and direction on the coastline in the vicinity of Cape St Francis (Kapp Prestedge Retief in CSIR, 1992).

Table 2.5 Summary of potential longshore transport calculations (CSIR, 1992)

POSITION	GROSS TRANSPORT		NET TRANSPORT	
	Magnitude m^3/yr		Magnitude	Direction
	S - N	N - S	m^3/yr	
KK1	100 000	45 000	55 000	S - N
KK2	375 000	386 000	11 000	N - S
KK3	91 000	151 000	60 000	N - S
KK4	135 000	191 000	56 000	N - S

WPR (1993) conducted some wave refraction calculation and longshore sediment transport estimates as part of a pre-feasibility study of groyne construction. Using the wave conditions in the vicinity of the mouth the cross shore distribution of the alongshore transport was calculated. These results shown in Figure 2.43 suggest that longshore transport is in a net northerly direction with 91% of the south to north transport occurring between the shore and -3m CD, this agrees with previous calculations in CSIR (1992) above. WPR (1993) also suggest that the Kromme Estuary mouth acts as a discontinuity to alongshore transport, due to the change in offshore bathymetry at the mouth and loss of sand into the estuary.

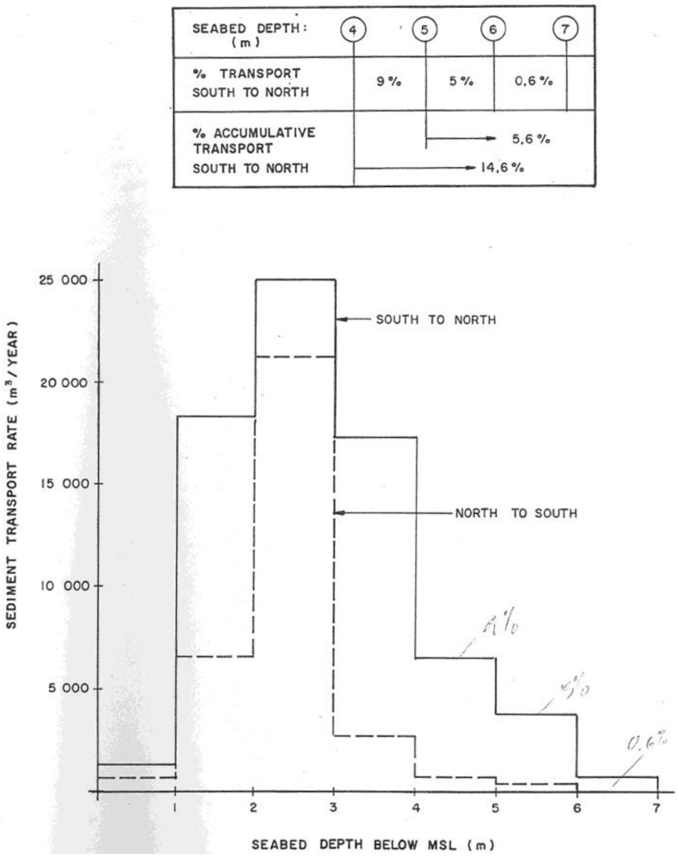


Figure 2.43 Longshore sediment transport distribution normal to the coastline at the Kromme Estuary mouth (WPR, 1993)

Turkish Engineers Otay and Samanci (2003) conducted a numerical modelling study to investigate the feasibility of permeable gum pole groynes at St Francis Bay Beach. They simulated wave conditions over a 20 year period and compared morphological changes to actual changes observed through aerial photographic analysis over the real time period (Illenberger and Burkinshaw, 1997). The simulated shore line changes were the opposite of what was observed in the aerial photographic analysis; their results were thus highly inconclusive. Due to limitations in scope and budget, no bathymetry or wave current data was collected at the site for any of the studies discussed above.

Mead *et al.* (2006) developed a nearshore wave climate for St Francis Bay. This was achieved by transforming 10 years of offshore WW III data to the nearshore using WBEND © numerical wave refraction model (Black, 2000), calibrated with measured inshore wave data collected by the author in 400 m offshore or St Francis Bay beach (further elaboration in chapter 4 and 5). This inshore wave climate was then used to conduct numerical modelling in order to investigate the dynamics and physical processes at work in St Francis Bay and conduct design testing of multi-purpose reefs (detailed in chapter 5 and 6).

2.9.3 Previous remediation recommendations

The CSIR (1992) conducted an extensive evaluation of coastal and sediment dynamics in order to provide background information to the sedimentation problems in the estuary and to assess the possibility of remedial measures. They proposed that the sedimentation could be improved by training the mouth by constructing a pair of breakwaters as shown in the conceptual drawing Figure 2.44 below. The objective being to maintain a dredged channel with the breakwaters acting as groynes to prevent longshore sediment transport from filling in the channel.

It was then stated that conditions at this location are well suited for this type of solution owing to the lack of strong longshore sediment transport and that this solution would lead to improvement of the St Francis Bay beach. Fluidization was also suggested in order to keep channels clear from sand bank formation. This process consists of a hydraulic and pneumatic piping system laid on the seabed in the estuary and used to fluidize the bottom sediments on the ebbing tide.

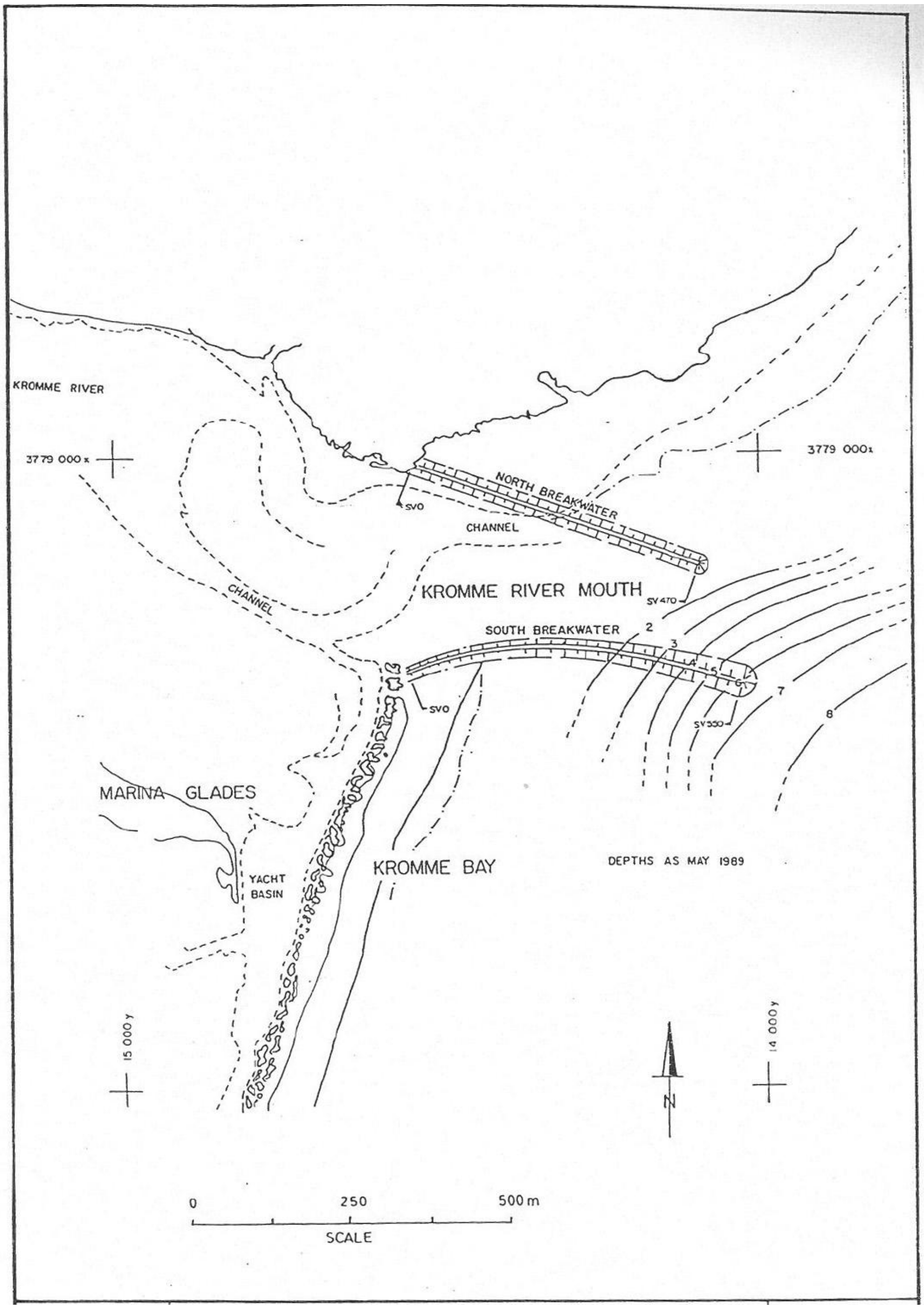


Figure 2.44 Kromme Estuary breakwater design, contributed by Kapp Prestedge Retief in CSIR, 1992).

This Study was followed shortly by a pre-feasibility study into groyne construction conducted by Coastal Engineers WPR in 1993. They aptly categorised 2 major components of the problem:

- The long term decrease in beach width caused by a lack of adequate supply of sand to the beach or loss of material into the estuary or a combination thereof.

- The short term erosion of the beach due to cross-shore sediment transport under steep storm waves.

Interestingly they went on to state that the latter short term cross shore erosion could be addressed by limiting the wave energy reaching the beach or beach nourishment, going on to recommend that the long term beach erosion could be solved by trapping sand with a structure or beach nourishment. From this evaluation and considering specific unique features of St Francis Bay, they proposed a solution entailing a single groyne structure at the mouth of the Kromme Estuary in combination with beach nourishment from estuary dredging. Due to the fact that the waves approach the present beach almost normal to the beach, they deduced that a single substantial groyne structure would increase the beach width over the whole length of the beach. Their initial design specifications were based on the longshore sediment transport calculations and the groyne was designed to extend to a depth of 3m (CD), and span a distance of 460 m. Although this study included slightly more detailed design specifications, several problems can be identified with this approach.

As with the CSIR (1992) recommendations, evidence from thousands of groyne projects around the world have shown that groynes are very effective in trapping sand in unidirectional longshore transport environments, however these structures are ineffective in cross shore transport dominated systems and in such environments groynes can even increase erosion by creating strong offshore currents adjacent to structures (Komar, 1998; Basco and Pope, 2004).

Considering the low supply of sediment to the St Francis Bay beach, they proposed that sand should be dredged from the estuary or pumped from the Sand River. Estimating that a volume of 900 000 m^3 could be won from the large sand banks on the southern bank inside the entrance of the estuary if dredging were conducted to a depth of 2m below CD. A “dive dredge” with capacity of 40 m^3 (solids)/hour with the capacity to dredge 200 000 m^3 per year operation for two 8 hour shifts per day was recommended. The idea of creating a sand trap at the road bridge or the confluence of the Sand River and pumping sand with a jet pump over 2km distance to the beach was also proposed as an option.

In addition it was suggested that rock revetment should be used where necessary in order to address the short term erosion threats to the back beach and if the long term comprehensive beach protection solution including groyne and nourishment should be carried out these revetments will act as a sleeping defence.

They proposed that the groyne on the northern side of the mouth could help train the mouth and maintain an open navigational channel, although the presence of rocky reef to the north of the mouth may negate this requirement.

In 2002, Entech Consultants (Pty) Ltd conducted a coastal erosion impact assessment specialist study as part of the St Francis Bay Beach Restoration Environmental Impact Assessment. They aims of this study were to identifying the existing processes shaping the coastline, describe the baseline conditions, assess alternative erosion mitigation measures identified by Interested and Affected Parties (IAP's), investigate potential positive and negative environmental impacts of the proposed development and alternative beach erosion control measures and recommend a preferred solution.

Alternative erosion mitigation measures evaluated included:

- Do Nothing
- Single Groyne
- Multiple Groynes
- Offshore shore parallel breakwater/Submerged Multi-Purpose Reef
- Beach Nourishment
- Revetments
- Non Conventional Techniques (MantaMats, Permeable Gum Pole Groynes)

Submerged multi-purpose reefs were evaluated and showed many advantages:

- Aesthetically pleasing, with no structures on the beach and the creation of gentler beaches in the lee of the structure
- Beach amenity value is retained and improved.
- Careful design would ensure the formation of a salient which would allow sediment flow through the system and minimize down drift impacts

Disadvantages included:

- Construction difficult, marine-based equipment required.
- Many structures will be required to protect the full length of beach.

From a technical and financial perspective this study concluded that two options were preferable, namely:

- Capital nourishment and continued maintenance nourishment
- Multiple groynes

Although the beach nourishment option was deemed to offer greater flexibility and limited environmental impact, a further study of sand sources (Entech, 2002b) indicated that due to transport distances, limited accessibly volumes and the poor performance of the existing sand pumping system, implementation of the groyne option should be given preference.

Ultimately these preferred remediation options were revised into the following two options (SRK, 2003):

- Beach Nourishment alone with 1 x 10^6 m^3 of capital nourishment.
- Multiple Groynes and Beach Nourishment with 500 X 10^3 m^3 capital nourishment.

2.9.4 Previous Remediation Efforts

In early 1995 the ST Francis Bay Municipality started pumping sand onto the beach from the lower entrance to marina. The sand supply system consisted of a roving jet pump connected to a shore booster station. A flexible 150mm PVC pipe was placed along the beach for 2km. Two discharge points were located at Anne Avenue and the Ski Canal (Southern end of the Marina Glades barrier dune) respectively. The design capacity of the system was 45 litres per second, with a 20% sand content this would amount to 65000 m^3 of sand being pumped onto the beach per year at full capacity (40h per week). This is within the range of the estimated longshore transport. In order to achieve improved delivery of sand on the beach the operation of the pumping system was privatised. Although council records indicated design capacity of 36 m^3 of sand per hour was attained during September 2000, the privatised pumping effort did not prove very effective No pumping performance records are available; however it was evident that no pumping had taken place since November 2001 (Entech, 2002b). Personal inspection of the pump facility by the author in mid 2006 revealed that it is in a state of disrepair.

In 2003, the municipality commissioned a permeable gum-pole groyne trial, however bedrock was encountered close to the surface and therefore only one pole was planted in shallow water at the chosen site close to the northern end of the beach. The project did not progress any further.

3 THE HYBRID SOLUTION

3.1 Introduction

As discussed in previous sections, numerous studies have shown that longshore transport along St Francis Bay beach is variable and generally waves arrive at the beach at a fairly shore-parallel orientation. Erosion on St Francis Bay beach is the result of a combination of acute erosion due to large storm waves from southerly and easterly directions. Groynes can be very successful in coastal environments with oblique wave incidence and associated dominant longshore transport, for example Hobie Pier in nearby port Elizabeth (Mead *et al*., 2008) However groynes are not effective in protecting against cross-shore erosion and can actually increase erosion by inducing the formation of strong rip currents (Basco and Pope, 2004).

In the case of cross shore dominant erosion processes, offshore breakwaters are the most effective form of coastal protection (USACE, 2006). Additionally considering the numerous examples of good salient formation behind natural reefs in the vicinity, it was concluded that Multi-purpose reefs would be an effective solution. Considering the sediment starved nature of the St Francis Bay beach environment, nourishment using sand from the large flood tidal delta on the southern banks of the mouth of the Kromme Estuary was also recommended. In addition numerous projects worldwide have shown the benefits of a natural functioning dune system acting as a buffer at the back of the beach, therefore dune rehabilitation with appropriate indigenous plant species was recommended as the third element of this three-pronged approach to remediation of the beach erosion at St Francis Bay (Mead et al. 2006), comprising:

- 3 or 4 Multi-Purpose Reefs offshore
- Capital beach nourishment in the order of 300 000 m^3 of sand dredged from the lower reaches of the Kromme estuary. Thereafter 20 000 – 40 000 m^3 per year maintenance nourishment.
- Dune rehabilitation with appropriate plant species.

The following chapter provides some background to the three elements of this hybrid approach to beach erosion remediation at St Francis Bay shown in (Figure 3.1) below.

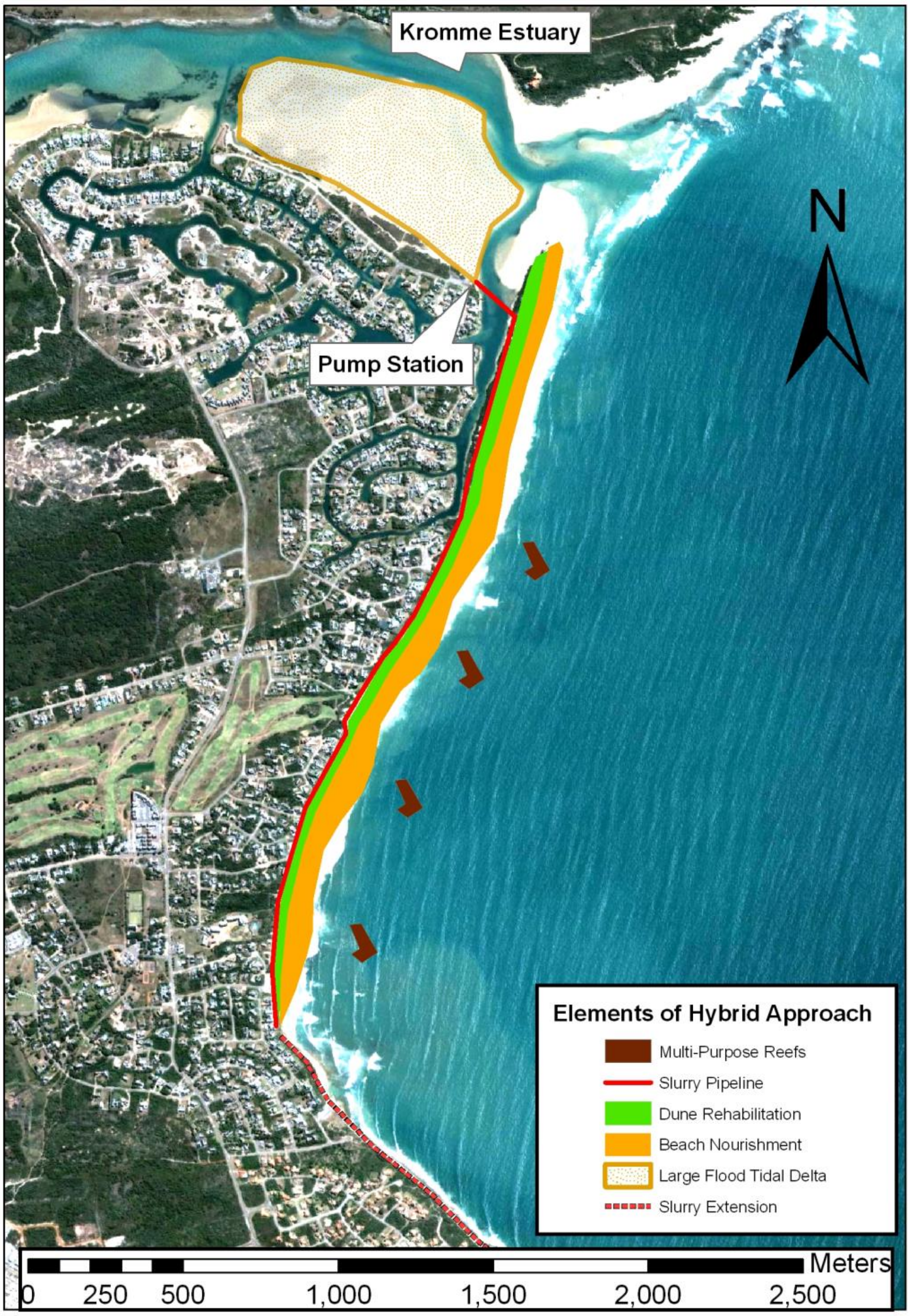


Figure 3.1 Elements of the hybrid approach to beach remediation proposed by Mead *et al*. (2006) including multi-purpose reefs, beach nourishment and dune rehabilitation. The possibility of extending the slurry pipeline up the point to discharge above Bruce's would have the added benefit of improving surfing wave quality at this world famous surfing break.

3.2 Multi-Purpose Reefs

3.2.1 Introduction

Limitations of traditional coastal engineering structures and approaches prompted Professor Kerry Black of the Coastal Marine Group at the University of Waikato in New Zealand to initiate the Artificial Reefs Programme (ARP) in 1995. The underlying inspiration came from the numerous examples in nature where natural reefs act as barriers to wave energy protecting the shore and creating additional amenity benefits. The investigations of the ARP aimed at understanding how natural reefs function in terms of coastal protection and surfing wave quality and other amenity enhancement. In addition the ARP was directed towards developing expertise within the research community and within private industry, while providing a sound basis for senior student education. A team of scientists and industry experts was involved, including biologists, physicists, engineers, planners and environmental managers, so that both the environmental aspects and the coastal processes could be fully investigated to enable the complete development of multi-purpose artificial reefs. A series of related studies provided the input into the broader program so that engineers involved in offshore protection works could incorporate the proposed concepts into structural designs to fulfil the demands and requirements of the marine environment, recreational users and developers (Black *et al*, 1997).

MPR's exhibit several benefits over traditional forms of coastal protection such as groynes, breakwaters and seawalls. Firstly they are positioned offshore with submerged crests so that visual and aesthetic impacts are reduced as compared to traditional emergent rock/rubble breakwaters and groynes. MPR's act as control points within the beach system, breaking waves and reducing wave energy, bending/refracting waves altering longshore currents and associated sediment transport (Black et al., 2001), and when placed at the appropriate distance offshore result in the creation of wave driven current circulation behind the reef which induces salient formation (Ranasinghe *et al*, 2006). As opposed to solid emergent structures which act as an absolute barrier to wave energy and sediment transport with negative down-coast impacts, MPR's can be designed to work within a system creating a salient without providing an absolute barrier to sediment transport (Black *et al*., 2001). The use of rocks, steel and concrete as ''hard coastal structures'' should be avoided where possible. Sand filled containers made of needle-punched non-woven geotextile offer more advantages as ''soft rock structures''. Additionally as flexible construction elements geotextile containers behave advantageously with respect to cyclical hydrodynamic loads and morphological seabed changes (Saathof *et al*., 2007).

The main objectives of the ARP have been achieved and in addition to numerous research theses, individual journal and conference papers and consulting reports, Special Issue No. 29 of the Journal of Coastal Research (Winter 2001), “Natural and Artificial Reefs for Surfing and Coastal Protection” includes more than a dozen scientific papers on the design, impacts and construction of multi-purpose reefs. The public’s demand for beaches for recreation, combined with the increasing value society places on the natural environment, has led to a dramatic increase in the development of submerged reef projects world-wide and more recently independent research is strongly supporting the findings of the initial ARP (e.g. Houston, 2002).

3.2.2 Case Study: Narrowneck Multi-Purpose Reef, Australia

The Gold Coast is Australia’s primary tourist destination, with the wide sandy beaches being a major attraction. The erosion problem on the Gold Coast was confined to a hotspot at Narrowneck, where only the coastal road separates the Broadwater from the sea. This causeway was breached several times in the previous century and coastal protection was proposed as part of the Gold Coast Beach Protection Strategy to address this problem. The Gold Coast has a predominant south easterly swell direction, which results in large net sediment transport in one direction (~500,000 $m^3.yr^{-1}$ to the north); although reversals of sediment transport direction occur frequently.

Traditional coastal protection methods were considered (e.g. groynes, tipped rock walls, etc.); however, a socio-economic assessment found that for every dollar spent on enhancing the beach, $60-80 was returned via tourism (Raybould and Mules, 1997 in Mead *et al*., 2006). Consequently, an offshore submerged reef was proposed and design works were undertaken by ASR consultants (Black *et al*., 2001).

The aims of the project were:

- to widen the beach and dunes along Surfers Paradise Esplanade.
- to improve the surfing climate at Narrowneck.

A comprehensive field program was undertaken, with the results being utilised for reef design and sediment transport modelling (i.e. to assess the functional performance of the reef). The resulting final design was a 120,000 m^3 submerged reef (Figure 3.2 and Figure 3.3) – reef crest level is ~0.5 m below LAT. The submerged artificial reef was constructed using approximately 390 large sand filled geotextile bags, dropped into place using a barge. The primary purpose of the reef was to stabilise the nourished northern beaches and to improve surfing conditions of the northern beaches (Boak *et al*., 2001). The construction work was undertaken during 1999 and 2000 and the impacts of the projects are currently being monitored using an ARGUS coastal imaging system, which has shown that wave energy is dissipated by the reef for up to 90% of the time and that Narrowneck reef is an erosion control point on the coast (Figure 3.4) (Turner, 2001).

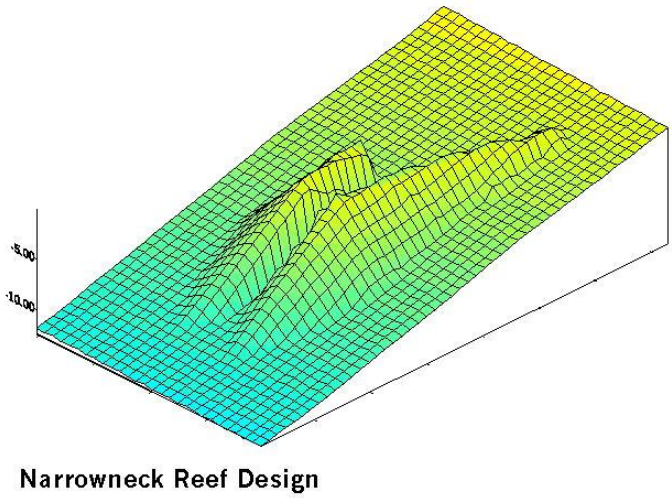


Figure 3.2 3-dimensional representation of the Narrowneck multi-purpose reef (Mead *et al.,* 2006).

Figure 3.3 The view of Surfer's Paradise with the multi-purpose reef in the foreground (Mead *et al.,* 2006).

Figure 3.4 Time-averaged WRL image prior to March storm [29/2/2004], demonstrates how successful the Narrowneck submerged reef has been at retaining nourishment material on Surfer's Paradise Beach. (Jackson *et al*., 2004)

The Gold Coast reef has been a huge success, not only in terms of coastal protection, but also providing a surfing facility (recent reports describe the reef as the 'best surfing spot on the coast') and a 'natural' reef ecosystem with that supports a dive trail (Figure 3.5). Ecological studies have determined that "*The biological communities associated with Narrowneck Artificial Reef appear to enhance biodiversity and productivity at a local scale, and may also contribute to overall regional productivity.*" (Jackson *et al*., 2004). An important outcome of the project was the confirmation (via beach profile monitoring and Argus coastal imaging) of no downdrift impacts on the coast. In 2000, the Narrowneck reef project won the prestigious Queensland State environmental award. Recent re-assessment of the economic impacts of the reef has confirmed a benefit:cost ratio of 70:1 (McGrath, 2002).

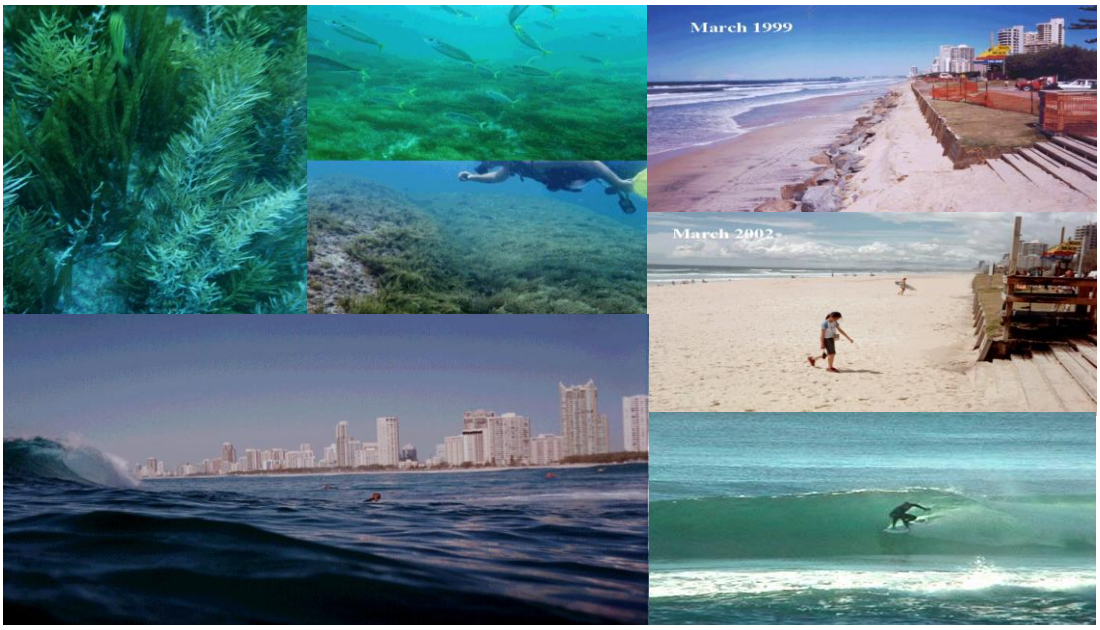


Figure 3.5 The Narrowneck multi-purpose reef. Clockwise from top left, colonization of the reef has resulted in a dive-trail; before and after reef construction (construction commenced in August 1999); surfing on the reef; the view from the surf.

3.2.3 Multi-Purpose Reefs for St Francis Bay

A small tidal range and many examples of good salient formation behind natural reefs in the vicinity, give good confidence in the suitability of MPR's as a form of coastal protection for St Francis Bay beach (Mead et al. 2006). Preliminary investigations indicate that 3 or 4 reefs will be required, each +/-115 m long, situated 200-225m offshore of MSL as presented in Figure 3.6. The reefs would be designed with a longer northern arm and shorter southern arm, in order to maximise the rotational effect, changing the wave angle behind the reef to reduce northerly longshore transport. The depth of the reef will be between 3.5 and 4.0 m (to chart datum (CD)). With a crest height of 0.0 m (to CD), which is 0.4 m below mean low water spring (MLWS). Preliminary modelling assessments indicated that the reefs would have volumes of 8,000-11,000 m^3 above the seabed, and cover areas of 3,600-4,400 m^2 (Mead *et al*., 2006)

Details of design theory, empirical calculations and modelling investigations are presented in Chapter 6. Furthermore chapter 0 presents results of physical modelling in which the computer design is assessed and refined in terms of surfing amenity and construction constraints.

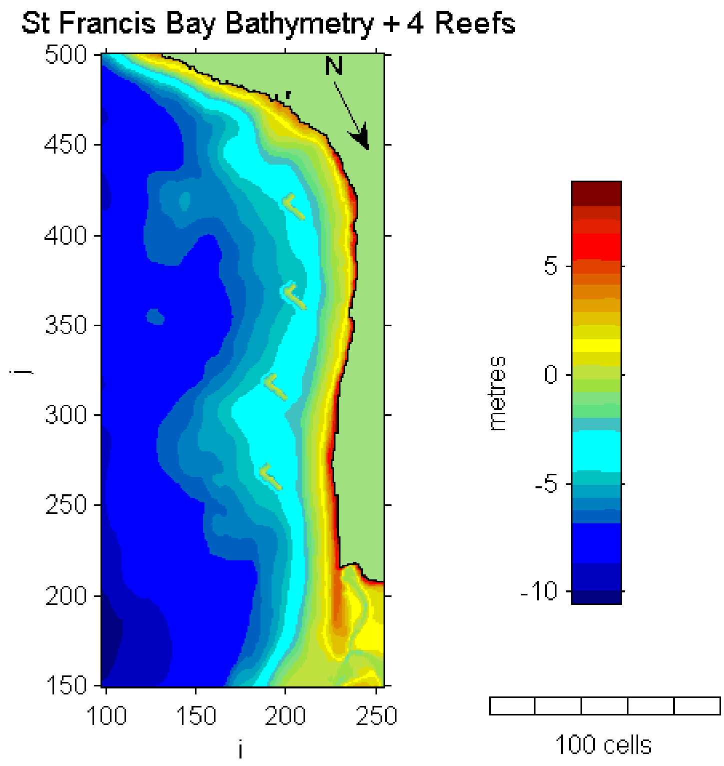


Figure 3.6 Bathymetry of St Francis Bay with four multi purpose reefs located 200-225m offshore of MSL, grid rotated 200° CCW for Numerical modelling, cell size 10X10m.

3.3 Beach Nourishment

3.3.1 Introduction

Beach nourishment or beach fill refers to the placement of sand on an eroded beach. This approach is considered a soft engineering solution to beach erosion and has gained popularity with coastal managers and coastal engineers over recent years. Beach nourishment is carried out throughout the world, with large scale projects in America, England and Australia. Nourishment attempts to directly address the deficit of sand on a beach, which may be due to natural processes or human induced interruption in sediment supply. Typically sand from offshore or onshore locations is dredged and pumped or trucked onto the beach.

Beach nourishment accomplishes several goals:

- builds additional recreational area
- offers storm protection

The second goal of storm protection is often under appreciated, when beach fill is eroded during storm wave conditions it is not entirely lost, but most of the sand is transported offshore into a bar system, from where it will be returned during calm wave conditions. However, usually beaches considered for beach nourishment are eroding; therefore beach nourishment is simply a means of providing a buffer. Without addressing the processes causing erosion the beach will erode back to its original state, but several factors affect the longevity of beach nourishment. Sand is placed on the beach at a slope steeper than equilibrium profile. The eroded beach is inherently out of equilibrium; therefore once sand is placed on the beach waves begin to restore equilibrium both in profile and planform. Usually the profile equilibration through cross-shore transfer of sand from the upper to lower portions of the profile and resultant shoreline recession, dominates in time scales in the order of years. The transfer of sand along the beach resulting from the planform anomaly created by the placed sand usually occurs in time scales in the order of decades. Background shoreline erosion due to pre-existing erosion processes are usually considered to continue at the same rate as prior to beach nourishment.

The placement of sand on the beach can be done mechanically or hydraulically. Mechanical transport usually refers to transport by truck or other land based means of transport. In general this method is used for small beach fills owing to the high cost of transportation and the impacts on traffic and road surfaces from heavy loads. A large majority of beach nourishment is conducted by hydraulic means where sand is lifted from the bottom by a hydraulic dredge and pumped via a pipeline and discharged onto the beach. In some cases material is dredged from offshore sources, placed in hopper barges and transported inshore where it is discharged into shallow water pumped directly onto the beach.

Several options for placement location of borrow material, include: nearshore, backbeach, dunes, foreshore or distributed over the profile. Planform options are to spread the fill material over the eroding beach, to place the fill primarily on the updrift end of the project area or place the fill in a groyne-like planform.

The ideal sediment source for fill is one that is of similar grain size and composition to that of the native (existing) beach sand. Finer sand will tend to erode more quickly and coarser sand will lead to profile steepening which may have adverse effects (Dean and Dalrymple, 2002).

International Examples of large scale beach nourishment projects include:

The coastline of Lincolnshire where after many years of rapidly lowering beach levels and deteriorating hard defences, the largest beach nourishment project in was the UK was undertaken between 1994 and 1998, where approximately 7.5 million cubic metres of sand was placed over two phases along 23 km of coastline. The sand material used for the nourishment was dredged from a source approximately 20km offshore of the frontage. Results were positive however intense monitoring indicates that the levels of annual loss have increased since nourishment. This could be attributed to the varied grain size of the fill material (Mocke *et al*., 2003).

The persistent erosion at the downdrift limit of the seawall at Sandy Hook, New Jersey in the USA has varied in magnitude over the past several decades because of sediment manipulation in updrift locations and sediment placement in the CZ. The losses in the current decade are much less than the historical maximum rate of loss (−174000 m^3/yr) because of two beach nourishment projects in the updrift communities (8000000 m^3 over the period 1994–96 and 2002) that have released sediment into the CZ (Psuty, 2008).

Large scale beach nourishment has been conducted along the Florida coastline on a range of beach environments and has proved highly beneficial in terms of coastal protection and beach amenity enhancement (Benedet *et al*., 2004)

In Australia, several successful examples of large scale beach nourishment are found, such as the Tweed River Bypass scheme. In an effort to improve navigation the breakwaters at the mouth of the Tweed River were extended in the early 1960s, effectively disrupting a large proportion of the net northerly littoral movement of sand along the coast. Over a 30 year period about 7,000,000 cubic metres of sand, or nearly half of the littoral drift, accumulated on the beach to the south of the training walls, on the entrance bar and within the lower reaches of the river. The bar at the entrance to the river reformed, and navigation again became difficult (Dyson et al., 2001 in Anderson *et al.,* 2003). The trapping of this sand caused serious erosion at Coolangatta and Kirra. To mitigate this impact, the Queensland authorities constructed revetments and groynes, and nourished the beaches. In 1995, the Tweed River Entrance Sand Bypassing Project was created by the NSW and Queensland Governments. The aims of this project are to restore and maintain the southern beaches of the Gold Coast and to maintain a navigable river entrance. The entrance was dredged and the dredged sand was used to nourish the beaches. In May 2001, a jetty-mounted sand bypassing system was commissioned to intercept the northerly littoral flow of sand before it reaches the ocean entrance of the Tweed River. The system collects sand from the southern side of the breakwater and pumps it to four outlet points at beaches along the southern Gold Coast in Queensland (Dyson et al., 2002 in Anderson *et al.* 2003). This bypass scheme has lead to the creation of the world famous 'superbank' surfing break, which attracts surfers from all over the world and provides a major influx of tourism revenue to the area.

Another project of great significance to the present study is the North Gold Coast Beach Protection Strategy, adopted by Gold Coast City Council in 1996 with two main objectives. Firstly to widen the beach and dunes along the Surfers Paradise Esplanade so as to increase the volume of sand within the storm buffer and also to provide additional public open space. Secondly, to improve surf quality at Narrowneck by the construction of a submerged artificial reef to stabilise the nourished beaches. Construction consisted of two major projects, beach nourishment and the construction of a submerged artificial reef. The beach nourishment involved the dredging of 1.1 million m^3 of sand from the Broadwater and placing it from Main Beach to Surfers Paradise (Boak *et al*., 2001). The details of MPR construction are contained in the case study in the previous section. Several similarities to the St Francis Bay Site exist. Firstly dredging of the Broadway waterway channels proved a major benefit to navigation from a boating and leisure perspective and secondly sand was hydraulically pumped and deposited in an up-drift location, from where some of this material will be transported back into the Broadwater waterway which acts as a sediment trap thus allowing recycling of beach sand.

3.3.2 Beach Nourishment at St Francis Bay

Past studies have identified several suitable sources for beach nourishment material. Entech, (2002b) conducted a technical study of sand sources which identified four potential sources of sand, shown with available volumes and transport distances in table below:

Table 3.1 Volume of sediment available and transport distance for four possible sources of beach nourishment (Entech, 2002b)

Sand source	Volume available (m^3)	Distance (km)
Kromme Estuary	600×10^3	0.2-3
Sand River dunefield	1×10^6	3.7
Marina canal system	100×10^3	4
Municipal waste dump site	$50 - 400 \times 10^3$	4.1

Table 3.2 Median grain size for the beach and four different sources evaluated in terms of suitability for use as beach nourishment (Entech, 2002b).

	Median Grain Size (D_{50})	
Location	**Phi**	**microns**
Upper Beach	2.5	180
Lower Beach	2.2	220
Dump	2.5	180
Estuary	2.5	180
Sand River Dunes	1.6	320

This assessment concluded that sand from all sources was comparable in gain size and composition to native beach sand and therefore considered suitable for use as beach nourishment. Transport by hydraulic means was considered preferential for sand from the large sand bank on the southern bank of the estuary within the mouth. Transport via truck was recommended for the other three locations.

The Sand River dunefield (the leading end of the Oyster Bay dunefield), was considered the most appropriate source for several reasons, mainly it could be initiated immediately and would alleviate the problem that the municipality has with wind-blown sand. However this option would have major impacts on the traffic and roads infrastructure in St Francis Bay. The impact to the community associated with hydraulic transport of sand from the lower banks of the Kromme Estuary was considered substantially lower and benefits to navigation and ecology meant that this source was considered preferable. However it was noted that the impacts of excavation from this source on the hydrodynamics of the Kromme Estuary should be investigated prior to extraction from this source. The hydrodynamic modelling conducted to assess the impacts of sand extraction from this source is presented in Chapter 8.

In conclusion it was recommended that the implementation of structures (groynes) should be considered preferable as this would reduce the volume of nourishment required and guarantee the safety of St Francis Bay beach without undue dependence on continuous supply from the sand pumping scheme. This agrees with Mead *et al*. (2006) although MPR's replace groynes as coastal protection structures.

3.4 Dune Rehabilitation

3.4.1 Introduction

The understanding of the importance of natural functioning foredunes in the beach sediment budget outlined in section (2.7.7) has resulted in numerous dune rehabilitation projects worldwide (French, 2001; Nordstrom *et al*., 2002; Dahm *et al*., 2005). Planting of appropriate native sand-binding plant species promotes dune growth during periods of calm low energy beach accretion periods, keeping sand in the beach system which may have been blown inland. During storm high energy beach erosion periods the dunes do not counter erosion but rather act as a ''buffer'' allowing sand to be moved offshore, providing protection by dissipating wave energy in the surf zone (Dahm et al., 2005). Foredunes are often the last line of defense against ocean storm wave attack and flooding from over-wash, where interior dunes exist; these may provide high ground and protection against penetration of over-wash, and against the damaging effects of storm-surge ebb scour (Bush *et al*., 2001). Dune restoration projects in New Zealand have been very successful (Jenks and O'Neill, 2004).

3.4.2 Dune Restoration for St Francis Bay

The severe erosion along St Francis Bay beach means that natural functioning foredunes are lacking for most of the beach. Rock revetments line the back of the beach along much of the beach length. The remaining unprotected areas consist of eroding barrier dune. During a site visit in February 2006 a small portion of the artificial sand spit had native foredune species and exhibited natural foredune morphology as shown in Figure 3.7 below. Planting of native sand binding dune vegetation will only be effective once sufficient beach nourishment has been carried out. It is proposed that the rehabilitation should be carried out in phases using different combinations of the diverse indigenous sand dune flora identified by Klages *et al.* (2002) and shown in Table 3.3, in order to investigate the relationship between plant and dune morphology. In particular it is proposed that the effect of the resultant dune morphology on dune stability be investigated and subsequent rehabilitation be implemented according to these results.

Figure 3.7 Native dune species and low sloping foredunes found along a small portion of the artificial sand spit.

Table 3.3 Potential species suitable for dune rehabilitation (Klages *et al*., 2002)

Shrublets	**Perennial herbs**
Scaevola plumi	*Ipomoea pes-caprae*
Tetragonia decumbens	*Gazania rigens.*
Chironia baccifera	*Arctotheca populifolia*
Hebenstretia cordata	*Dasispermum suffruticosum*
Passerina rigida	*Zaluzianskya maritima*
Stoebe plumosa	*Silene primuliflora*
Myrica cordifolia	*Vellereophyton vellereum*
Psoralea repens	
Tetragonia fruticosa	

4 FIELDWORK AND DATA COLLECTION

4.1 Introduction

All previous studies recommended the collection of field data as an utmost priority (CSIR, 1992; WPR, 1993; Entech, 2002a; Otay and Samanci, 2003). This chapter describes the different aspects of fieldwork that were undertaken in order to improve the understanding of the present state, coastal processes and dynamics of St Francis Bay, additionally ensuring that the numerical models used for the multi-purpose reef design testing were using reliable input data. Fieldwork included: a series of bathymetric surveys; diving surveys and helicopter flight; sediment sampling; beach profiling and deployment of a wave/current meter. The Author was responsible for most of this fieldwork and data collection, the beach profiling was conducted by land surveyors Maarschalk and partners according to guidelines provided by the author. The wave and current data was collected by the author and analysed by Mead *et al*. (2006) Where deemed significantly important to the interpretation of the chapters to follow, processing and results of certain elements of the fieldwork are presented.

4.2 Bathymetric Surveys

Reduction in sediment supply to St Francis Bay due to the various factors discussed in the previous chapter, has led to a shoreline retreat of 1.5-3 $m.yr^{-1}$ along 3km of beach between the Kromme Estuary mouth in the north and the Cape St Francis Headland in the south. Studies and monitoring conducted thus far include aerial photographic analysis (CSIR, 1992 and WPR, 1993, Illenberger and Burkinshaw, 1997) and beach profile monitoring, all limited to the portion of the beach above the beach above the low tide line, with the aerial photography analysis using the high water mark (WPR, 1993) and storm line (Illenberger and Burkinshaw, 1997) as reference and the beach profiles extending until -0.5 m below Mean Sea Level (MSL) on average.

The last comprehensive hydrographic survey of St Francis Bay was conducted by the South African Navy (SAN) Hydrographic Office in 1952 (Figure 4.1). Considering the reduction in sediment supply since the stabilization of the Santareme dunefield and the observed level of shoreline retreat, large changes in the bathymetry of St Francis Bay would be expected. Indeed it is now widely accepted that sediment transport occurs well beyond the depth of closure, mainly due to wave orbital motion suspending sediment which is then transported by wind driven currents (Black *et al.,* 2008). Previous studies recognized the collection of new nearshore bathymetric data as being of foremost priority (CSIR, 1992, WPR, 1993; Entech, 2002a; Otay and Samanci, 2003) in order to assess the changes in bathymetry within St Francis Bay and provide updated accurate bathymetry for numerical modelling (Mead *et al.*, 2006).

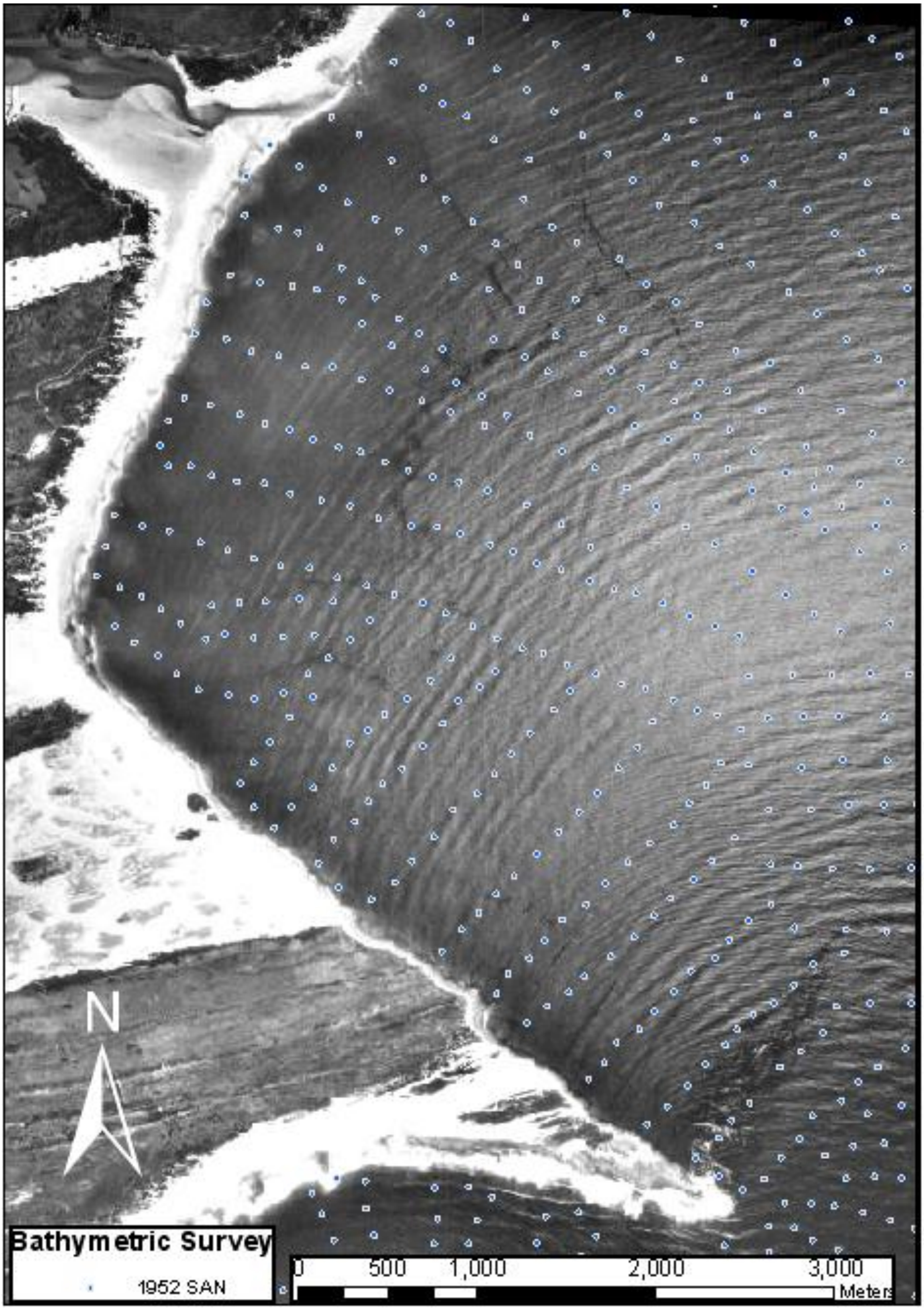


Figure 4.1 Bathymetric survey data collected in 1952 by the South African Navy (SAN) overlain on an aerial photograph from 1961.

The SFBBT sponsored a series of bathymetric surveys, between December 2005 and June 2006, conducted by the author (**Figure.4.2**). Depth was measured using a 200 kHz single beam echo-sounder, horizontal position was measured by means of a Garmin GPS receiver, depth and horizontal position data was transmitted via NMEA 0183 at a frequency of 0.5 Hz and captured to laptop computer using hyperlink © windows software. An initial comprehensive survey was conducted in December 2005 with initial transects at 1km intervals from +/- 2m (CD) depth to +/- 20m. Thereafter transects at 250m interval were conducted between the initial transects from +/- 2m to +/- 15m.

In Early 2006, following a dive inspection and initial numerical modelling exercises, two more detailed surveys were conducted to improve resolution over the southern corner of the bay adjacent to the headland and over the reef areas offshore of the central part of the beach, with transect spacing +/- 30m. Surveying was only conducted in small wave conditions to reduce inaccuracy due to wave interference. Data was then edited and reduced to chart datum by subtracting tidal levels, using tidal data measured at port of Port Elizabeth some 70 km away, courtesy of the South African Navy. Spikes and obvious anomalies were removed and the data was smoothed using a running average to remove the effects of wave action.

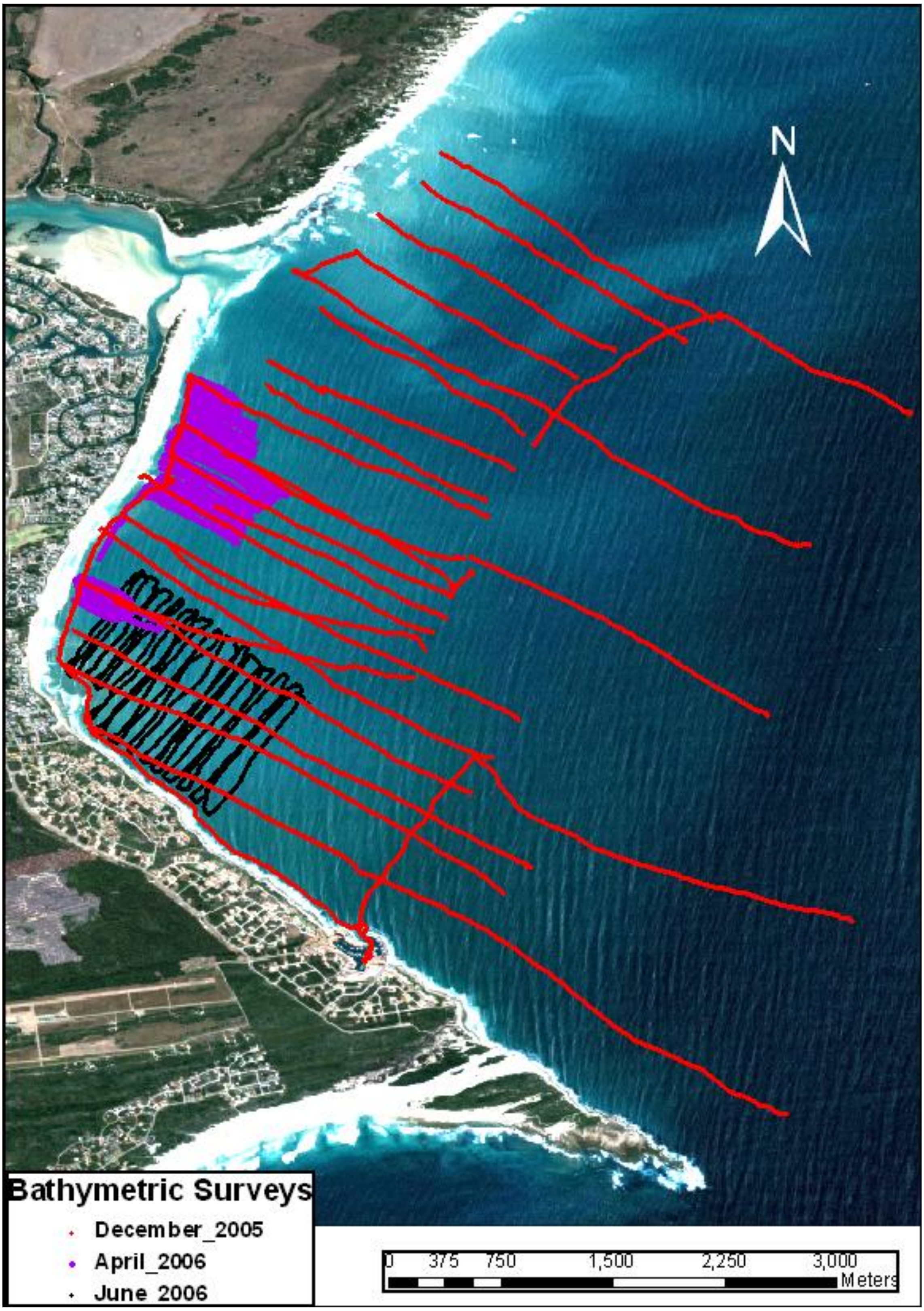


Figure.4.2 Bathymetric Surveys conducted by the author between December 2005 and June 2006.

The SAN survey of 1952 and combined data set made up of surveys of 2005 and 2006 were then gridded using the Kriging interpolation method in Surfer ™ contouring and mapping software to create grids of the two data sets. These grids were then used to create contour plots. Firstly the contour plots of the 2005 survey were analyzed to identify possible problematic data and these were deleted. Once satisfied with the quality of the data the edited data set was interpolated once again as described above. Contour plots of the two data sets were created in order to identify changes in bathymetry (Figure 4.3).

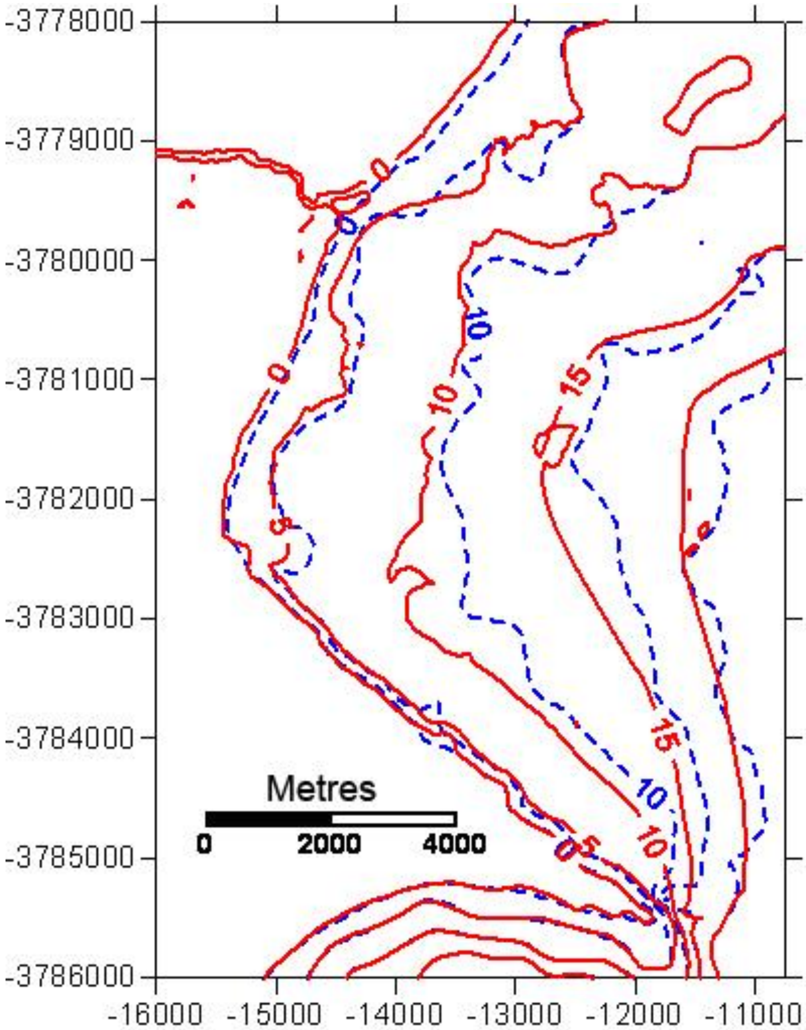


Figure 4.3 Comparison of bathymetry between SAN survey of 1952 (dashed blue) and the surveys of 2005/06 conducted by the Author (solid red). This comparison indicates that the sand loss is notably greater in the deeper regions (10 – 20 m), coordinates projection: metric UTM LO 25.

The deeper areas appear to have undergone the most change the lower variation in the shallows can most likely be attributed to the presence of low profile reef in the shallower regions < 5m water depth, verified through dive investigations (see section 3.2) and aerial photographic analysis. Large bathymetric features identified include Umzuwethu reef which dominates the central area of the beach out to +/- 8m water depth and the deeper ancient Kromme river course offshore of the present Kromme Estuary mouth, extensive shallow reef is found on the northern side of the Kromme River mouth.

In order to quantify the deepening of the bay volume calculations were conducted of the two surfaces. Firstly the two data sets were gridded in Surfer © using the kriging interpolation method at a 50 m cell size. Then the data sets were overlain as post maps and the areas considered unsuitable for comparison (areas which did not overlap or where data resolution was poor in one of the data sets) were excluded by blanking. Due to the large distance between run-lines in the 2005 survey in the 15-20m depth range this area was not considered acceptable for accurate comparison. These calculations were conducted using an overlapping area of 10, 6 X 10^6 m^3, covering roughly the area between 2m to 15m water depth (CD).

The calculated volume change over the area discussed above was 8.8 X10^6 m^3. It should also be noted that the deepening of the offshore areas would likely have led to increased volume losses from the nearshore, as deepening offshore leads to greater wave penetration and greater erosion. However the presence of rocky substrate in the shallows +/- 5 m water depth explains why there has not been considerable deepening in this depth range (Figure 4.4).

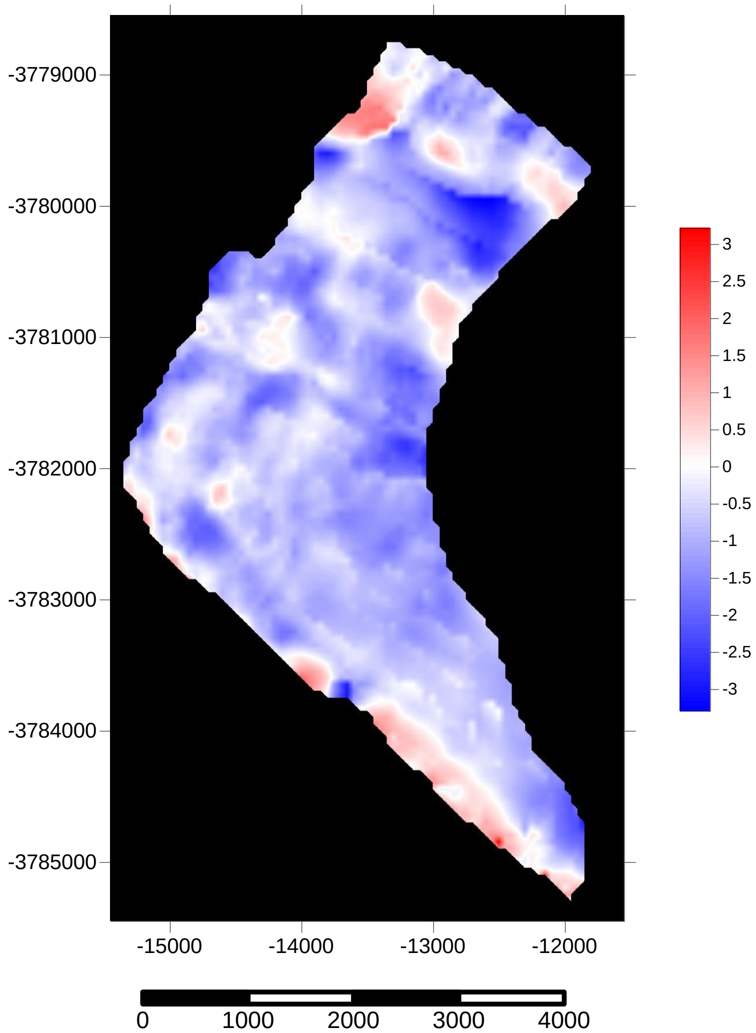


Figure 4.4 Surface difference plot between 1952 and 2005/2006, greatest deepening (erosion) indicated as negative (blue) and shallowing (accretion) as positive (red), metric projection coordinates UTM LO 25.

4.3 Aerial and Dive Surveys

Several methods were used to survey the extent of existing sediment and its distribution within the Bay. An aerial survey via helicopter from the western side of Cape St Francis to the Kromme River along the coast indicated low volumes of sand in shallow waters (Figure 4.5) comparison to that between the small transverse dune system (Figure 4.6) out near the Cape and the Port breakwater (Figure 4.7). However, to ascertain the extent and nature of the sediment and rock/reef substrate within the bay, diver surveys and grab-sample surveys (section 3.4) were undertaken.

Figure 4.5 Oblique aerial photograph of the shallows looking north, a wave can be seen breaking on Umzuwethu reef on the left of the picture, low scoured reef partially inundated in sand can be seen.

Figure 4.6 Oblique aerial photograph of coast and shallows near the small dunefield on Cape St Francis, shallows are rocky and large volumes of sand are found greater than 20m offshore.

Figure 4.7 Oblique aerial photograph of Port St Francis and close offshore, seabed is completely sandy, with no reef visible.

Spot dives were undertaken along the study site in depths of up to 4 m, during these surveys, the extents of Umzawethu and Anne Ave reefs were also recorded with GPS for the later high resolution bathymetric surveys described in section 3.2, dive sites and reef waypoints are shown in (Figure 4.8) below. This dive survey of the nearshore area confirmed the seabed types in the shallow sub-tidal area, with the obvious contrast between the shallow scoured low-profile reefs (Figure 4.9), the ‘fingers’ of sand between patch reef (Figure 4.10) and elevated reefs of Umzuwethu and Anne Ave (Figure 4.11).

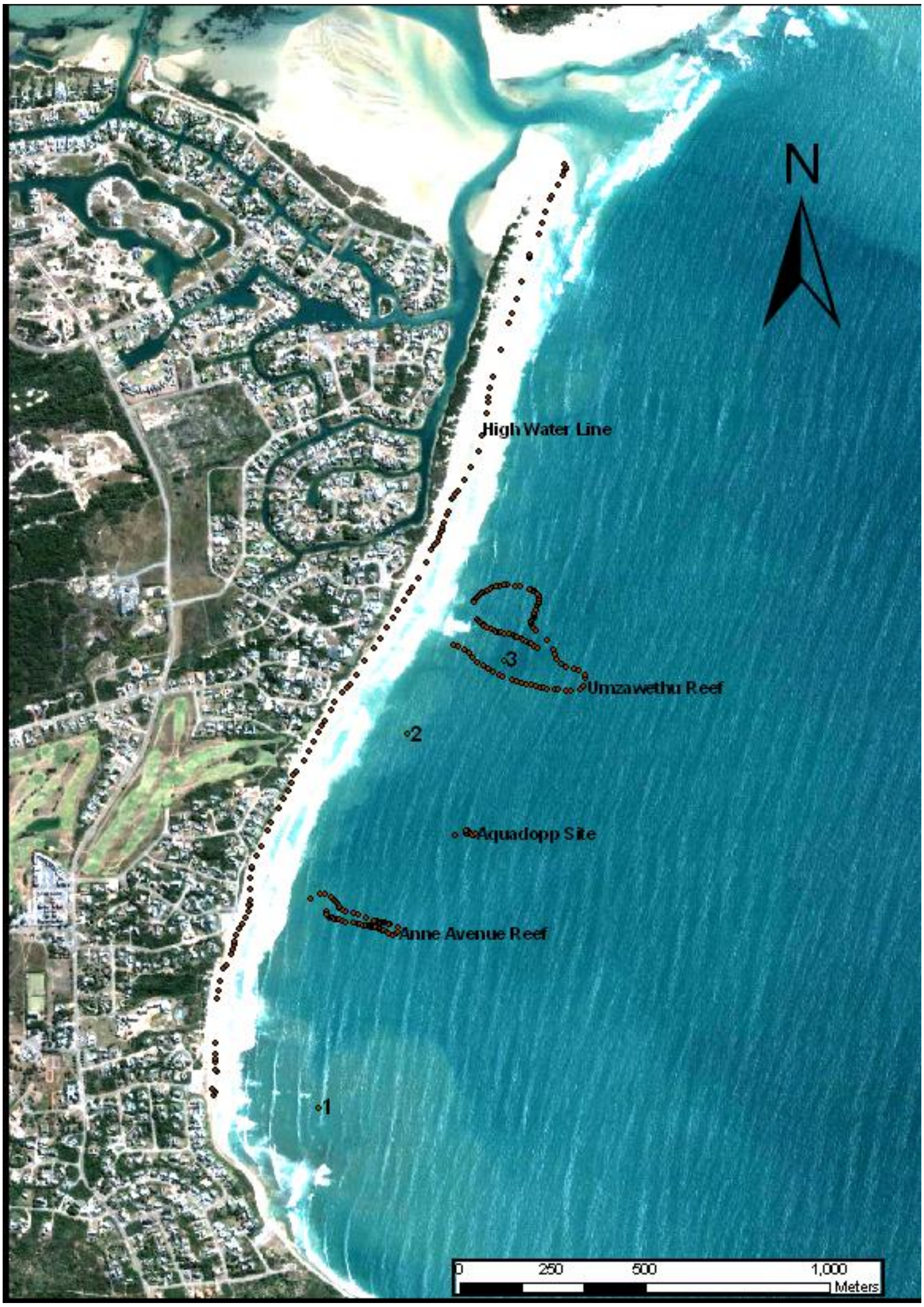


Figure 4.8 Locality map of St Francis Bay showing GPS measurements captured in February 2006 overlaid on an aerial photograph. Numbers 1-3 correspond to dive inspection sites, the positions of the Aquadopp wave/current meter, and the location of Anne and Umzuwethu Reefs is plotted, in addition the waypoints along the beach represent the position of the High Water Line.

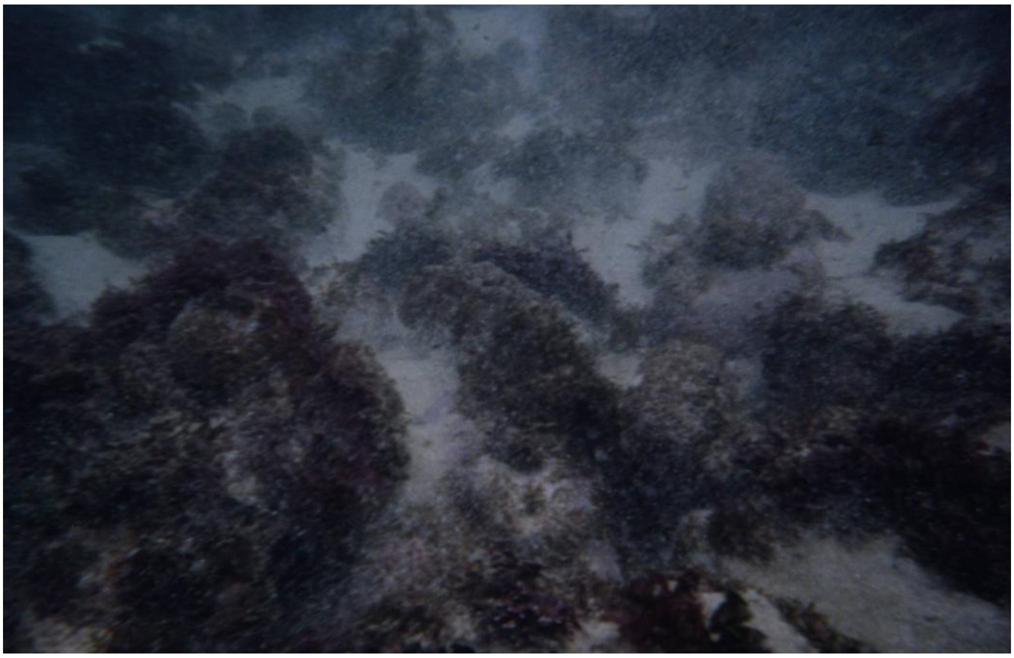


Figure 4.9 Turfing red algae on the low scoured reef at site 1 (Mead *et al*., 2006).

Figure 4.10 Sand patches in the shallow sub-tidal zone at site 2 (Mead *et al*., 2006).

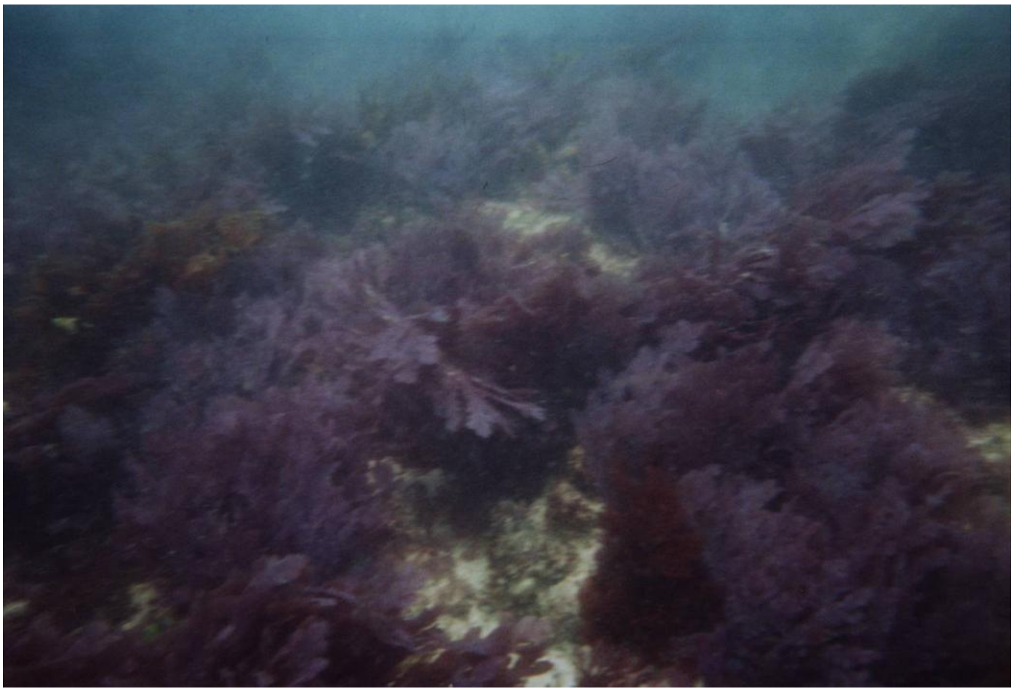


Figure 4.11 Large red algae on a prominent outcrop on Umzuwethu Reef at site 3 (Mead et al. 2006).

4.4 Beach Profiling

Beach profiling was carried out on a quarterly basis from 1991 until 2006 as discussed in section 2.9.1. The last set of profile measurements collected in this manner were conducted by the author in May 2006. Severe storms in September 2006 prompted the initiation of more detailed monthly beach surveys in October 2006. These surveys were conducted by land surveyors, Maarschalk and Partners using a Real Time Kinetic (RTK) Geographical Positioning System (GPS). This system makes use of a GPS receiver located at a known position which transmits satellite correction data to a roving receiver which can be carried by the surveyor or mounted on a vehicle, such as a quad bike, thus allowing continuous data collection on the move. This system allows high resolution data to be collected, which can then be used to create virtual surfaces from which volume changes can be calculated (see figure of RTK survey data). The beach was divided into four areas in order to identify possible longshore differences in erosion as represented in Figure 4.12 below.

Figure 4.12 Beach areas: 1) Corner to Anne Avenue, 2) Anne Avenue to Peter Crescent, 3) Peter Crescent to Aldabara run and 4) Aldabara run to the Kromme River mouth the sand spit/artificial barrier dune.

The volume changes were calculated on a monthly basis and are presented in Figure 4.13 below. Analysis of volume change calculations over the year between October 2006 and September 2007, indicate that the highest levels of erosion were experienced in area 4 and 2 during February and March 2007, over the full year both areas showed some recovery with the greatest loss from area 4 and a net loss for the whole beach of 40 000 m^3 of sand. This shows a different trend to the results of earlier aerial photographic analysis (WPR, 1993; Illenberger and Burkinshaw, 1997) which indicated that until the end of their analysis period (1993) the southern half of the beach had experienced the highest retreat (as discussed in section 2.9.1).

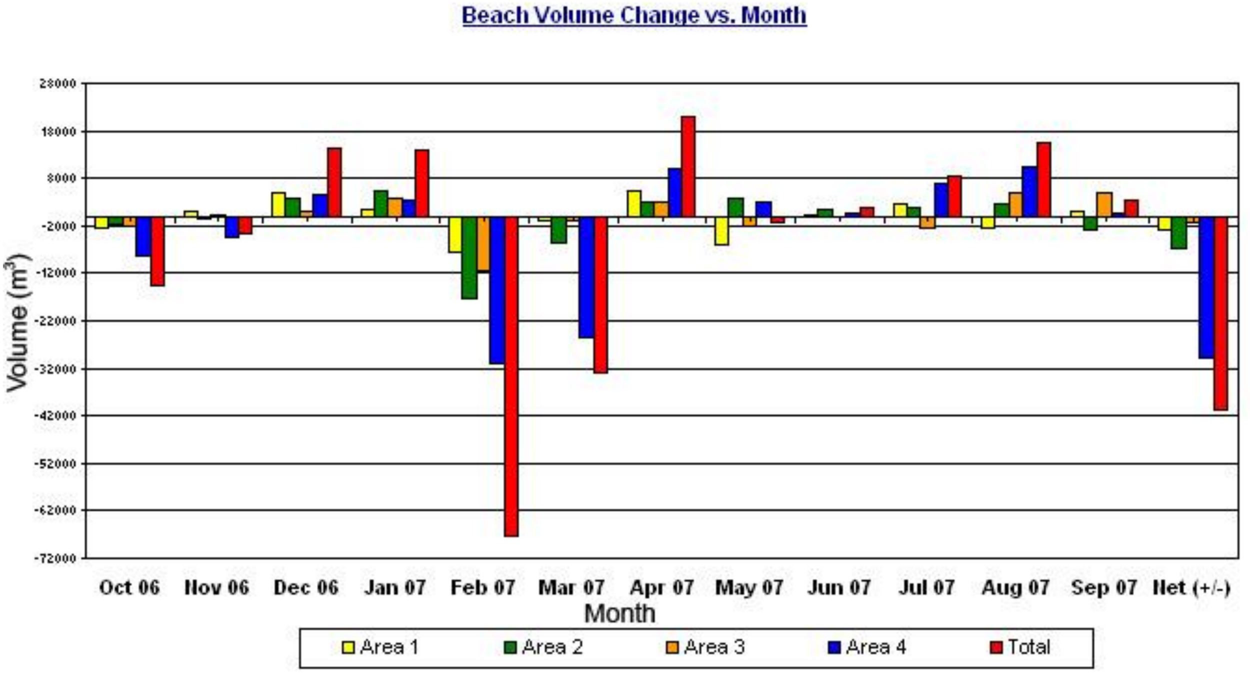


Figure 4.13 Monthly beach volume changes form October 2006 to September 2007, calculated from high resolution RTK GPS surveys which were initiated after the major erosive storm events of August and September 2006.

During the event of 18-20 March 2007 when strong onshore winds associated with a cut-off low off the coast of Kwa-Zulu Natal (Figure 4.14) led to large storm waves, which occurred in combination with unusually high equinox tides (Figure 4.15), these conditions resulted in massive erosion and destruction of coastal infrastructure on the Natal coast. The effects were also felt at St Francis Bay where large (max 4.8m) south easterly (+/- 135 degrees) long period (12 seconds) waves, resulted in acute erosion of St Francis Bay beach and damage to infrastructure. Worst affected areas were the unprotected area near Anne Avenue parking where erosion resulted in the undermining and collapse of a 40 m section of Ralph Road with the final erosion line reaching within metres of the property adjacent to the road (Figure 4.16). A substantial volume of sand was eroded from the section 4 along the barrier dune (Figure 4.17).

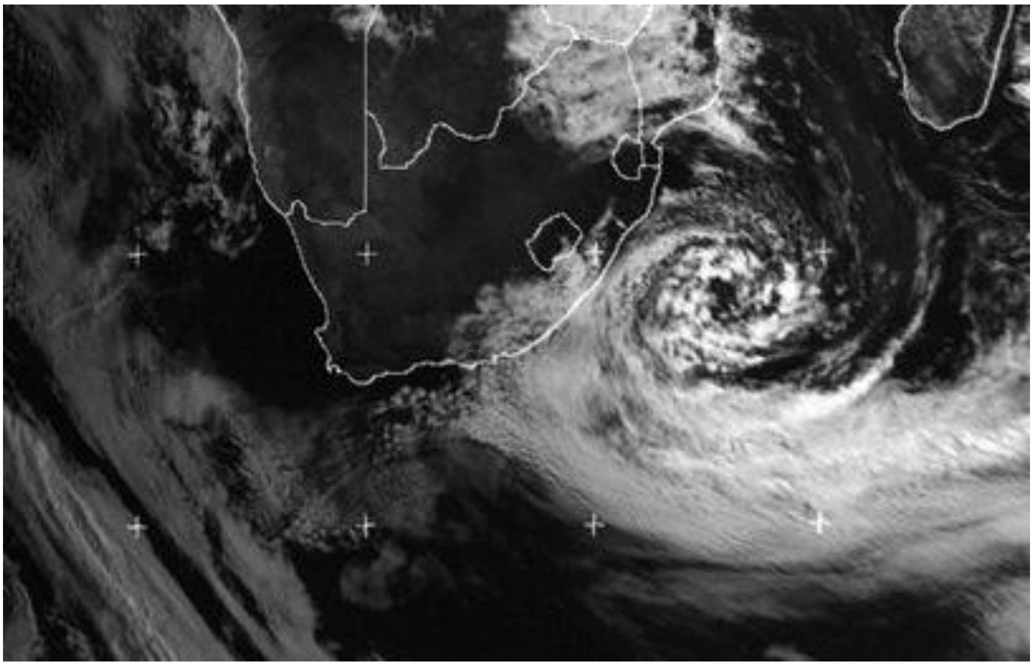


Figure 4.14 Satellite image from 19 March 2007, note the cut-off low situated off the east coast of South Africa, this feature was responsible for strong easterly winds which generated large easterly waves and storm surge.

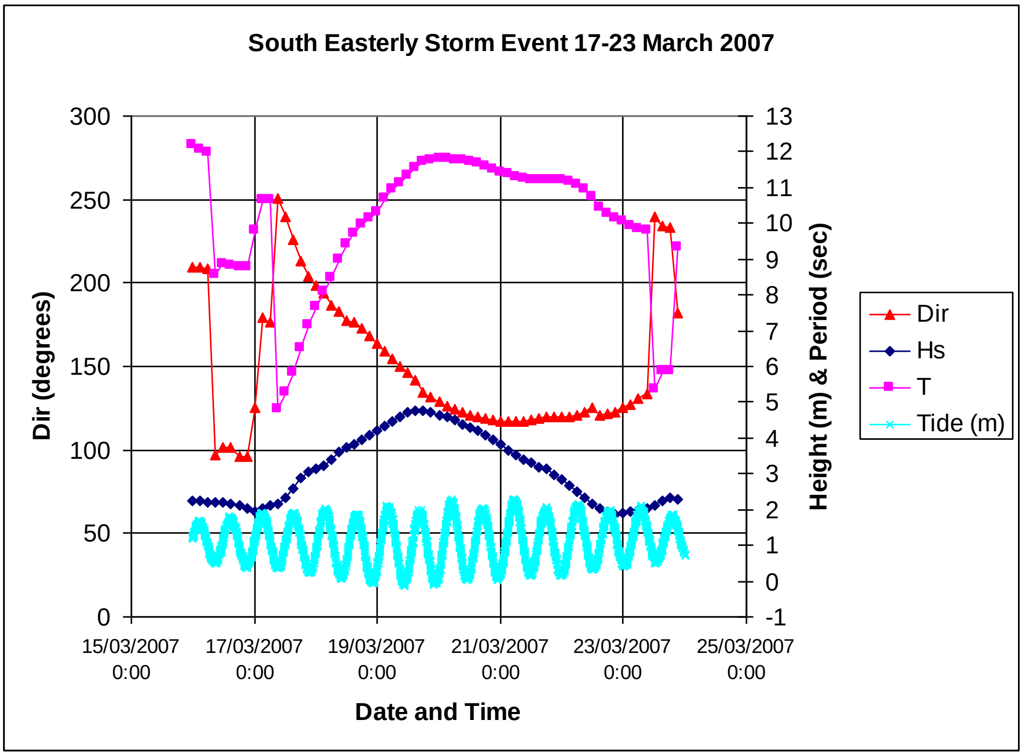


Figure 4.15 Offshore wave record (WW3): direction (dir), significant wave height (Hs) and period (T) and tidal levels from Port Elizabeth Harbour, for the period 16 - 24 March 2007.

Figure 4.16 photograph taken at 10 am, 20 March 2007, a 40 m section of Ralph road was totally undermined and erosion cam with 2m of the property behind (Picture by Author).

Figure 4.17 photograph taken 10:30 am, 20 March 2007, large volumes of sediment were eroded from the dune areas along the artificial barrier dune, this storm exposed an old line of revetment which had sunk and been buried (picture by the author).

4.5 Sediment Survey

Sediment samples were collected from the offshore seabed, beach and estuary (139 in total) during March 2006 (Figure 4.18). Sub-tidal samples were collected at +/- 1m depth increments offshore using a Ponar© grab sampler. Beach surface samples were collected along 5 transects at 4 positions along the beach profile, namely: the base of the dune; high water line; mid water and swash zone. Surface samples were also taken from the large Flood Tidal Delta in the Kromme Estuary mouth area.

Samples were then processed in the laboratory in preparation for grain size analysis using a settling column. Firstly a small portion of each sample was wet sieved using a 63 micron sieve to remove the silt fraction. This silt fraction was then determined via the pipette method, proving to be negligible, amounting to <1% of the total mass of any sample. The remaining sand fraction was then dried, before being sieved to remove all fragments and sand grains > 2 mm (<-1 phi). The remainder of the sample was then analysed in a settling column to determine the grain size distribution. The mean grain size distribution, expressed as phi_{50} as they were found throughout the Bay, is presented in Figure 4.19. Out of the 100 samples within the Bay (excluding those adjacent to the headland), 26% were found to be reef, this is a higher percentage of reef than previously estimated from aerial photographs (i.e. 15%). It can be seen that the beach sand and sand in the shallow sub-tidal areas (<3 m depth) is mostly of a similar grain size classified as fine sand according to the Wentworth Scale, found all down the headland and along the beach. However in regions of relatively deep nearshore bathymetry either side of Umzawethu reef, very fine sand is present (Phi >3), while offshore of Umzawethu reef relatively coarser medium sand is present in a large lobe (Phi < 2). The local bathymetry is likely to be influencing this distribution of sediment, with finer sediments accumulating in the deeper areas adjacent to Umzawethu reef. Samples collected at the surface of the Flood Tidal Delta inside the estuary mouth are identified as fine sand (Phi_{D50} = 2.053) very similar to the beach (Phi_{D50} = 2.015) and offshore (Phi_{D50} = 2.186) thus confirming the marine origin of the sand in the lower estuary as previously discussed in Chapter 2 (Reddering and Esterhuysen, 1983)

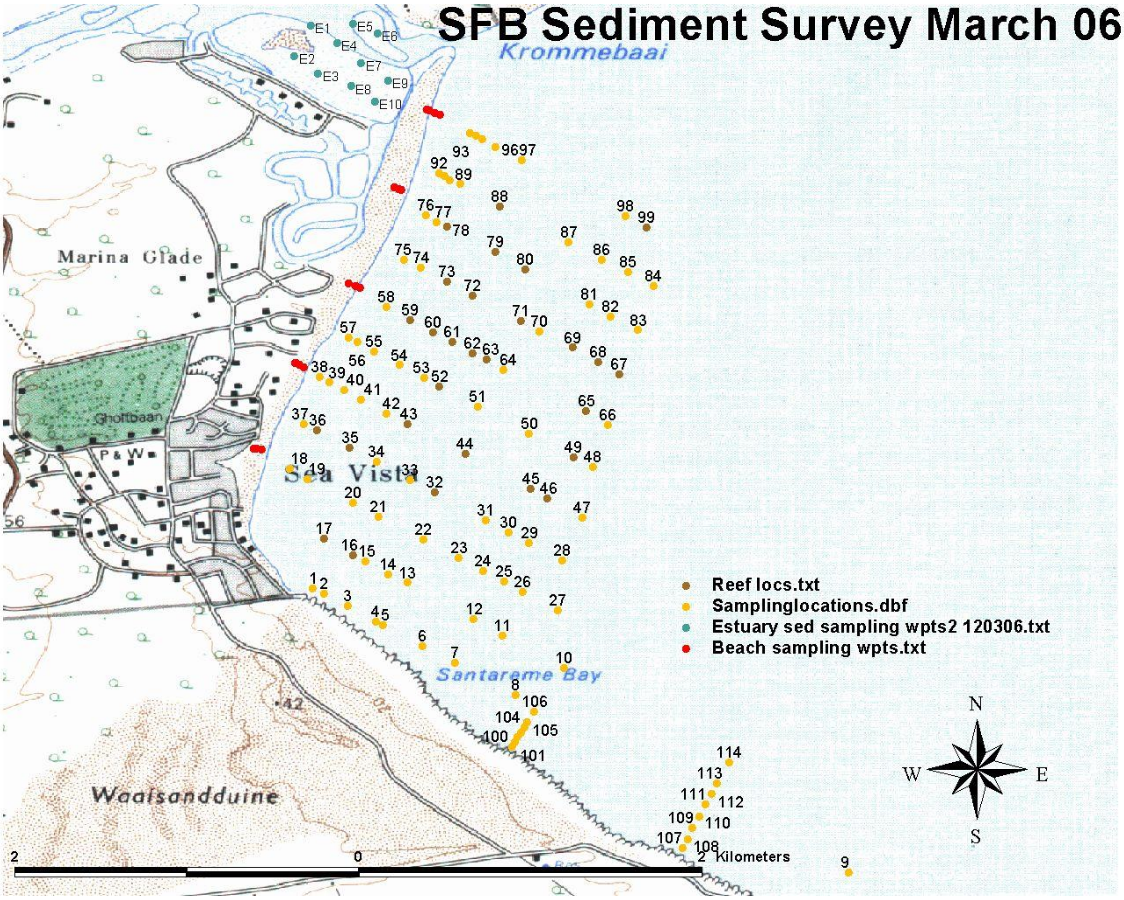


Figure 4.18 Locality map of sediment samples collected in St Francis Bay.

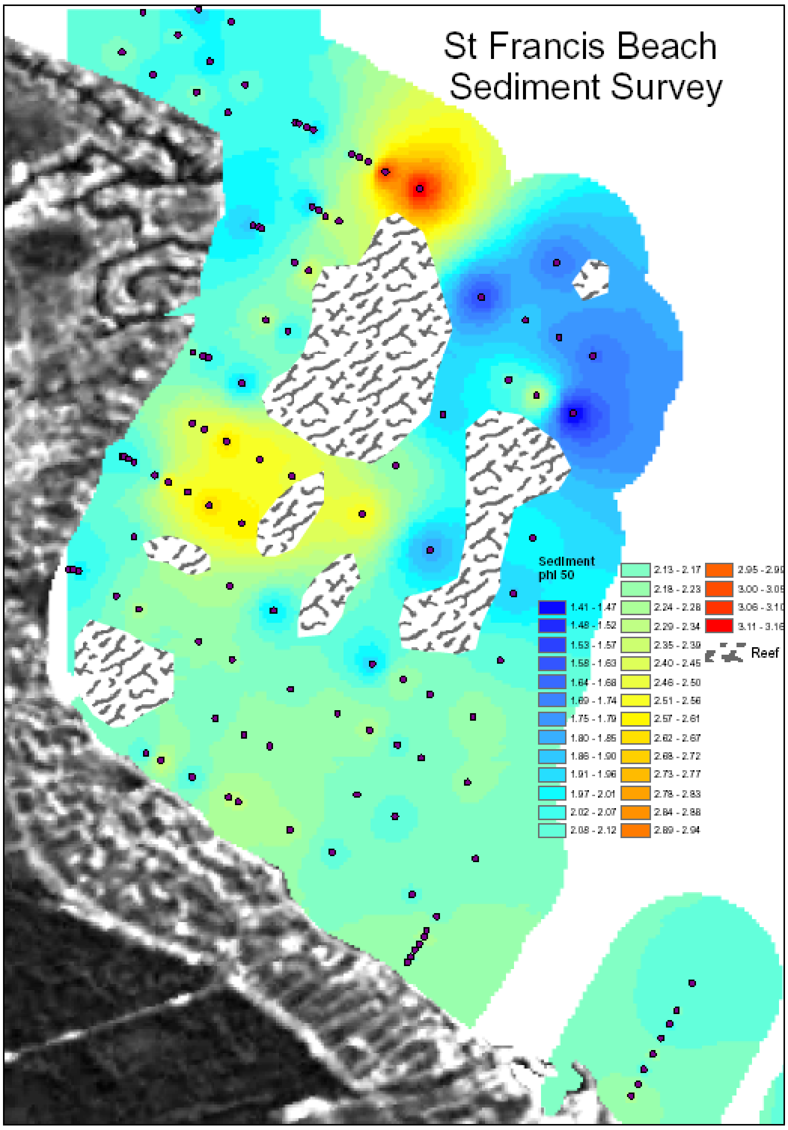
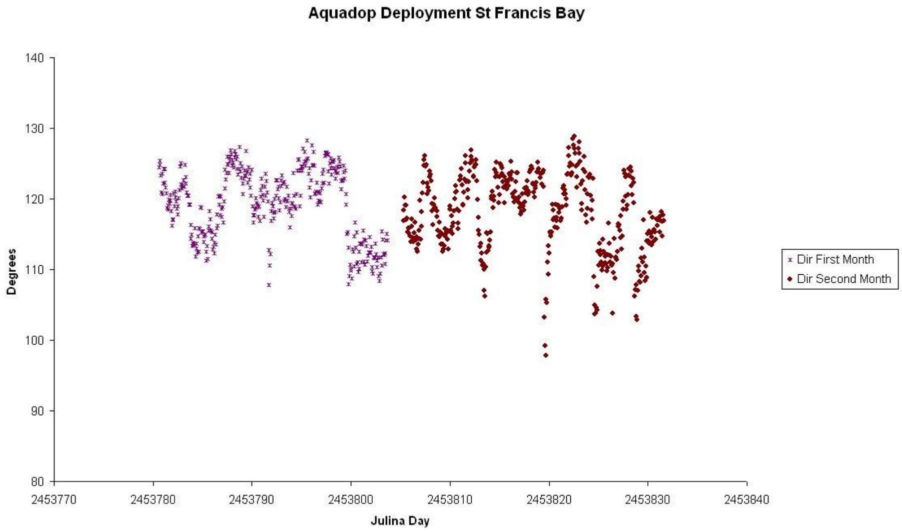


Figure 4.19 Contour plot of sediment grain sizes in St Francis Bay (Mead et al., 2006). The mean sand grain diameter in millimetres is calculated by 2^{-phi}

4.6 Waves and Currents

On 9 February 2006, an Aquadopp wave/current meter was deployed in 6.5 m depth of water. The instrument was programmed to collect wave data every 90 minutes (17 min bursts) and current data every 30 minutes. Servicing and data retrieval were conducted by the author every 4 weeks for a total period of three months. These data were processed and used to determine local wave conditions and to calibrate numerical models (described in more detail in the following chapter). Here results of the first two deployment periods are presented and compared to the offshore wave data during the period of the deployment.



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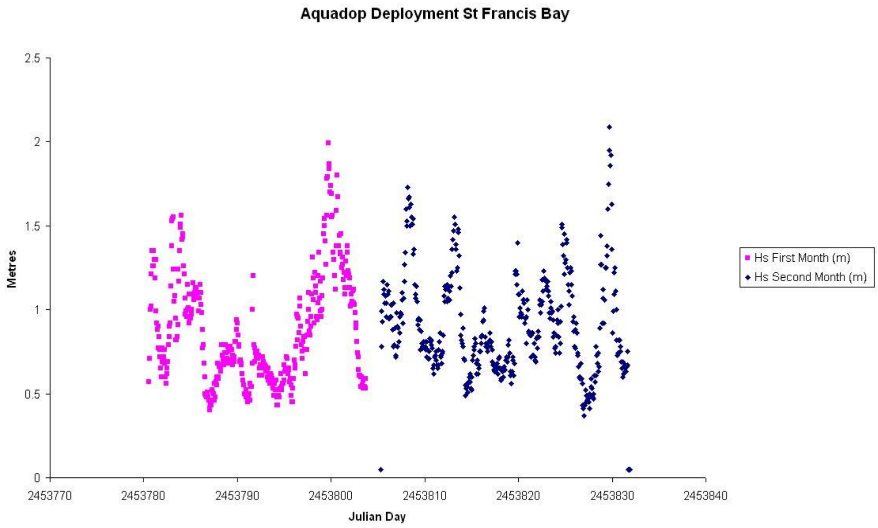

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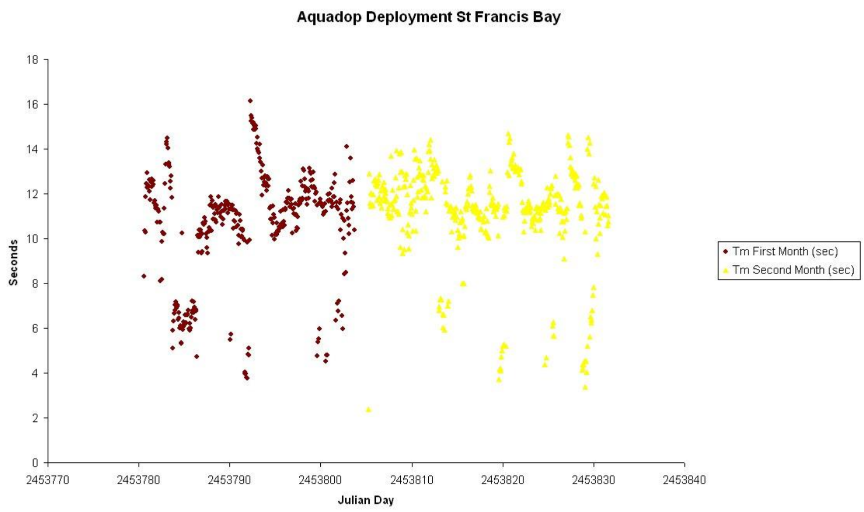


C

Figure 4.20 Wave data for St Francis Bay from 9 February to 5 April 2006 – A) Direction, B) Height and C) Period (Mead *et al.* 2006).

Figure 4.20 plots wave direction (ºTrue), height (m) and period (sec) recorded during the instrument deployment. The data show wave heights averaged 0.89 m during the deployment. Two events during the period had significant wave heights of ~2 m. Wave directions varied about a mean of 119° with a directional spread of 32° (97-129°). Periods averaged 11 sec, with a range of 3 to 16 sec. Location of Aquadopp wave/current meter and summarized wave directions are shown in Figure 4.21.

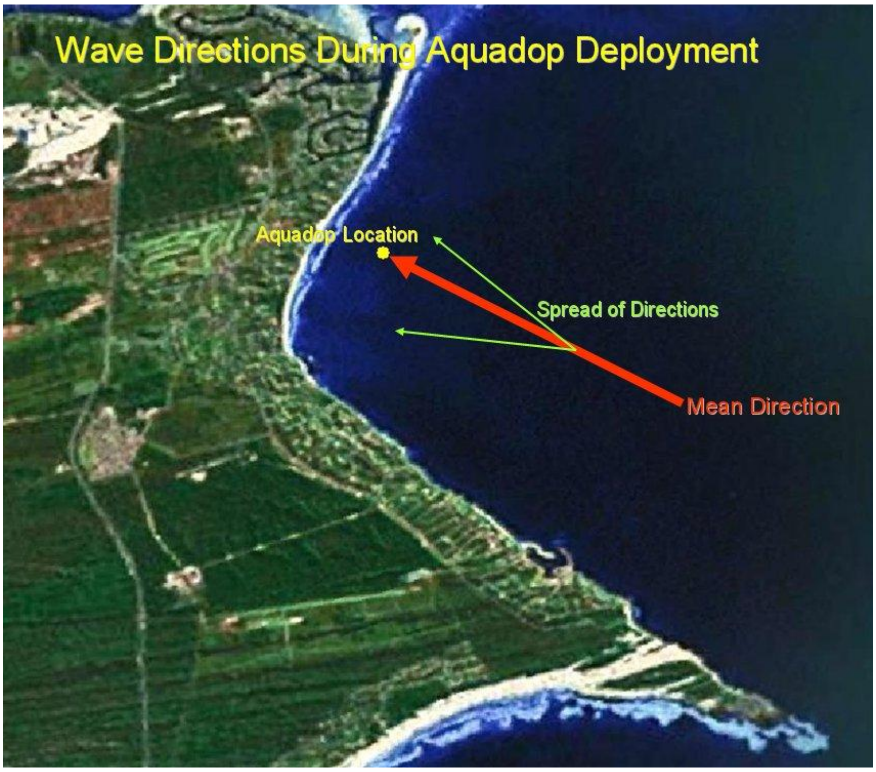


Figure 4.21 Summary diagram for wave directions at St Francis Bay from 9 February to 5 April 2006 (Mead *et al*., 2006).

The data suggest that at the instrument site, the direction of wave approach would favour sediment transport to the south west along St Francis Bay beach, i.e. into the southwest corner of the Bay. This is counter intuitive, since the dominant wind and waves originate from the southwest, and would be expected to drive sediment to the north and east as seen along the majority of this coast. However, numerical modelling supports the data collected by the instrument. Figure 4.22 shows wave crests from a large southwest swell being diffracted around Cape St Francis and rotated to a more westerly orientation to the southwest of Umzawethu reef. In addition, easterly wave events dominate St Francis Bay (see Figure 4.28) due to the shelter of the Cape from the large south-westerly waves and strong winds (Mead *et al*. 2006).

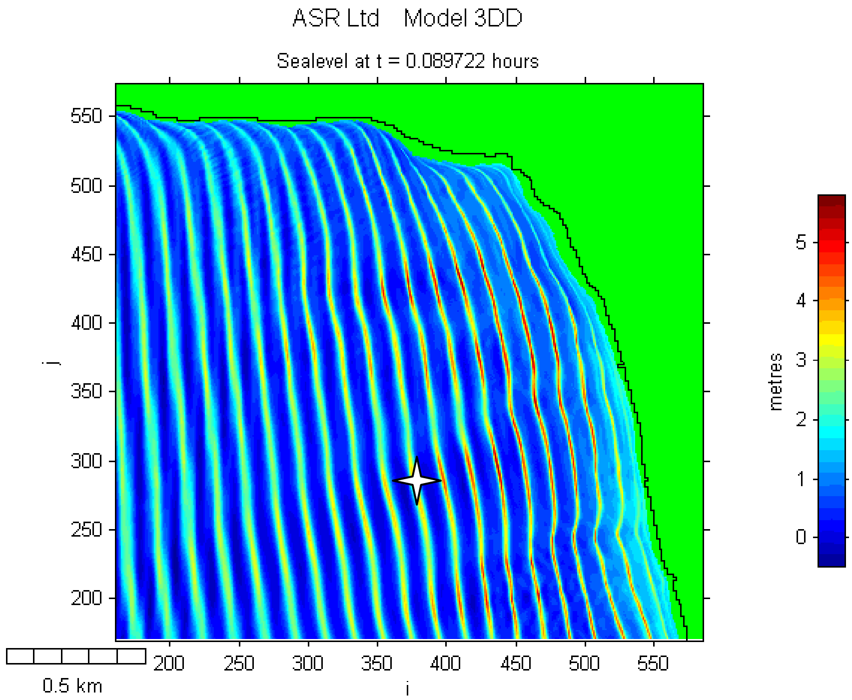


Figure 4.22 Boussinesq model output showing a large offshore SW wave event in St Francis Bay – the star indicates the position of the Aquadopp. Note that offshore wave directions are west of the beach orientation in this location – the grid has been rotated 135° for modelling purposes (Mead et al. 2006).

The main trend in the data (Figure 4.20) is larger wave events have an east south east direction (i.e. 100-110°) and have short periods (i.e. 3-8 sec). Large, short period waves (defined as steep waves in oceanographic terms) are generated by local winds and tend to erode beaches by moving sand to deeper water (as discussed in chapter 2). When the winds for the deployment period are considered (Figure 4.23) it can be seen that strong winds from the easterly quarter dominated, creating the wave events with relatively higher wave heights and shorter periods – this is typical for this period of the year. In comparison, the long-term Wave Watch 3 (WW3) hindcast wind data show a predominance of south westerly winds (Figure 4.24).

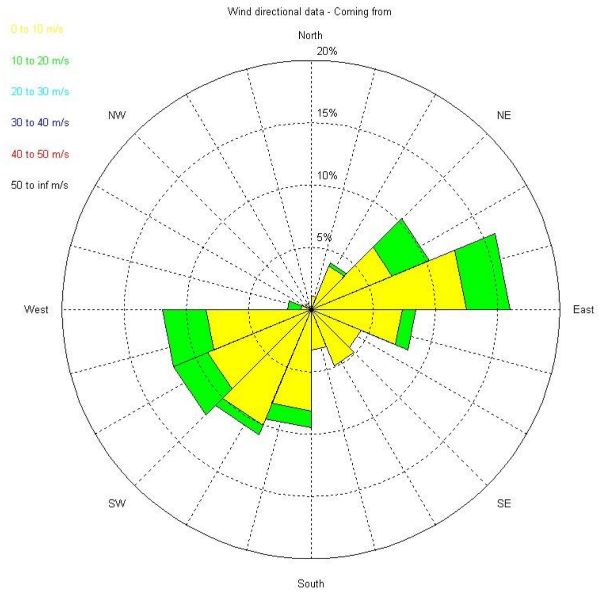


Figure 4.23 Wind rose of speed, direction and occurrence during the Aquadopp deployment (WW3) (Mead *et al.,* 2006).

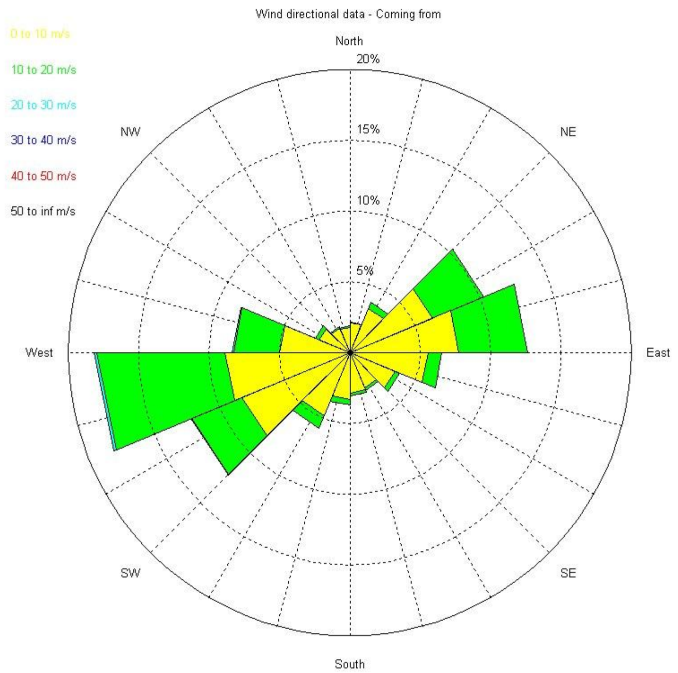


Figure 4.24 Wind rose of speed, direction and occurrence from 1997 to 2006 for offshore Cape St Francis (WW3) (Mead *et al*., 2006).

Figure 4.25 presents a wave 'rose' of the wave heights, which shows the directions and percentage occurrence measured by the Aquadopp. When compared to the wave rose for the offshore WW3 wave data during the same period (Figure 4.26) the large directional change due to refraction of waves around the Cape is obvious. When compared to the offshore wave data from February 1997 April 2006 (Figure 4.27), it can be seen that the deployment period was fairly representative of the long-term wave conditions, although the large events of the winter months are not present (Mead *et al*. 2006).

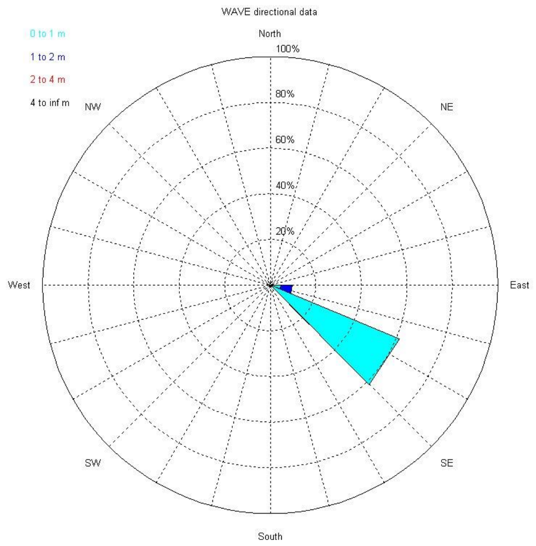


Figure 4.25 Wave rose from measured Aquadopp data for St Francis Bay from 09 February to 5 April 2006 (Mead *et al.*, 2006).

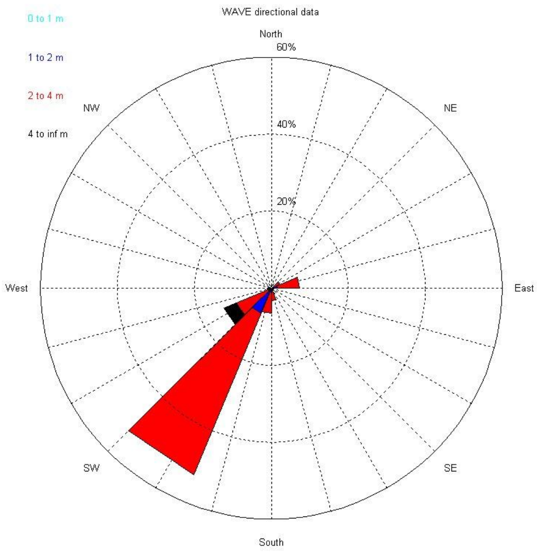


Figure 4.26 Wave rose for the offshore deepwater wave statistics from 09 February to 5 April 2006 (Mead *et al*., 2006).

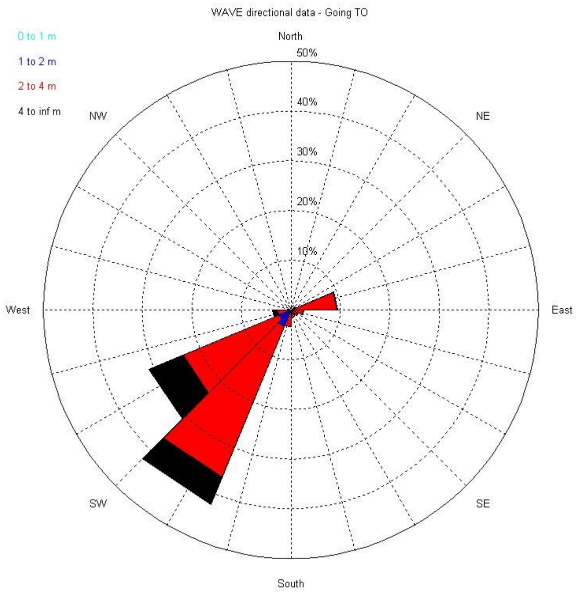


Figure 4.27 Wave rose for the offshore deepwater wave statistics from 1 February 1997 to 30 April 2006 (Mead *et al*., 2006).

While fairly complicated, Figure 4.28 from Mead *et al.* (2006) provides a useful comparison between the offshore wave data and the inshore Aquadopp data that shows the sheltering and rotational effect of Cape St Francis. This Figure demonstrates the dominance of the locally generated easterly seas, with even very large westerly events showing low wave heights in St Francis Bay. The implications of the wave data recorded in St Francis Bay are that this beach is subject to frequent erosive events from the easterly quarter. Current speeds and directions at the Aquadopp site are presented in Figure 4.29 and are dominated by wave driven currents, i.e. height currents correspond to high wave events.

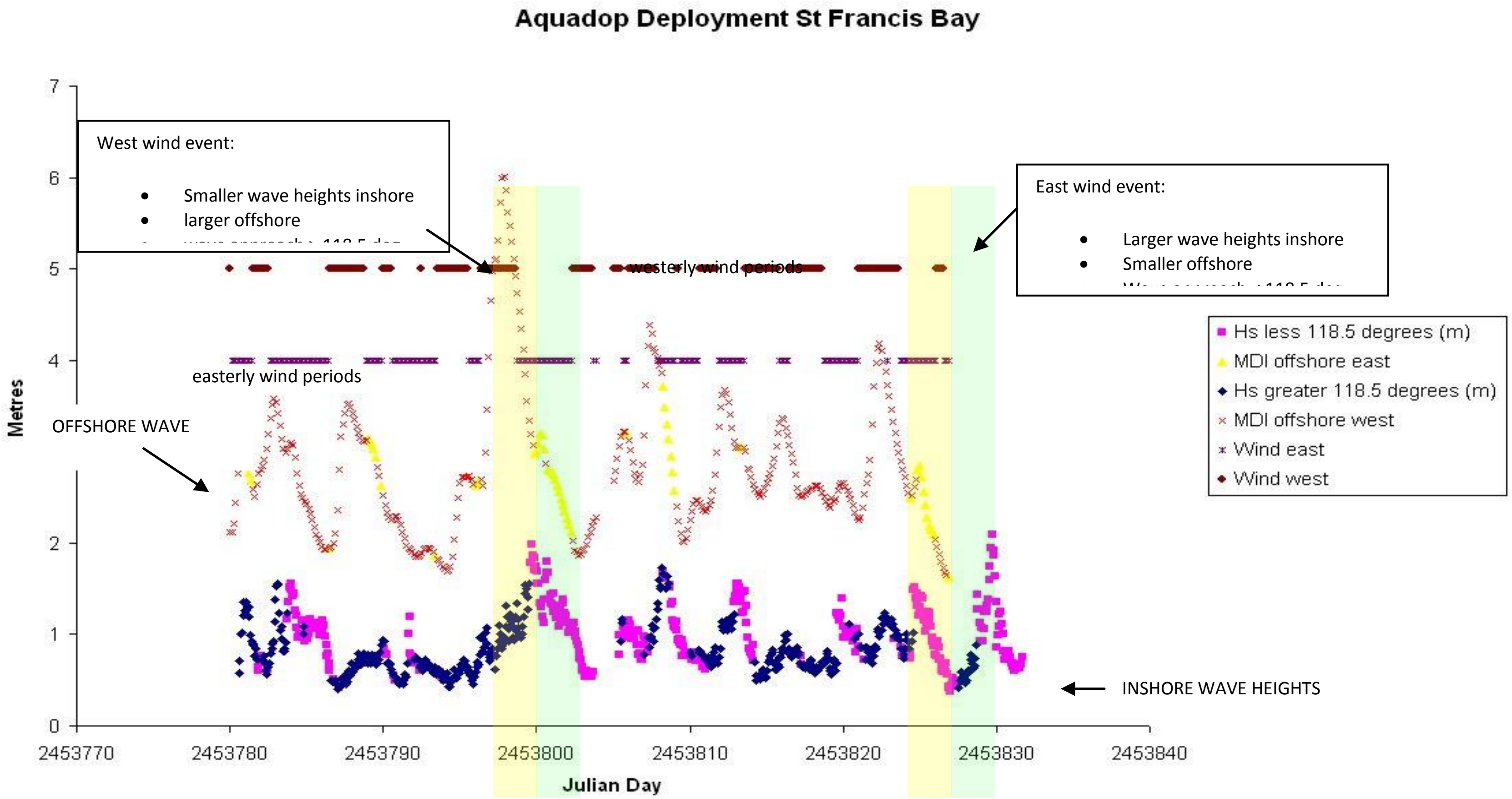


Figure 4.28 A comparison of the offshore wave data and Aquadopp data showing the different heights and directions and wind directions. The straight lines at 4 and 5 m height are not wave heights but wind directions, with the higher line representing west winds and the lower east winds. The two wave height lines represent the MDI offshore data (highest) and the inshore data recorded by the Aquadopp (lower). These wave height data lines are also colour coded to indicate the direction that the waves were coming from. It can be seen that the higher wave events at St Francis Bay occur during easterly wind conditions, even though these events are relative small offshore (green box examples), and that when waves are large from the west offshore, they are relatively small in St Francis Bay (yellow box examples) (Mead *et al.*, 2006).

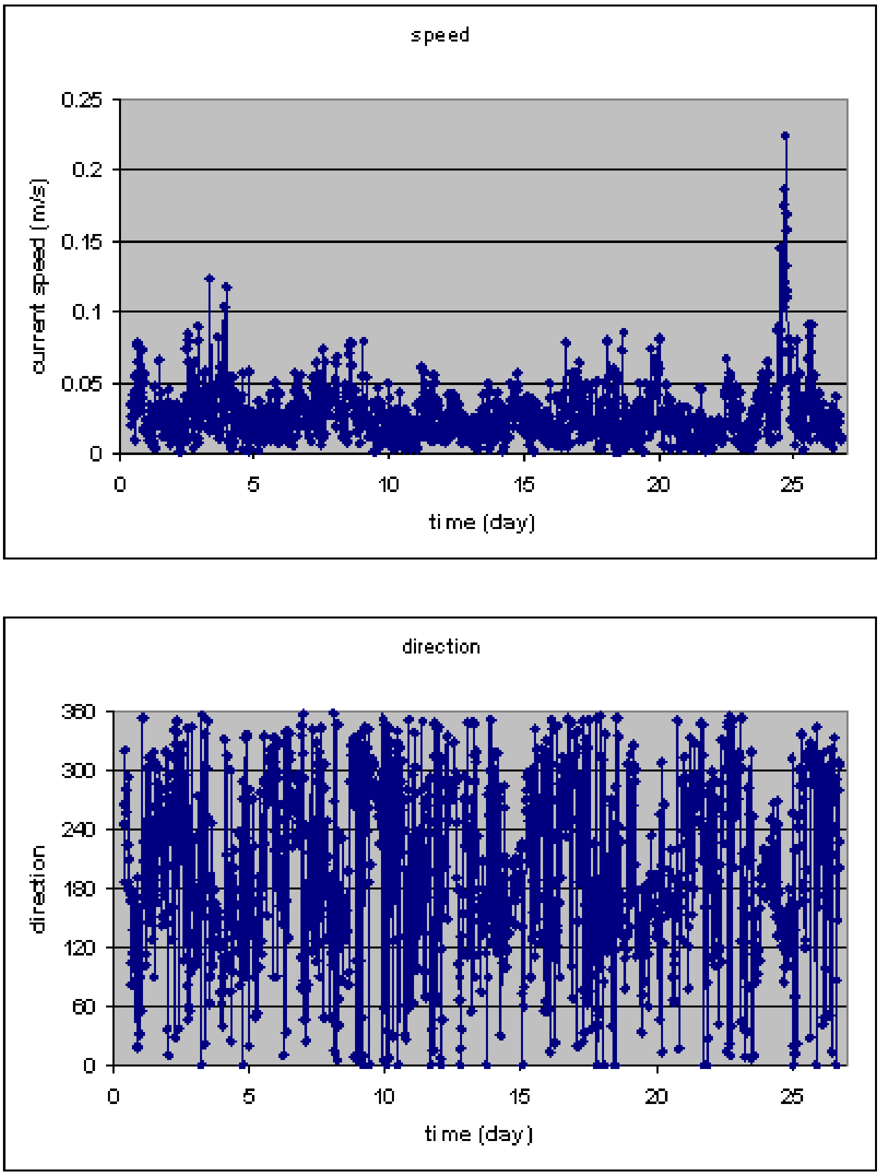


Figure 4.29 Current speed and direction during the Aquadopp deployment (Mead *et al*., 2006).

4.7 Discussion

The investigations and data collected during the field work have increased the knowledge and understanding of St Francis Bay and provided valuable information for confident numerical modelling. Fieldwork included: detailed bathymetric surveys; helicopter and dive surveys; RTK GPS beach surveys; sediment sampling and measurement of waves and currents.

Comparison of recent (2005/2006) and old (1952) bathymetry data for St Francis Bay indicates that the most dramatic losses have occurred in the deeper areas 10-15m water depth. However, the inshore areas (+/-5 m depth) have remained relatively stable. This result may seem strange, however site investigations, including aerial photographic analysis, a helicopter survey and a dive survey, indicate the presence of low profile reef substrate in this shallower depth range through much of the bay. Thus it is proposed that while the offshore deepening would normally lead to increased wave energy and erosion of the inshore, the inshore area cannot be eroded due to the fact that the existing beach is perched on top of this rock shelf. In terms of the construction of offshore coastal protection structures this rocky substrate and shallow nature of the inshore area is advantageous, providing a solid foundation and reducing structure volume respectively. Large bathymetric features identified include Umzuwethu reef which dominates the central area of the beach out to +/- 8m water depth and the deeper ancient Kromme river course offshore of the present Kromme Estuary mouth, extensive shallow reef is found on the northern side of the Kromme Estuary mouth.

Considering it has been calculated that 90 000 m^3 of sediment used to be blown into the bay from the Santareme dunefield prior to stabilization (McLachlan et al., 1994), as a rough estimate one could be expect that the bay could have deepened by 90 000 m^3 per year since stabilization, this would result in a loss of roughly 2.7×10^6 m^3 over 30 years since stabilization. In order to quantify the deepening of the bay, volume calculations were conducted between the surfaces created from the 2005/2006 and 1952 bathymetric survey data sets, these calculations were conducted using an overlapping area of 10,6 X 10^6 m^3, covering roughly the area between 2m to 15m water depth (CD), where sufficient data was present for each survey. The calculated volume change over the area discussed above was 8.8 X10^6 m^3; this is somewhat higher than expected. However considering the long period between surveys (53 years) and the difference in survey methods and resolutions this volume is within an acceptable range. Reduced sediment supply has led to similar erosion of the offshore areas in other locations internationally. For example in Napier, New Zealand, some 1.4 mln m^3 of sand was eroded to depths of 18m over a 28 year period due to the construction of a breakwater port (Mead *et al*. 2001), while some 80 mln m^3 of sand was calculated to have been eroded from Stockton Bight in Australia over a 100-year period due to construction of estuary mouth training walls (Umwelt Ltd. 2001 – cited by Black and Swilinkels 2001 in Mead *et al*., 2006). In both cases beach erosion is evident, with losses in the order of 2.3 mln m^3 from Stockton Beach.

Dive investigations, aerial photographic analysis and a helicopter survey confirmed that three main substrate types are found within St Francis Bay, with the dominant type being sand, and to a lesser extent low-profile scoured reef such as Anne Avenue and Huletts Reef with a dominant elevated reef area found in the middle of the beach, known as 'Umzuwethu'. This is the surface protruding expression of a large feature which dominates the bathymetry of St Francis Bay beach.

Monthly RTK GPS surveys of the beach down to ~0.5 below MSL indicate significant erosion events and partial recovery during calm periods with a net loss of 40 000 m^3 over a one year period, from October 2008 to September 2007. The greatest loss was experienced along the northern sand spit/artificial barrier dune section adjacent to the mouth of the Kromme Estuary. This scenario differs to the results of earlier aerial photographic analysis (Illenberger and Burkinshaw, 1997), discussed in Chapter 2, when the southern part of the beach exhibited the greatest erosion over the period between 1975 and 1993, with a measured retreat of some 40 - 60m along the southern half of the beach with no retreat measured on the northern half of the beach (Illenberger and Burkinshaw, 1997).

An extensive sediment sampling survey of the beach, offshore and estuary flood tidal delta and subsequent grain size analysis indicated a fairly consistent grain size, generally falling in the fine to medium sand class according to the Wentworth Scale (Dean and Dalrymple, 2002). Some exceptions were found such as finer sand found adjacent to the large reef feature in the middle of the beach known as "Umzuwethu" especially in the deeper water to the north offshore of the Kromme River mouth. A lobe of coarser sediment was found offshore of this same reef feature to the north. Similar sediment distributions have been found around the sediment limited nearshore rocky reefs on New Zealand's Taranaki coast (McComb et al., 2000).

Deployment of an Aquadopp wave and current meter at 6.5m water depth roughly 400m offshore of St Francis Bay beach, provided valuable information and quantification of the wave and current condition inshore of St Francis Bay. Analysis of wave data (Mead et al., 2006) showed a mean wave height of 0.89 m, a mean direction of 119° and a mean period of 11 seconds during the months of February and March 2006.

While the majority of the South African Coast is exposed to the predominant south westerly winds and waves (Rossouw, 1989 in Entech, 2002a) St Francis Bay's orientation means that the predominant long period waves from a south westerly direction undergo a great degree of refraction and diffraction around the Cape St Francis headland greatly reducing the wave height experienced at St Francis Bay beach during these wave conditions. However this orientation allows a direct approach of waves from a south easterly to easterly direction. This means that moderate sized waves from an offshore south westerly direction result in small waves at St Francis Bay beach, while moderate offshore waves from a south easterly to easterly direction result in relatively large waves at St Francis Bay beach. In addition waves from the south east to easterly direction are mainly locally generated and therefore have shorter wave periods; therefore these 'steep' waves are most likely to lead to increased cross shore erosion.

5 EXISTING PHYSICAL PROCESSES IN ST FRANCIS BAY

5.1 Introduction

On open beaches, sediments are most commonly transported by wave energy and the resultant currents. In order to design an effective coastal protection structure that performs the required functions, a good understanding of the inshore wave climate and existing physical processes is required. Understanding the range and frequency of wave sizes, directions and periods at the site is critical to define reef design parameters such as orientation, size, gradient, width and crest level. In particular, accurate wave climate estimates help to ensure that the desired beach response can be achieved with minimized construction volumes (Mead *et al.*, 2006).

This chapter provides a summary of the numerical modelling investigations conducted as part of the feasibility study (Mead *et al.*, 2006) before presenting subsequent detailed hydrodynamic modelling conducted by the author.

As demonstrated by the analysis of the wave data collected off St Francis Bay Beach presented in section 4.6, the site is very sheltered from the predominant south westerly quarter waves, with waves from this direction reducing to less than a third of their offshore wave height. Along with the wide white sandy beaches, the smaller, ‘calmer’, conditions of St Francis Bay are no doubt one of the qualities that first attracted people to this part of the coast. In the first part of this chapter the outcomes of modelling conducted by (Mead *et al.*, 2006) are presented briefly. These investigations included calibrated modelling to transform the long-term offshore wave data into the study site using the 3DD numerical models WBEND and Boussinesq. The calibrated models and inshore wave climate were then used to briefly investigate existing hydrodynamics. In addition, preliminary sediment transport and wind driven current modelling was carried out. The remainder of the chapter presents further numerical modelling conducted by the author to investigate the dynamics and physical processes in more detail. This work included calibrated numerical modelling to transform the long term offshore wave data to the inshore of St Francis Bay using the numerical model SWAN. The inshore wave climate was then used as input conditions for further assessment of the hydrodynamics using the numerical model 2DBEACH (Black and Rosenberg, 1992a&b).

5.2 Long Term Wave Data

Long-term wave data was extracted from ASR's MDI (Metocean Data Interface). The MDI contains world-wide wave and wind data dating back to 15th February 1997. The significant wave heights, peak frequencies and peak directions were extracted at three hourly intervals from the NOAA WW3 wave model hind-cast and archived in the system. The WaveWatch3 (WW3) wave model is the world standard, third generation ocean wave propagation model. WW3 solves the spectral action density balance equation for wave number-direction spectra (Jensen, 2002). The model domain is the entire globe between 78°N and 78°S with grid points spaced at 1° latitude and 1.25° longitude.

The wind fields used to drive the WW3 wave generation come from the NOAA Global Forecast System (GFS), which combines data assimilation and a forecasting model – these data are also uploaded into the ASR MDI every month. The near surface wind field was converted to 10 m wind speed over the WW3 grid. The WW3 hindcasts were run with the archived (historical) wind fields. Wind data is also provided in three hourly bins and can be extracted on a grid of regularly spaced points of wind velocity components.

5.3 Transformation Modelling

Wave data were transformed from the offshore hind-cast site using a combination of numerical models WBEND and the Boussinesq component of 3DD as detailed in Mead *et al*., (2006) extraction sites are shown in Figure 5.1 below. The WWIII offshore hind-cast wave data from site (A) for the Aquadopp deployment period was modelled to the inshore, data was extracted at site (B) in 24m of water depth offshore of St Francis Bay and used as input into Boussinesq wave model, which was calibrated using the Aquadopp data. Thereafter this calibrated set of numerical models was used to transform the long-term offshore wave climate to the inshore of St Francis Bay.

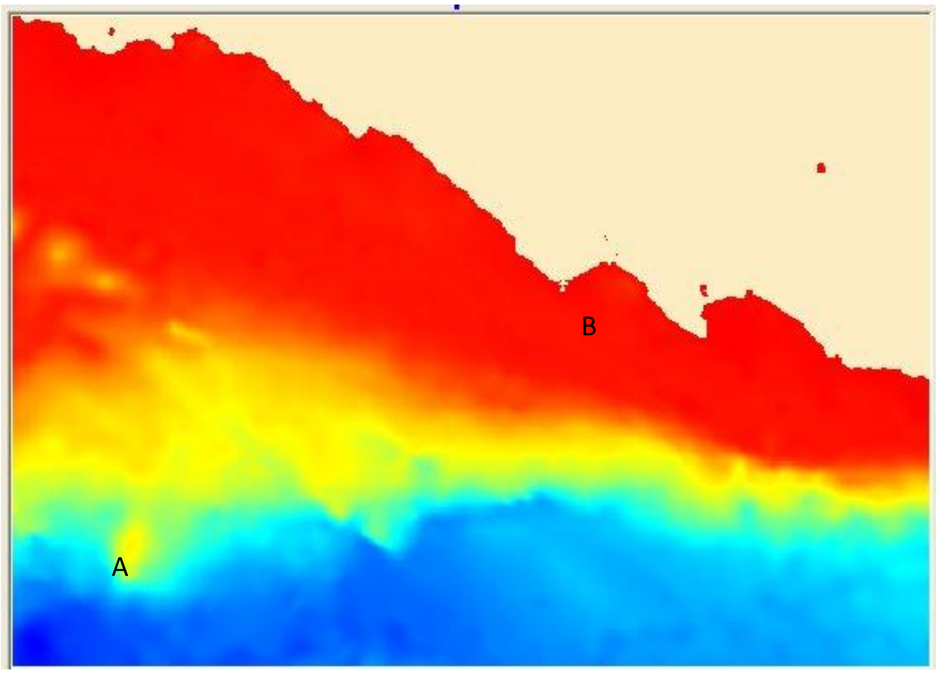


Figure 5.1 Large (1000 m by 1000 m cell size) numerical model grid developed from the full set of bathymetric data (rotated 30º for modelling purposes). A) Offshore WW3 hindcast site used for WBEND modelling and B) inshore extraction site used for Boussinesq modelling (Mead *et al*., 2006).

5.4 Alongshore Sediment Transport Estimates

Using the inshore wave climate Mead *et al.* (2006) conducted basic sediment transport modelling; in addition wind-driven current modelling was conducted.

5.4.1 Wave-Driven Sediment Transport

As described in chapter 2, previous studies indicate wave driven sediment transport direction is variable along the St Francis Bay beach. The model GENIUS was used to consider the wave-driven sediment transport along St Francis Bay Beach. This did not incorporate wind-driven currents, which were considered later and appear to have a large influence on sand transport in the bay. It was clearly noted that the results are general implications of the sediment transport regime, rather than exact quantities of sediment transported (Mead *et al.*, 2006).

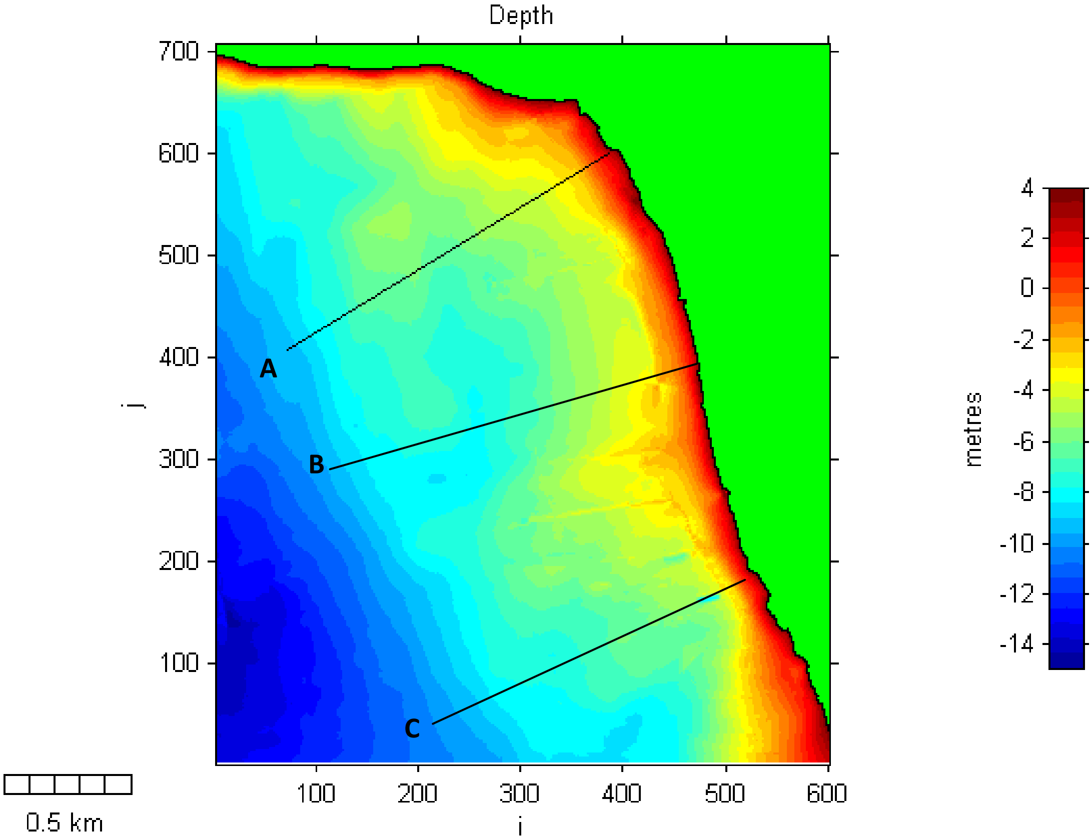


Figure 5.2 Location plot of the GENUIS transects used for sediment transport simulation (note the bathymetry is rotated 135º for modelling purposes (Mead *et al*., 2006).

The steps undertaken for the development of the boundary conditions for GENIUS from the available wave data are described in section Mead et al. (2006). Outputs were based on the alignment of bathymetry contours, and taken normal to these. The modelling profiles were generated from a 2 m by 2 m grid cell bathymetry of St Francis Bay for the GENUIS sediment transport simulation (Figure 5.2). Profiles extend offshore to depths of 9-10 m to account for alongshore sediment transport out beyond the 'depth of closure' (~7 m). The results of the first simulation (A) were:

71,833 m^3/yr (south westerly directed)
-29 m^3/yr (north easterly directed)

That is, a <u>net wave-driven sediment transport of 71,804 m^3/yr to the south west</u> (in towards the corner of the beach). This result is counter-intuitive at first sight, since the dominant wave direction is from the west-south-west, and therefore should drive sand to the northeast and out of St Francis Bay (causing erosion if the sediment supply from the west is limited).

However, as will be seen in the following Chapters (from field measurements and numerical modelling), wave directions vary along the length of St Francis Bay Beach due to refraction around the Cape.

Further along the Beach, the results of simulation B (Figure 5.2) were similar:

76,895 m^3/yr (south westerly directed)
-22 m^3/yr (north easterly directed)

That is, a net wave-driven sediment transport of 76,873 m^3/yr to the south west. However, beyond Umzuwethu reef, where the refractive influence of the Cape is less, the results of simulation C (Fig. 4.8) were different:

4,372 m^3/yr (south westerly directed)
-25,640 m^3/yr (north easterly directed)

That is, a net wave-driven sediment transport of 21,278 m^3/yr to the north east, towards the Kromme River Entrance. Thus, we have an alongshore sediment transport regime within St Francis Bay that changes from a south westerly direction to a north easterly direction moving towards the Kromme Estuary. These results concur with results of calculations presented in CSIR (1992) and Bickerton and Pierce (1987) as discussed in section 2.9.2.

5.4.2 Wind-Driven Currents

At Cape St Francis strong winds previously delivered large amounts of sand to the Bay (described in section2.8.1). In addition Mead *et al.* (2006) suggest that wind-driven currents can have a large influence on the fate of beach sand suspended by wave action.

In order to test this theory Mead *et al.* (2006) conducted numerical model simulations to determine the circulation patterns of wind-driven currents in St Francis Bay, with the focus on the predominant west south west and east north east wind directions. Figure 5.3 presents the results of simulated 30 knot winds from the west south west (A) and east north east (B). These results suggest that wind driven currents are greatest around the tip of the Cape, and are low in the south-western corner of the Bay. There is little evidence of complex circulation, with currents along St Francis Bay Beach either running northeast due to the west south west winds, or southwest due to east north east winds. Westerly winds occur more than twice as often as easterly winds, and reach higher velocities (Figure 4.24). Thus it was concluded that the predominant wind driven currents in St Francis Bay result in a net north easterly sediment transport.

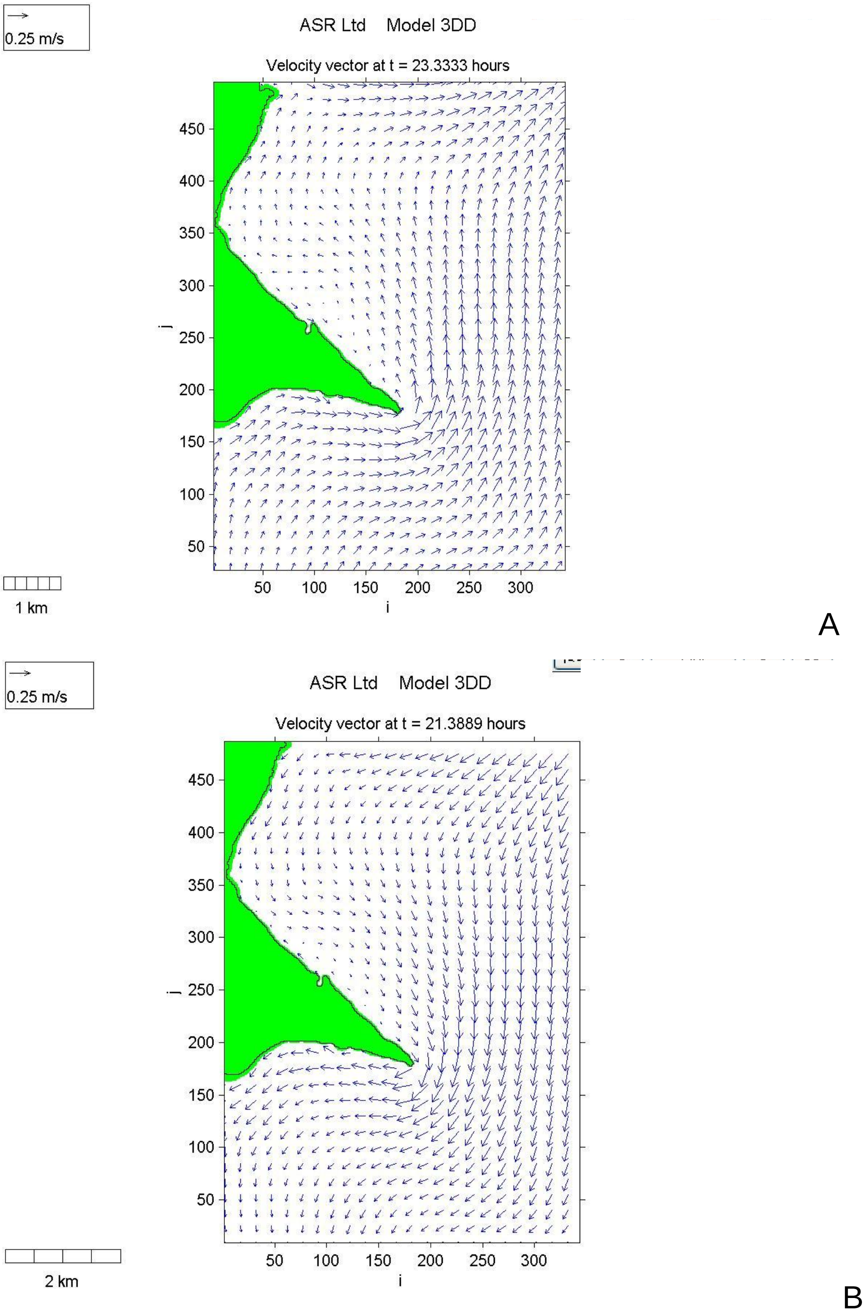


Figure 5.3 Wind-driven currents due to 30 knot west south west winds above (A) and 30 knot east north east winds below (B) (Mead *et al*. 2006).

5.5 Detailed Hydrodynamic Modelling

5.5.1 Wave Climate Development

In order to investigate the hydrodynamics in greater detail, further numerical modelling was conducted by the author. Firstly a large bathymetry grid was created by combining inshore bathymetry data collected by the author during 2005/2006 was with offshore data from SAN 1952 to +/- 100m water depth (Figure 5.5). Then the offshore NOAA Wave Watch 3 (NOAA, 2007) wave data for the 3 month instrument deployment period from 9/02/06 to 05/05/06 was extracted from the offshore location: -34.0 S, 26.25 E (Figure 5.4), this location is east of Cape Recife over 100 km away, however it was the closest actual WW3 output location and therefore considered more accurate than closer interpolated wave data. NOAA WW3 hind-cast data provide wave height, peak period, peak direction and offshore wind at 10 m above sea level, but does not provide the wave direction spread needed for the model. A relationship was found with the Aquadopp data between the peak period and the directional spread. This relationship is consistent with findings from Bosserelle *et al* (2008) and was used to calculate the offshore directional spread.

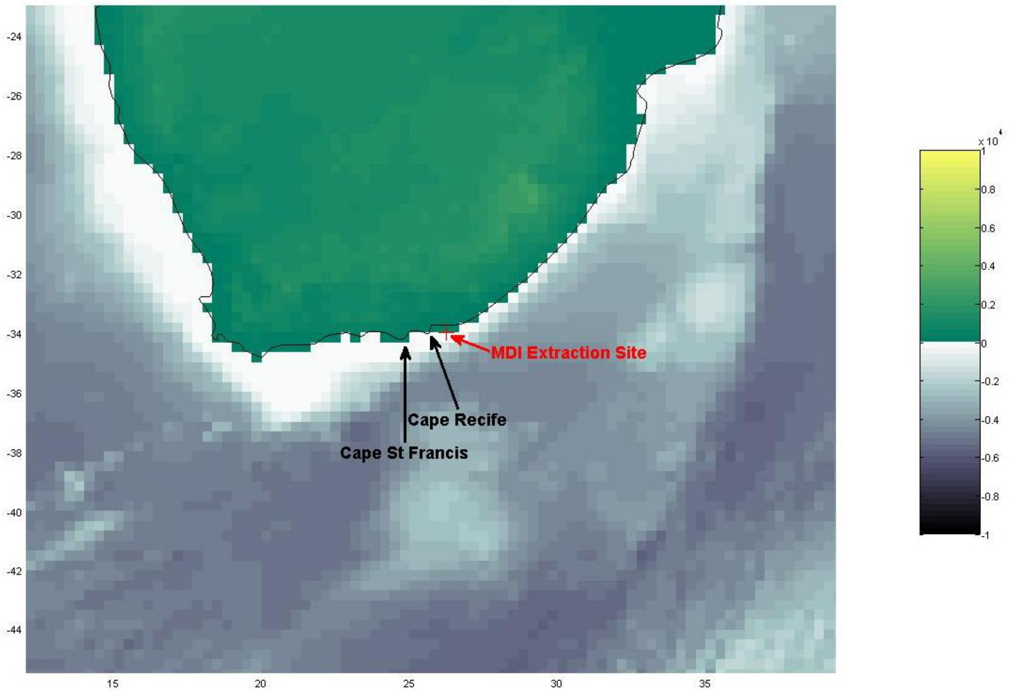


Figure 5.4 Offshore MDI WW3 data extraction site, east of Cape Recife.

The offshore wave data was modelled with SWAN (Simulating Waves in the Nearshore) (Booij *et al*., 2004). SWAN treats generation, propagation and transformation of wave fields in both deep water and nearshore regions by solving the spectral action density balance equation for frequency-directional spectra. The growth, refraction, and decay of each component of the sea state, each with a specific frequency and direction, are individually considered. Simulated physical processes include the generation of waves by the surface wind stress, dissipation by white-capping, resonant nonlinear interaction between the wave components, bottom friction and depth limited breaking.

The modelled output for the instrument deployment location was compared with measured data and parameters were adapted until a good agreement was achieved (
Figure **5.6**). Some anomalies were experienced between the modelled and measured Aquadopp data; this can be attributed to the WW3 offshore wave data extraction site and closeness of the eastern boundary of the bathymetry grid used for Swan modelling. This extraction site was used because it is the closest actual WW3 virtual buoy location and therefore more accurate. Once satisfied with the model behaviour, the long term offshore hindcast WW3 wave data for the period 15 February 1997 to 15 February 2007 was extracted at 3 hourly intervals. This data was used to calculate the offshore wave climate using the ASR Matlab ® joint probability toolbox.

This offshore wave climate was then modelled employing a steady state boundary condition to create an inshore wave climate at a point in the centre of the 2DBEACH modelling grid. The 10 yr WW III offshore wave climate and transformed inshore climate used for 2DBEACH numerical modelling is given in Table 5.1. Figure 5.7 summarizes the transformation of wave heights from offshore MDI site to inshore of St Francis Bay, with waves from the SW experiencing the greatest reduction in wave height due to a great degree of refraction and diffraction around the Cape St Francis headland through to waves from the ESE which experience very little reduction in wave height due to the direct approach from this direction. However this comparison ignores the effect of wave period which is critical to wave refraction. Longer period waves experience greater refraction than shorter period waves. Waves from the SW show two linear trends in wave height transformation, this can be attributed to the range in period.

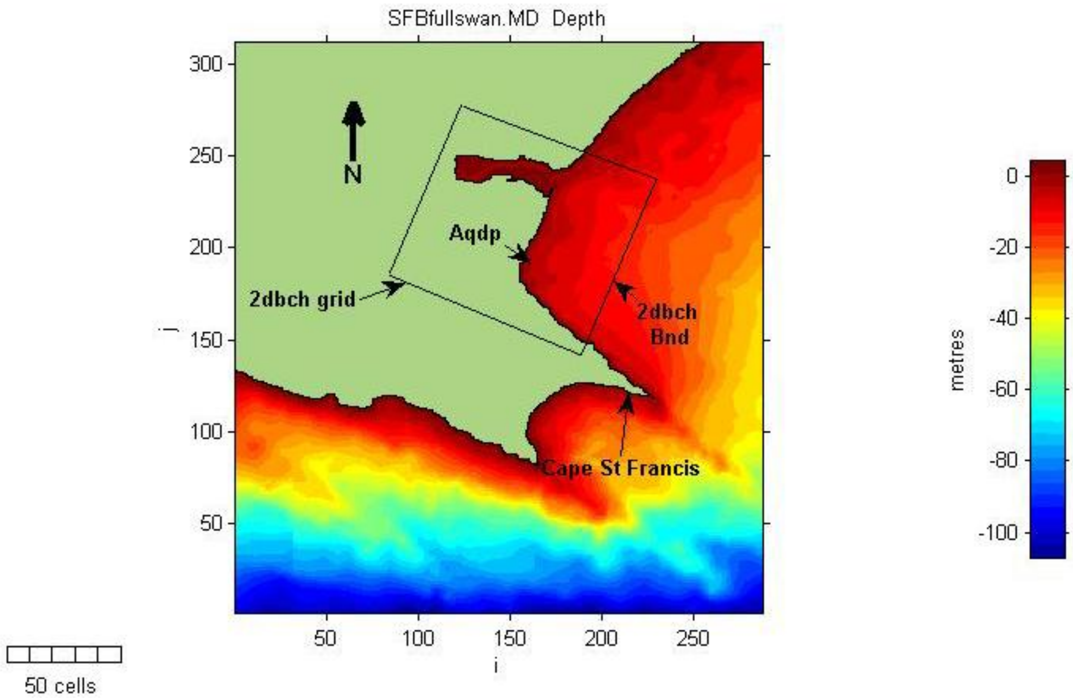


Figure 5.5 Full bathymetry grid 50m cell size for Cape St Francis and offshore until +/- 100m depth, for Swan wave refraction modelling conducted to transform offshore WW3 wave climate to an inshore wave climate within St Francis Bay. Labelled: Instrument site (Aqdp), 2DBEACH modelling grid (2dbch grid), 2DBEACH boundary extraction point (2dbch Bnd).

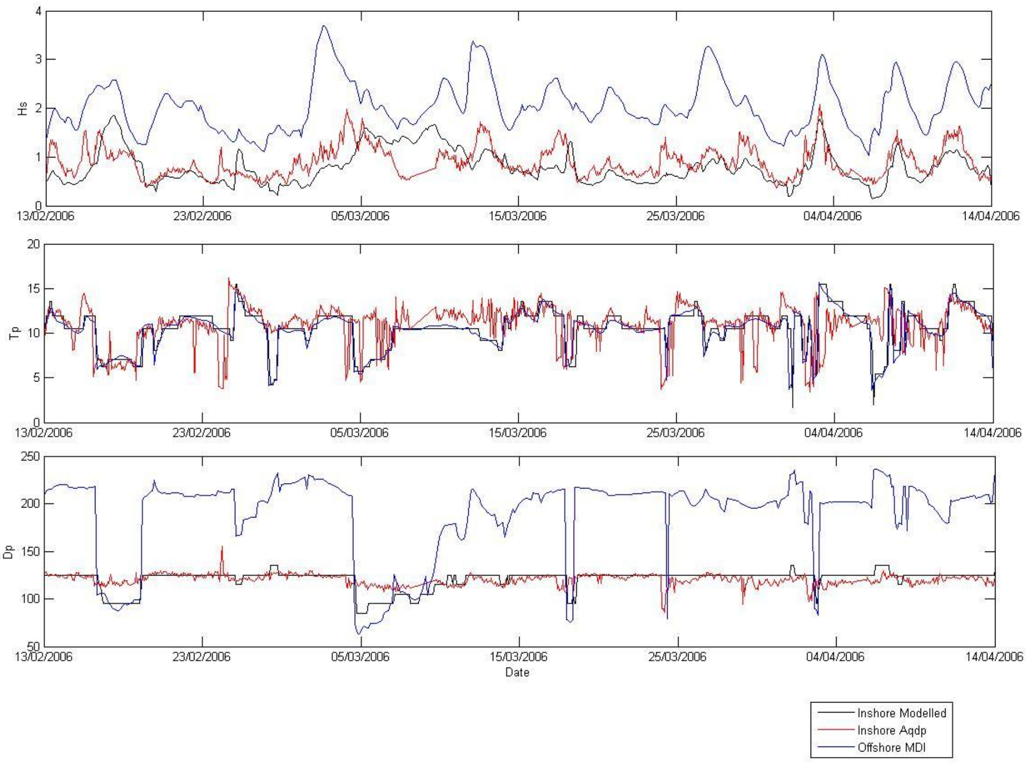


Figure 5.6 Comparison of wave height (Hs), peak period (Tp) and peak direction (Dp) for inshore modelled, inshore measured (Aqdp) and Offshore MDI WW3 hind-cast data for the period 13/02/2006 to 14/04/2006.

Table 5.1 Offshore wave climate created from 10 years of WW3 data and transformed into St Francis Bay to create an inshore wave climate for 2DBEACH modelling. Data includes: Probability (Prob), wave height offshore (Hoff), period offshore (Toff), direction offshore (Doff), wave height inshore (Hin), period inshore (Tin), direction inshore (Din), peak direction inshore (Dpin), peak direction inshore rotated 200° CCW (Dpin 200° rot).

Prob	**Hoff**	**Toff**	**Doff**	**Hin**	**Tin**	**Din**	**Dpin**	**Dpin 200° rot**
(%)	**(m)**	**(sec)**	**(deg)**	**m()**	**(sec)**	**(deg)**	**(deg)**	**(deg)**
17.18	1.75	11.14	225.00	0.42	11.91	134.76	135.00	-25.00
15.75	2.25	11.53	225.00	0.56	11.91	134.51	135.00	-25.00
8.31	2.75	11.85	225.00	0.75	11.91	134.80	135.00	-25.00
7.57	1.75	10.33	195.00	0.74	10.47	130.98	135.00	-25.00
6.80	2.25	11.13	195.00	0.96	10.47	130.65	135.00	-25.00
4.49	3.25	12.04	225.00	0.93	11.91	134.89	135.00	-25.00
4.48	1.25	10.61	225.00	0.29	10.47	135.24	135.00	-25.00
4.31	1.75	8.09	105.00	1.45	8.08	97.87	95.00	15.00

3.30	2.75	11.57	195.00	1.21	11.91	130.45	135.00	-25.00
3.16	2.25	8.35	105.00	1.86	8.08	97.88	95.00	15.00
2.88	1.25	9.87	195.00	0.51	10.47	131.25	135.00	-25.00
2.23	1.75	9.24	165.00	1.07	9.20	123.42	125.00	-15.00
2.20	3.75	12.36	225.00	1.09	11.91	134.78	135.00	-25.00
2.01	1.75	8.88	135.00	1.33	9.20	111.44	115.00	-5.00
1.71	2.25	9.22	165.00	1.37	9.20	123.37	125.00	-15.00
1.58	3.25	11.76	195.00	1.49	11.91	130.76	135.00	-25.00
1.32	1.25	7.88	105.00	1.03	8.08	97.85	95.00	15.00
1.20	2.25	9.34	135.00	1.73	9.20	111.83	115.00	-5.00
1.14	4.25	12.69	225.00	1.27	11.91	134.64	135.00	-25.00
0.93	2.75	8.18	105.00	2.25	8.08	97.59	95.00	15.00
0.92	1.25	9.18	165.00	0.76	9.20	123.42	125.00	-15.00
0.84	2.75	9.25	165.00	1.67	9.20	123.37	125.00	-15.00
0.69	3.75	12.11	195.00	1.78	11.91	130.87	135.00	-25.00
0.64	1.25	8.77	135.00	0.95	9.20	111.39	115.00	-5.00
0.48	4.75	12.86	225.00	1.47	13.56	134.66	135.00	-25.00
0.42	2.75	9.08	135.00	2.10	9.20	111.35	115.00	-5.00
0.37	3.25	8.49	105.00	2.64	8.08	97.50	95.00	15.00
0.35	4.25	12.53	195.00	2.01	11.91	130.59	135.00	-25.00
0.33	3.25	9.50	165.00	1.97	9.20	123.39	125.00	-15.00
0.29	2.25	5.36	255.00	0.22	5.48	150.30	155.00	-45.00
0.24	1.75	4.55	255.00	0.16	4.81	151.61	155.00	-45.00
0.20	2.75	6.68	255.00	0.33	7.10	146.28	145.00	-35.00
0.20	4.75	12.94	195.00	2.32	13.56	130.53	135.00	-25.00
0.17	3.25	9.26	135.00	2.47	9.20	111.33	115.00	-5.00
0.17	3.75	10.35	165.00	2.34	10.47	123.28	125.00	-15.00
0.14	5.25	13.21	225.00	1.72	13.56	134.52	135.00	-25.00
0.11	3.75	8.88	105.00	3.07	9.20	97.42	95.00	15.00
0.09	3.75	10.27	135.00	2.92	10.47	111.99	115.00	-5.00
0.07	3.25	8.37	255.00	0.41	8.08	140.90	145.00	-35.00
0.07	4.25	10.95	135.00	3.31	10.47	112.14	115.00	-5.00
0.07	5.25	13.35	195.00	2.73	13.56	130.62	135.00	-25.00
0.06	1.25	4.04	255.00	0.10	4.23	153.85	155.00	-45.00
0.05	0.75	8.00	165.00	0.45	8.08	122.07	125.00	-15.00
0.05	0.75	9.06	195.00	0.31	9.20	131.43	135.00	-25.00
0.04	3.75	9.28	255.00	0.50	9.20	139.14	145.00	-35.00
0.04	5.75	13.92	225.00	1.94	13.56	134.16	135.00	-25.00
0.03	0.75	8.10	135.00	0.57	8.08	110.27	115.00	-5.00

0.03	0.75	10.62	225.00	0.18	10.47	135.39	135.00	-25.00
0.03	4.25	10.19	105.00	3.63	10.47	97.39	105.00	5.00
0.03	4.75	10.54	105.00	4.07	10.47	97.31	105.00	5.00
0.02	0.75	8.90	105.00	0.64	9.20	97.95	95.00	15.00
0.02	4.25	10.49	165.00	2.67	10.47	123.28	125.00	-15.00
0.02	4.25	9.12	255.00	0.57	9.20	139.29	145.00	-35.00
0.02	4.75	10.33	135.00	3.65	10.47	111.57	115.00	-5.00
0.02	5.25	10.74	105.00	4.45	10.47	97.24	105.00	5.00
0.02	5.25	9.16	135.00	3.80	9.20	109.75	115.00	-5.00
0.02	7.25	13.34	105.00	5.86	13.56	97.17	105.00	5.00
0.01	4.75	7.51	255.00	0.62	8.08	143.07	145.00	-35.00
0.01	5.75	10.72	195.00	2.68	10.47	132.06	135.00	-25.00
0.01	6.25	14.79	225.00	2.20	15.44	133.87	135.00	-25.00
0.01	6.75	12.78	105.00	5.55	13.56	96.94	105.00	5.00
0.01	7.75	13.39	105.00	6.04	13.56	97.48	105.00	5.00

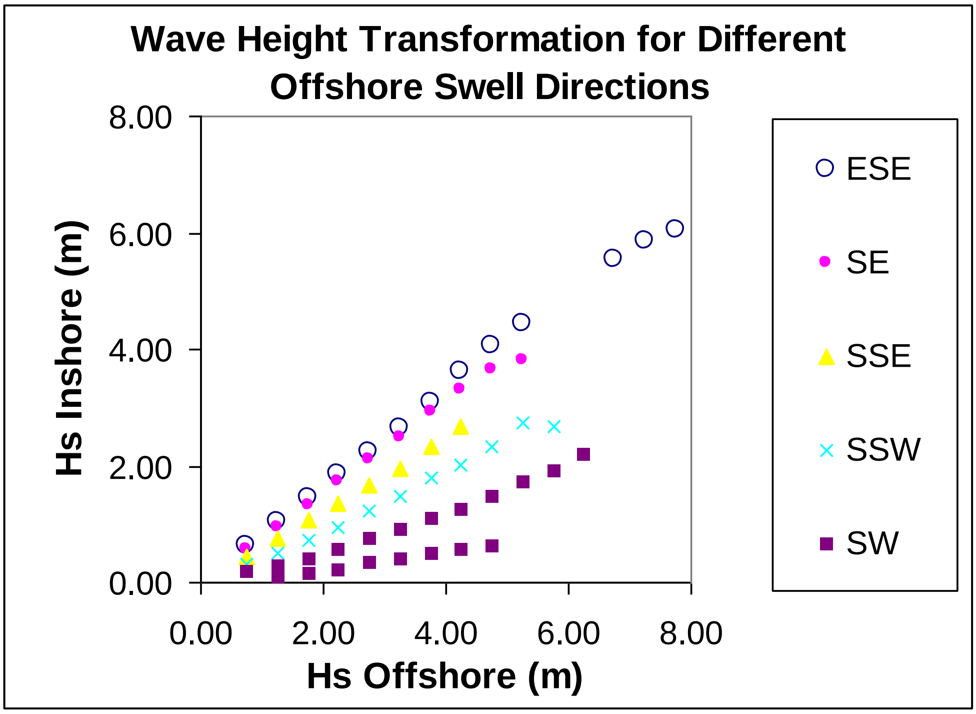


Figure 5.7 Wave heights offshore and inshore for a range of offshore swell directions showing the large reduction in wave height from the SW direction through to least reduction in height experienced by waves emanating from the ESE.

5.5.2 Bathymetry

A Bathymetry Grid of 10m cell size was created using bathymetry data from 2005/2006, SAN bathymetric data from 1952, beach survey data, estuary survey data and data digitized from aerial photographs using Arc GIS and Surfer. The grid was rotated 200 degrees counter clock wise (CCW) for modelling purposes as described previously. A smaller grid was selected for 2DBEACH modelling (Figure 5.8 and Figure 5.9), the offshore boundary was located just inshore of Port St Francis). Interesting features include the relatively minor "Huletts reef" in the corner of the bay, the small and low profile Anne avenue reef, the large pronounced "Umzuwethu" reef offshore of the central part of the beach. North of Umzuwethu lays the ancient drowned Kromme River valley and north of the Kromme Estuary mouth extensive reef is found. Port St Francis was chosen as the outer limit of the grid due to the substantial discontinuity to longshore currents created by the port breakwater (Figure 5.10)

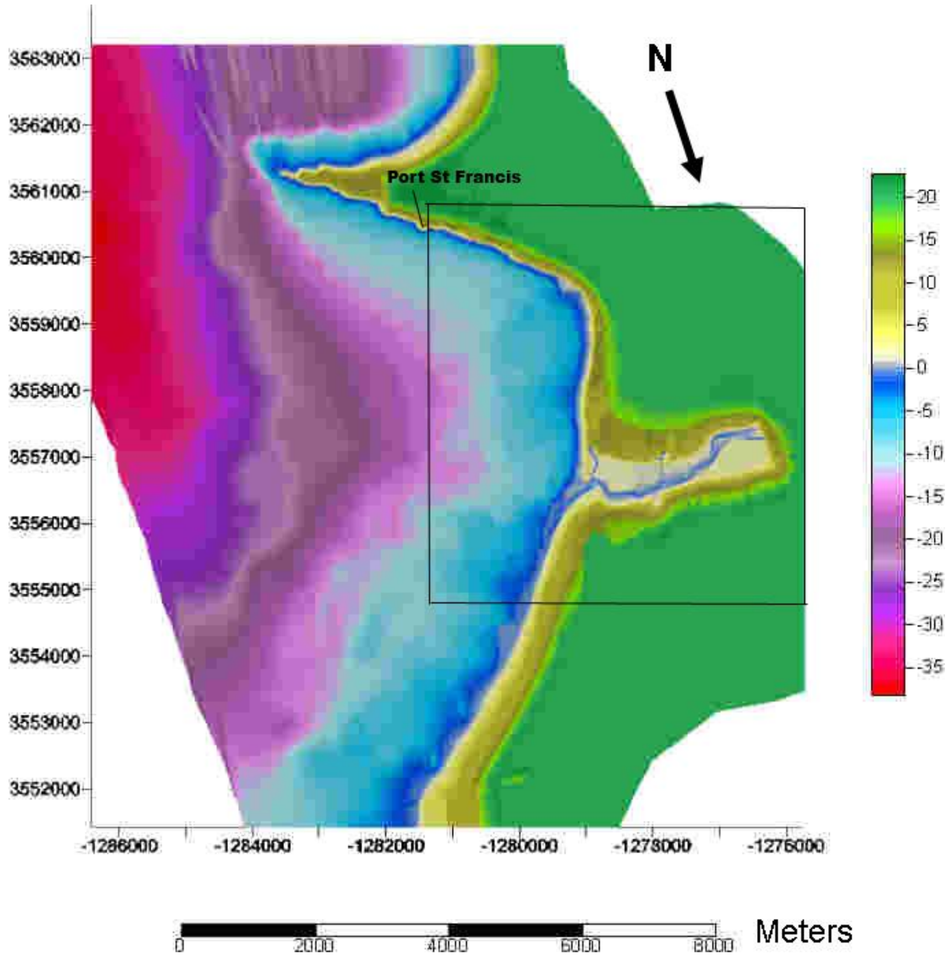


Figure 5.8 Bathymetry of St Francis Bay, cell size 10m, rotated 200° CCW, area selected for 2DBEACH grid shown in black with outer boundary inshore of Port St Francis, projection: metric UTM LO25.

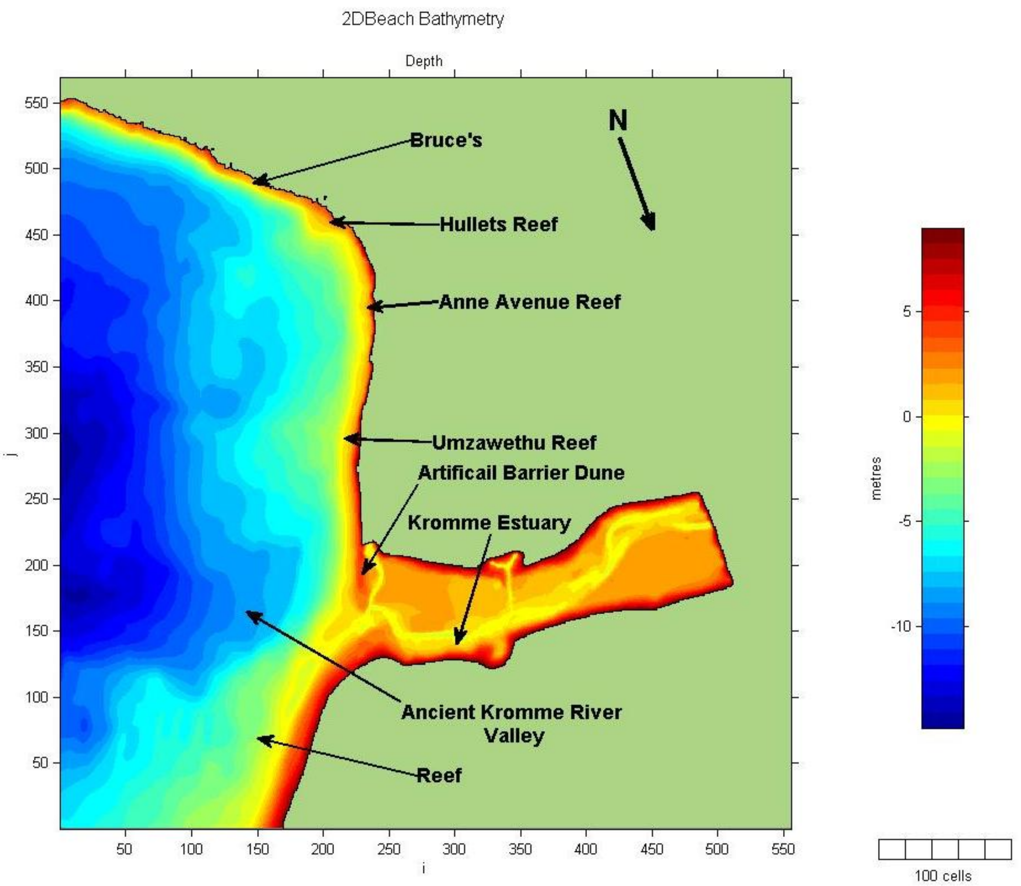


Figure 5.9 Bathymetry grid, cell size 10m, rotated 200° for 2DBEACH modelling, waves driven from boundary on the left (eastern boundary) bottom boundary (northern boundary) open, with the main features labelled.

Figure 5.10 Port St Francis acts as a substantial interruption to longshore currents along the Cape St Francis Headland.

5.5.3 Hydrodynamic Modelling

The inshore wave climate was then manually manipulated into a representative time series by distributing all bins of greater than 0.5% probability, representing 99.6 % of the total wave climate (Figure 5.11). This resulting time series was used as boundary conditions for subsequent 2DBEACH modelling. 2DBEACH is a non-linear numerical circulation model for irregular waves containing five coupled simulations of physical processes: (i) wave height transformation, (ii) wave angle refraction, (iii) wave dissipation due to breaking and friction, (iv) radiation stress-driven circulation and (v) sediment transport. The wave and hydrodynamic modules are described by (Black and Rosenberg 1992a&b).

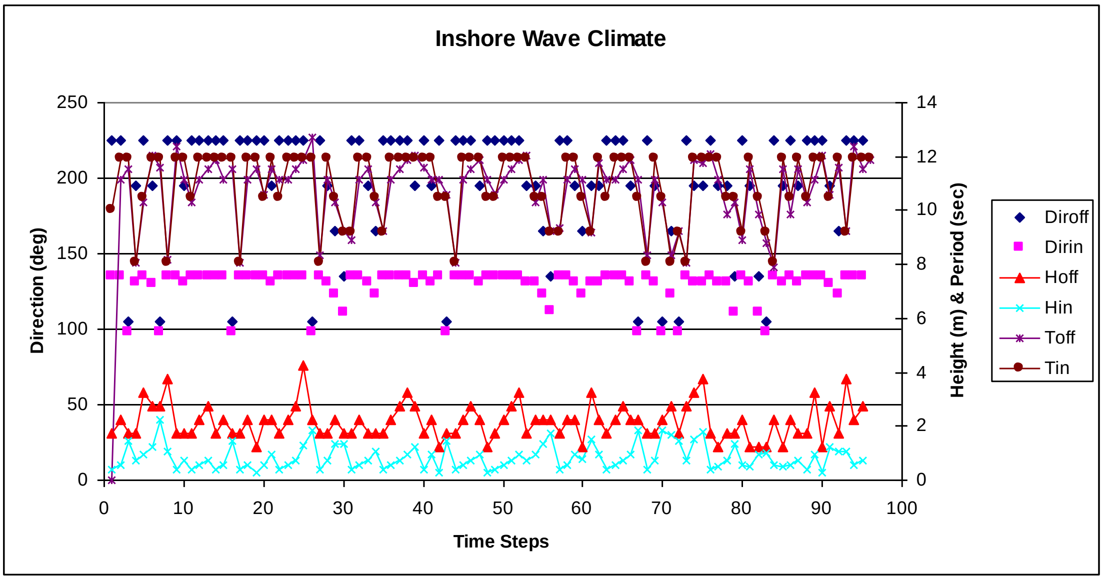


Figure 5.11 Offshore and inshore wave climate, manually manipulated for use as boundary conditions for hydrodynamic and sediment transport modelling using 2DBEACH.

The inshore wave climate described above was run from the left hand boundary, initially without sediment in order to provide an initial assessment of the hydrodynamics of St Francis Bay. This initial modelling concurred with previous calculations (Bickerton and Pierce, 1988; CSIR, 1992; Otay and Samanci, 2003; Mead *et al.*, 2006) with strong longshore currents persisting down the headland where waves constantly arrive and break at an oblique angle during all swell conditions. Also as previously calculated (Bickerton and Pierce, 1988; CSIR, 1992; Otay and Samanci, 2003; Mead *et al.*, 2006) relatively slower longshore currents persist along the beach due to near shore parallel angle of wave incidence, with current directions varying depending on wave height, period and direction. Intuitively one would expect longshore direction to be governed by offshore wave direction, with SW swells driving currents in a north easterly direction and ESE swell driving currents in a south westerly direction. 2DBEACH Modelling was conducted using the representative wave climate described above with following settings:

Tidal levels:	MSL
Wave Heights:	0.29m to 2.25 m
Angles:	95° to 135° or -25° to 15° model angles
Horizontal eddy viscosity:	5 m^2s^{-1}
Horizontal eddy diffusivity:	2m^2s^{-1}
Breaking criterion :	Madsen
Roughness length:	0.008 m
Wave friction factor:	0.01

Over the next few pages a range of scenarios from 2DBEACH hydrodynamic modelling are presented for a selection of wave conditions representing 51% of the overall wave climate (Figure 5.12 to Figure 5.19)

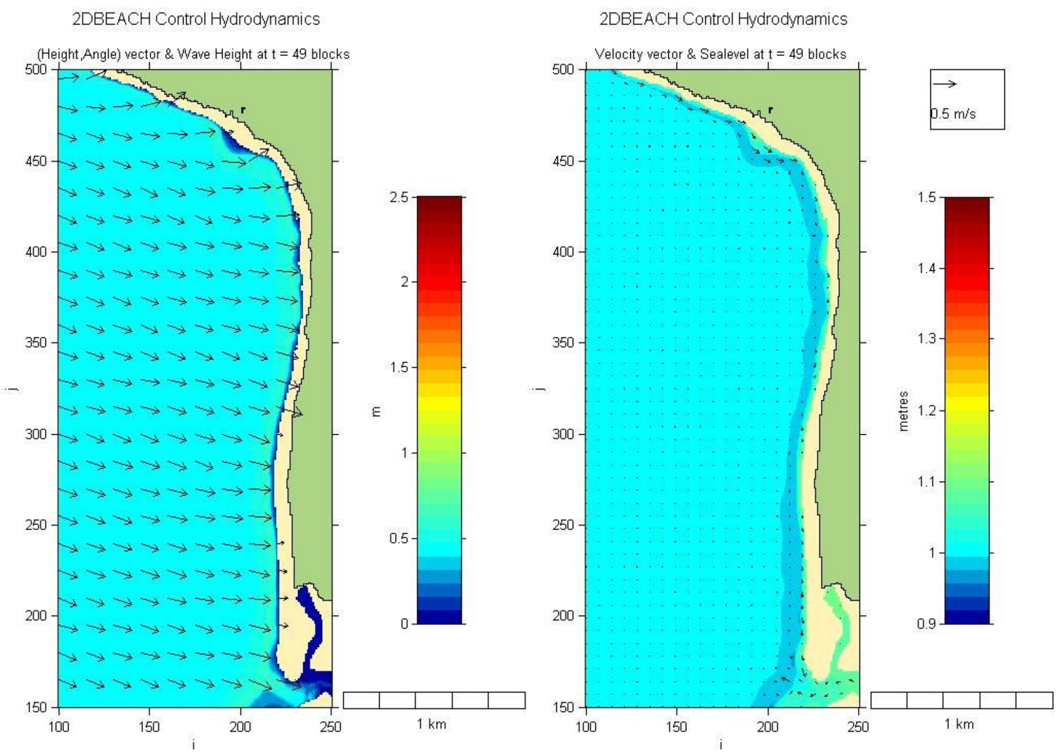


Figure 5.12 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SW: Hs = 1.75m; Dir = 225°; T = 11.14sec, Inshore: Hs = 0.42m; Dir = 135°; T = 11.91sec probability = 17%.

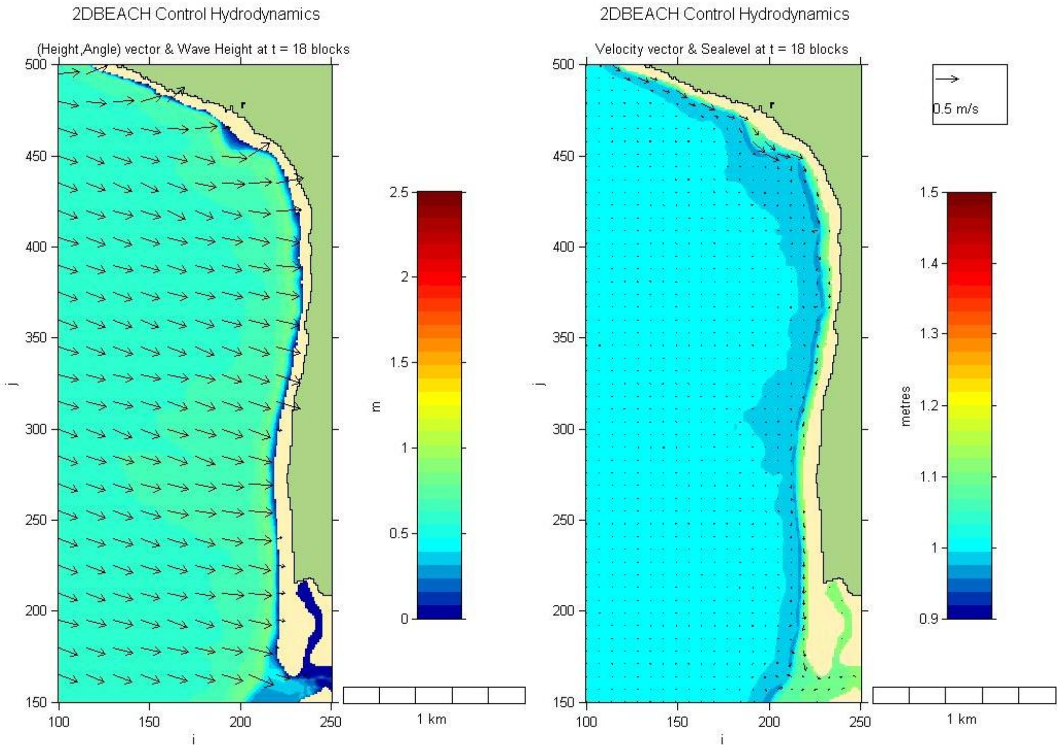


Figure 5.13 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SW: Hs = 2.25m; Dir = 225°; T = 11.53sec, Inshore: Hs = 0.56m; Dir = 135°; T = 11.91sec and probability = 16%

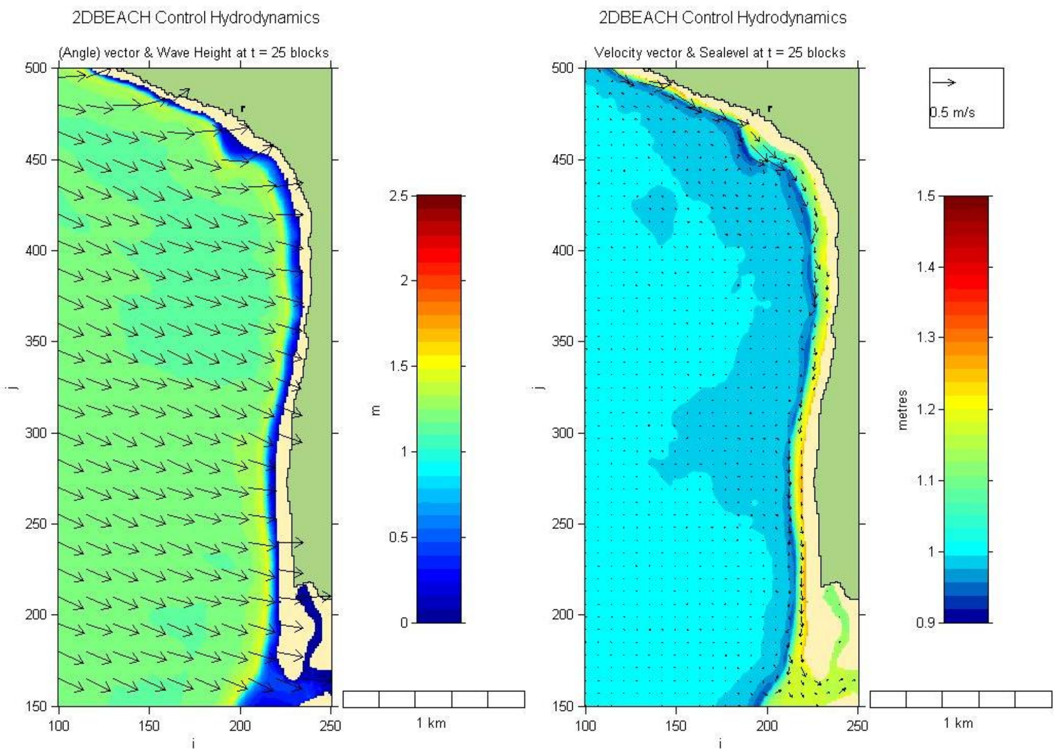


Figure 5.14 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SW: Hs = 4.25m; Dir = 225°; T = 12.69sec, Inshore: Hs = 1.27m; Dir = 135°; T = 11.91sec and probability = 1%.

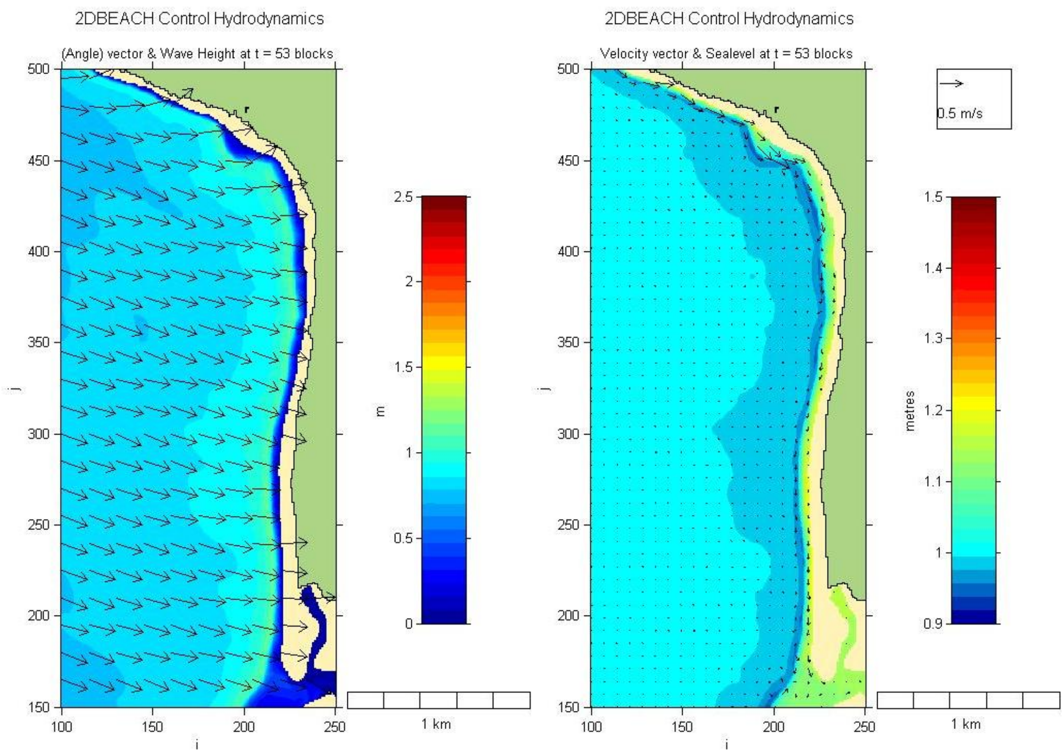


Figure 5.15 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SSW: Hs = 1.75m; Dir = 195°; T = 10.33sec, Inshore: Hs = 0.74m; Dir = 135°; T = 10.47sec and probability = 8%.

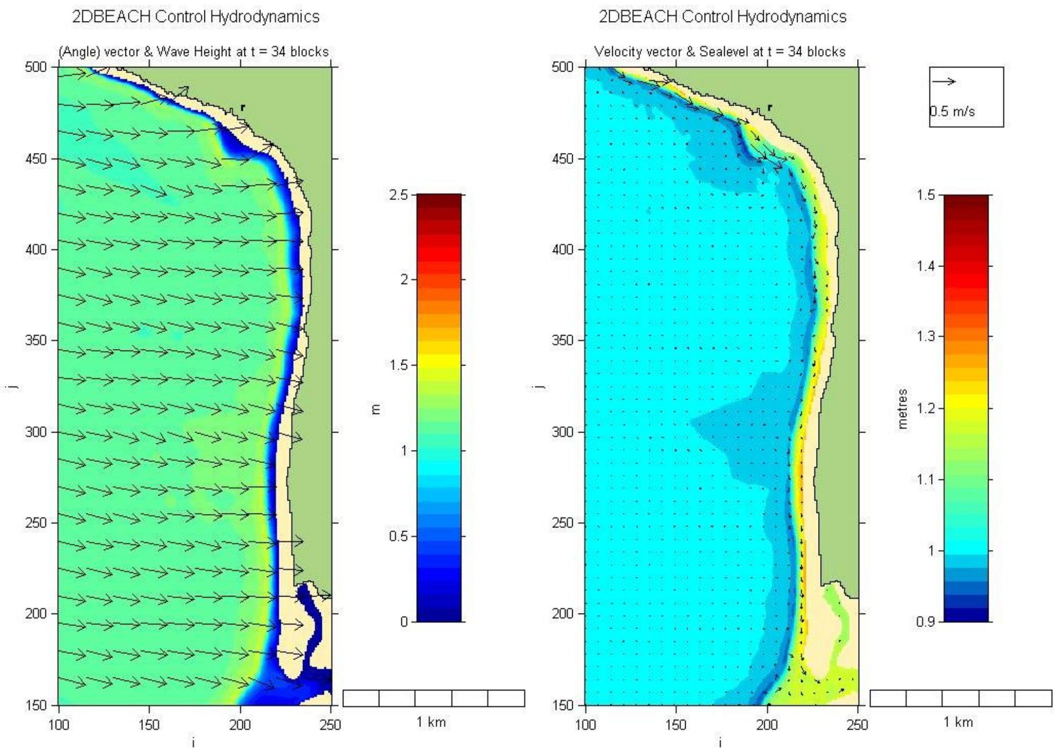


Figure 5.16 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SSE: Hs = 1.75m; Dir = 165°; T = 9.24sec, Inshore: Hs = 1.07m; Dir = 125°; T = 9.20sec and probability = 2%.

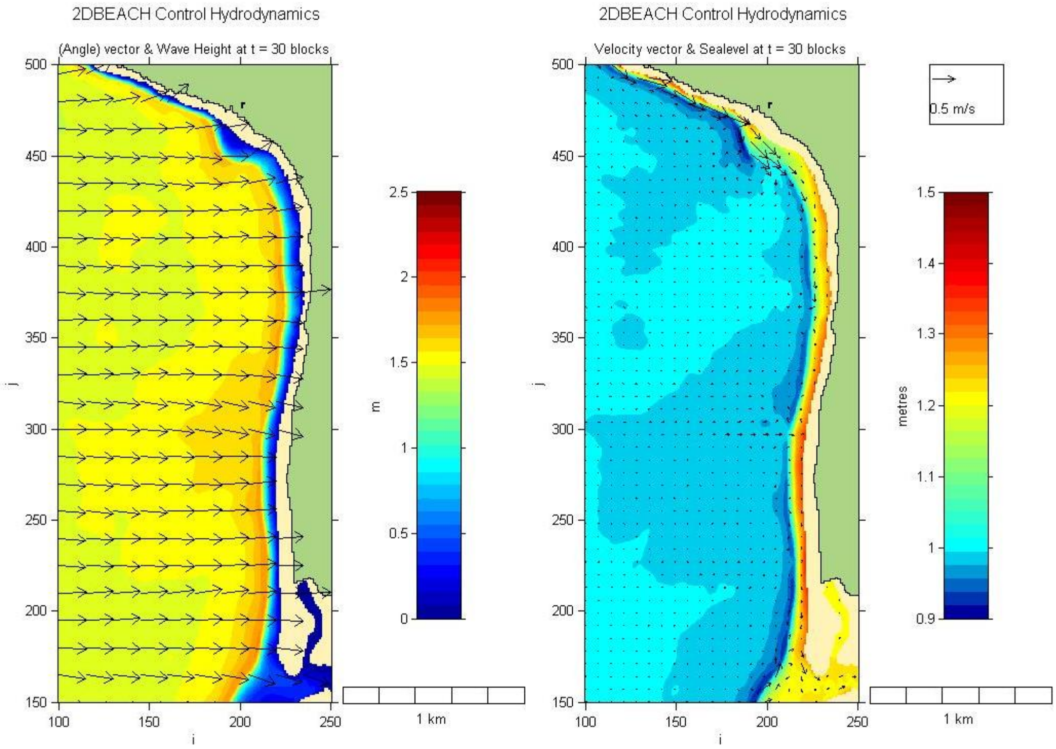


Figure 5.17 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore SE: Hs = 1.75m; Dir = 135°; T = 8.88sec, Inshore: Hs = 1.33; Dir = 115°; T = 9.20sec and Probability = 2%

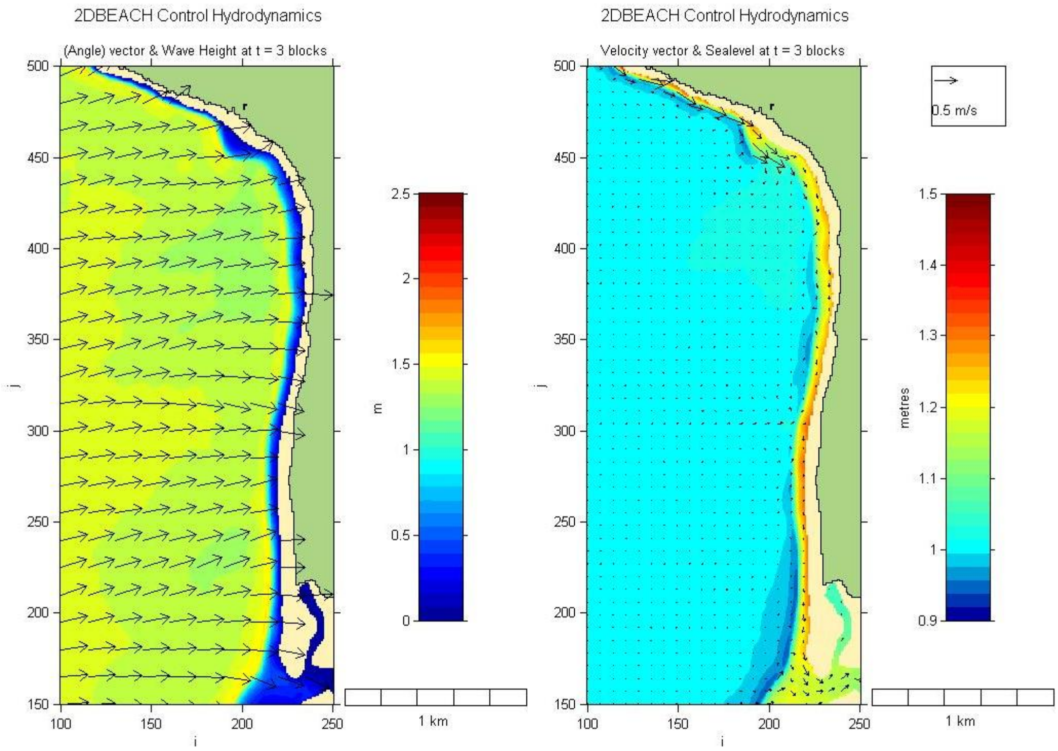


Figure 5.18 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore ESE: Hs = 1.75m; Dir = 105°; T = 8.09sec, Inshore: Hs = 1.45; Dir = 95°; T = 8.08sec and probability = 4%.

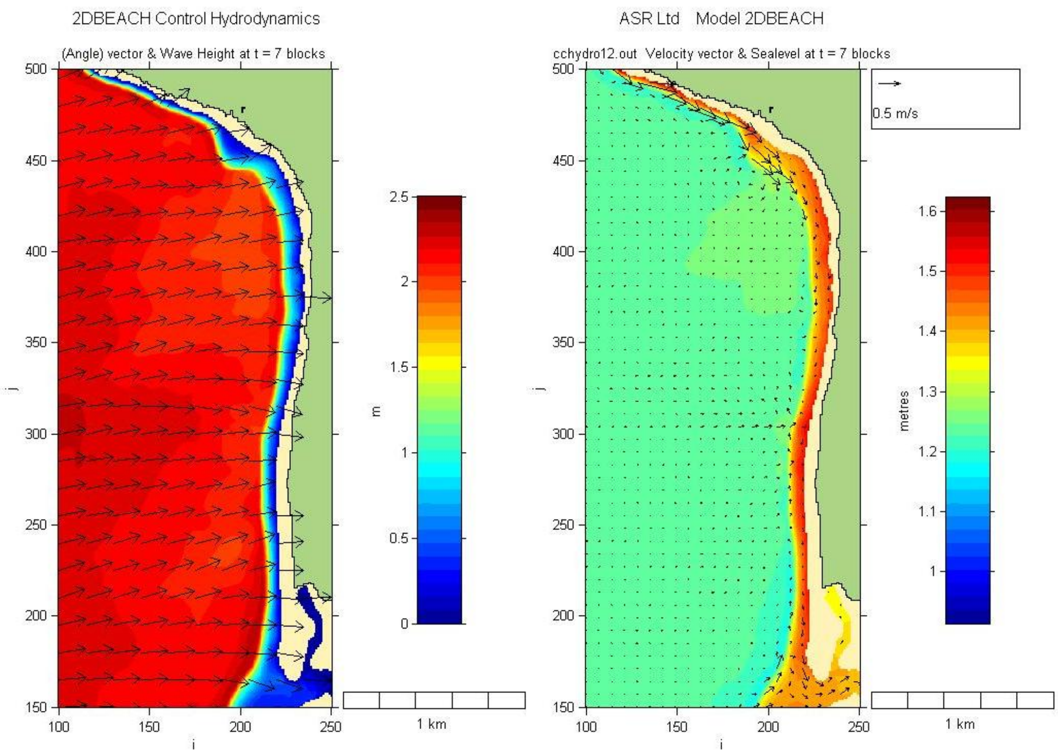


Figure 5.19 Wave angle vector and wave height (left), current velocity vector and sea level (right) for Offshore ESE: Hs = 2.75m; Dir = 105°; T = 8.18sec, Inshore: Hs = 2.25; Dir = 95°; T = 8.08sec and probability = 1%.

5.5.4 General Interpretation

The evaluation of wave driven currents reveals some interesting results. As discussed previously all scenarios exhibit unidirectional longshore currents along the headland due to the large angle of wave incidence. The dominant wave conditions offshore of Cape St Francis are moderate long period south westerly swells, which result in small (0.42m - 0.56 m) waves within St Francis Bay persisting for 33 % of the time as shown in Figure 5.12 and Figure 5.13 respectively. Under these conditions longshore currents along the headland are relatively slow, (0.2 - 0.5 $m.s^{-1}$) and longshore currents along the beach are very slow (0 - 0.2 $m.s^{-1}$) in a north easterly direction. During the less frequent (1% probability) large offshore SW event shown in

Figure 5.14 wave height within the bay is still relatively small (1.27m) and longshore currents are moderate north easterly along the beach (+/- 0.3 $m.s^{-1}$). In Figure 5.15a relatively small, 1.75m SSW event offshore results in a small waves within the bay and weak north easterly longshore currents along the beach, with a slight discontinuity experienced at Umzawethu reef. Small offshore waves 1.75m from a SSE direction result in moderate 1.07 m waves inshore and weak mostly north easterly longshore flow along the beach (Figure 5.16). When small 1.75m offshore waves arrive from a SE direction they are allowed a fairly direct approach to the beach and little reduction in wave height is experienced waves are 1.33m

within the bay and longshore currents are strong along the headland and into the corner of the bay (>0.5 $ms.s^{-1}$) but relatively weaker along the beach with some variation found south and north of Umzawethu reef, weak south west and easterly flows respectively (Figure 5.17) The last two scenarios presented are small (1.75m) and moderate (2.75m) offshore waves from the ESE, occurring 4% and 1% respectively. Waves from this direction are allowed a direct approach and experience very little reduction in wave height (inshore wave height of 1.45 m and 2.25m respectively) and drive strong longshore currents along the headland into the corner of the bay, however as in previous scenarios, longshore currents are weak and variable along the beach (
Figure **5.18** Figure 5.19).

5.5.5 Important Features

Several interesting features are found in St Francis Bay. Firstly the beach is bound by a headland to the south with unidirectional longshore currents varying in strength depending on wave height and direction. Secondly a rocky reef known as "Huletts" exists in the south western corner of the and seems to exhibit some influence on wave driven currents coming down the headland. Under predominant medium SW waves offshore, small waves within St Francis bay result in minimal set-up and minor longshore transport due to wave driven currents (Figure 5.20). However under medium offshore waves from the ESE direction, relatively large short period waves inshore create a large set up along the point and beach with lower set-up experienced immediately north of Huletts where offshore flows are experienced (Figure 5.21) . Interestingly when a large offshore SW swell was simulated after the ESE event (Figure 5.22), increased longshore currents into the corner of the bay are induced, possibly due to the remnant sea level imbalances induced by the easterly waves. This offshore flow immediately north of Huletts reef is verified by a significant sediment plume evident in aerial photograph (Figure 5.23) taken during a medium size ESE swell.

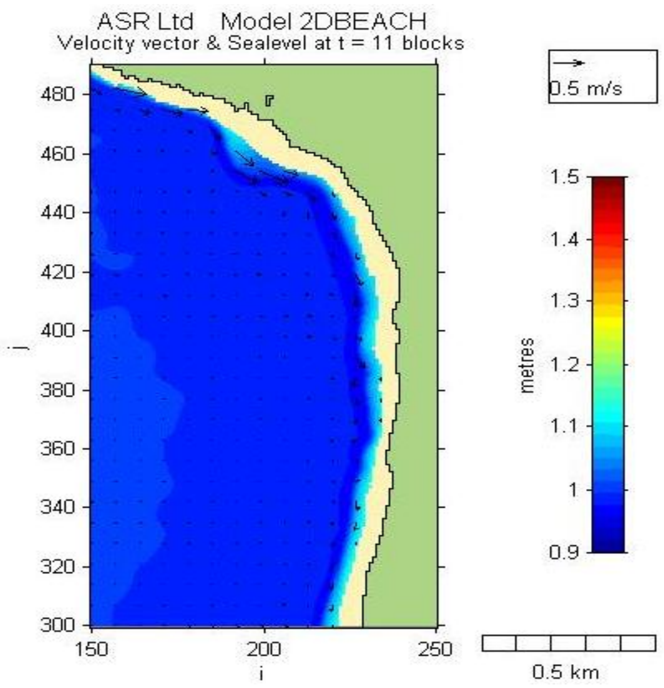


Figure 5.20 Current velocity vector and sea level for Offshore SW: Hs = 1.75m; Dir = 225°; T = 11.14sec, Inshore: Hs = 0.42; Dir = 135°; T = 11.91sec and probability = 17%.

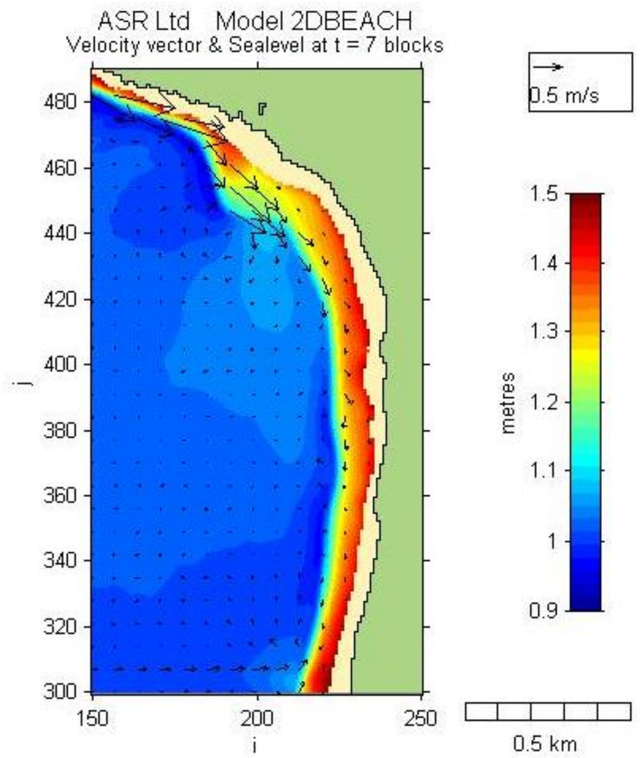


Figure 5.21 Current velocity vector and sea level for Offshore ESE: Hs = 2.75m; Dir = 105°; T = 8.18sec, Inshore: Hs = 2.25; Dir = 95°; T = 8.08sec and probability = 1%.

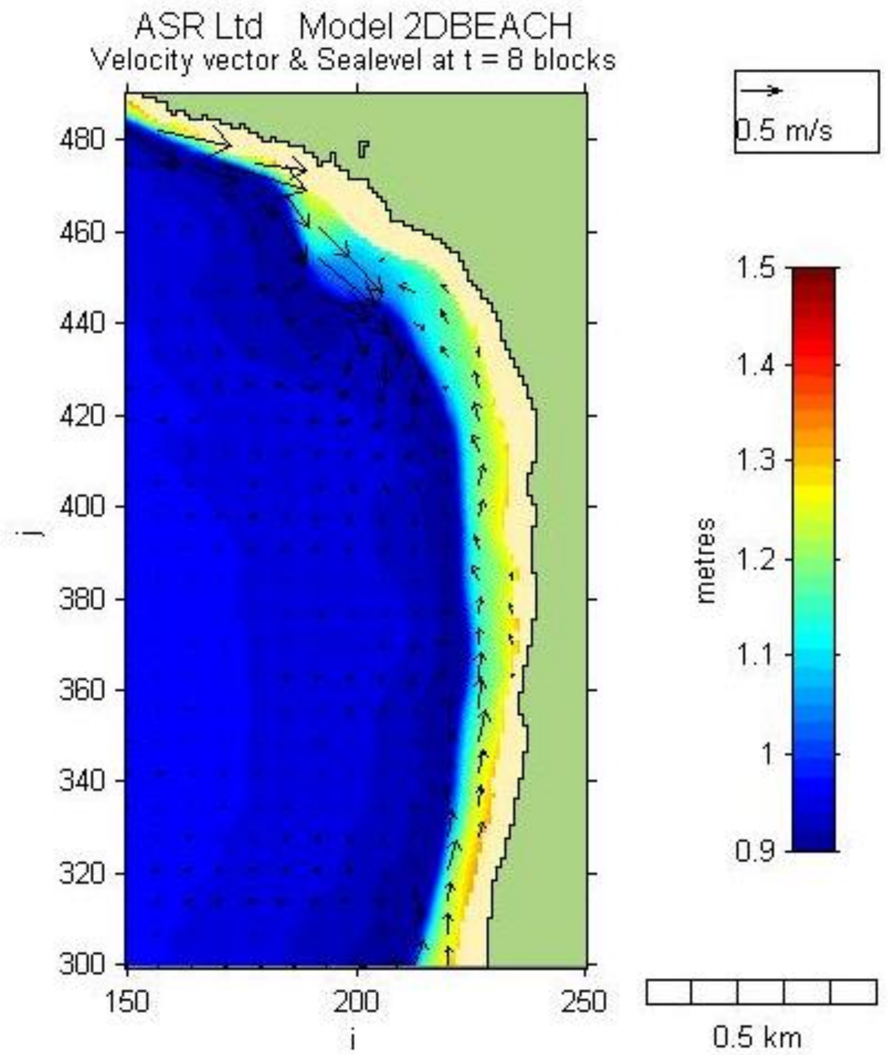


Figure 5.22 Current velocity vector and sea level for Offshore SW: Hs = 3.75m; Dir = 225°; T = 12.36sec, Inshore: Hs = 1.09; Dir = 135°; T = 11.91sec and probability = 2%.

Figure 5.23 ESE offshore waves resulting in interesting circulation with an offshore flow north of Huletts Reef visible as a plume of suspended sediment (Google Earth, 2008).

The large Umzuwethu reef in the middle of the beach has a major influence on wave refraction and wave driven currents along the beach. Indeed this feature has undoubtedly led to the formation of a large salient giving the beach a “dog leg” shape. Under predominant offshore wave conditions from the SW small waves breaking on St Francis Bay beach result in very low but generally north-easterly transport along the full length of the beach either side of Umzuwethu beach as shown in Figure 5.24. However results indicate that moderate offshore waves from the SE or ESE lead to a variation in longshore transport direction either side of Umzuwethu reef, with currents flowing in a south westerly direction south of Umzuwethu reef and north easterly to the north of Umzuwethu reef, shown in Figure 5.25, Figure 5.26 and is most clearly evident during relatively larger 2.75m ESE offshore wave conditions shown in Figure 5.27 .

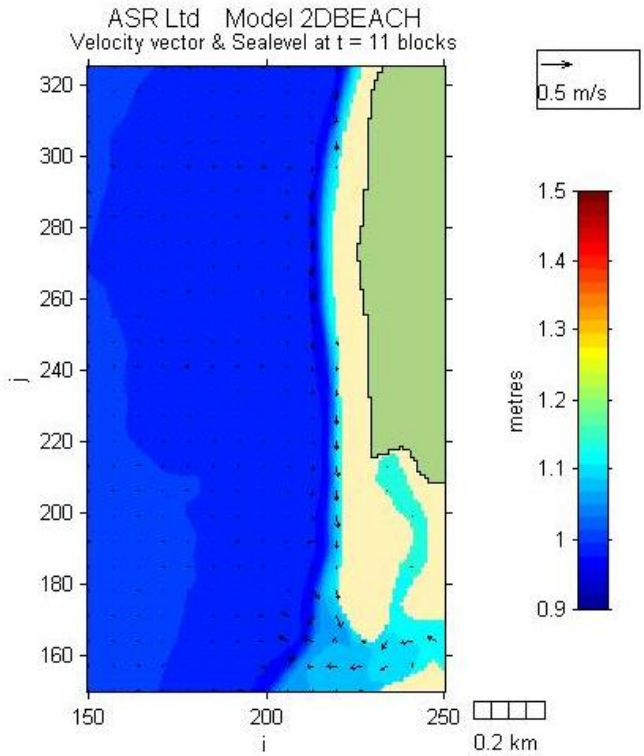


Figure 5.24 Current velocity vector and sea level for Offshore SW: Hs = 1.75m; Dir = 225°; T = 11.14sec, Inshore: Hs = 0.42; Dir = 135°; T = 11.91sec and probability = 17%.

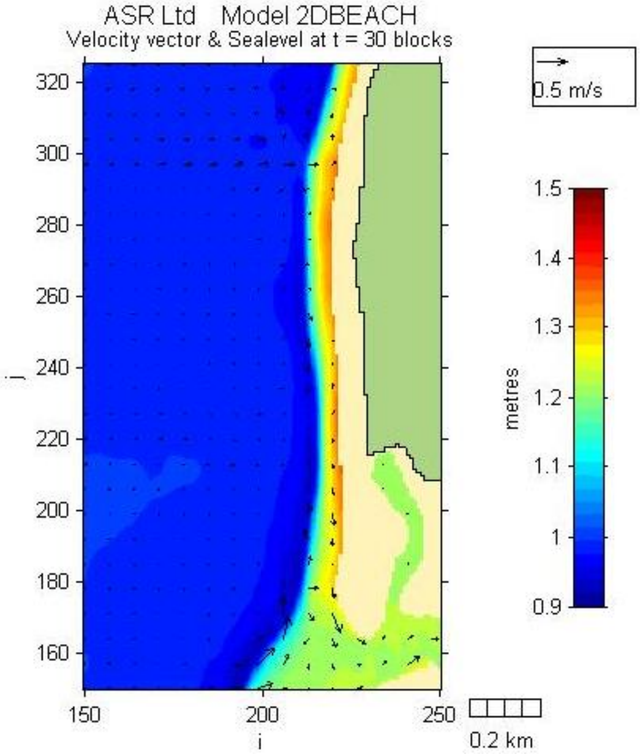


Figure 5.25 Current velocity vector and sea level for Offshore SE: Hs = 1.75m; Dir = 135°; T = 8.88sec, Inshore: Hs = 1.33; Dir = 115°; T = 9.20sec and probability = 2%.

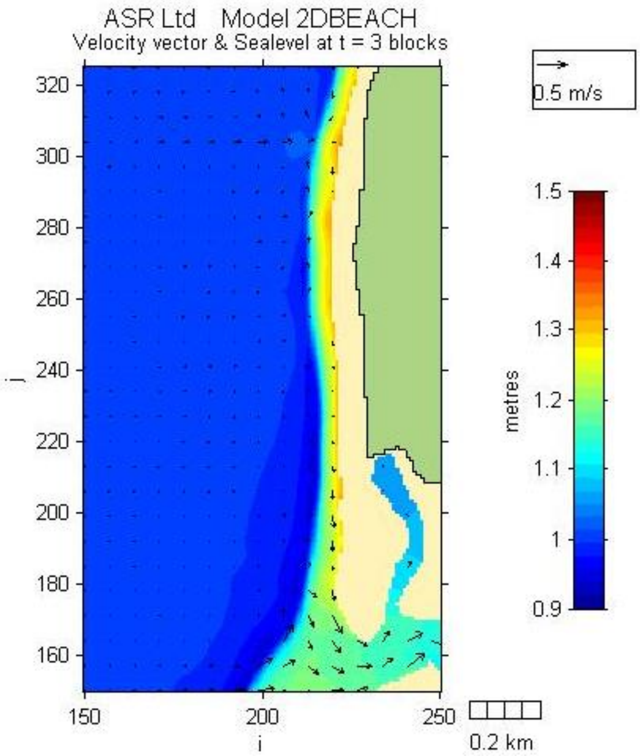


Figure 5.26 Current velocity vector and sea level for Offshore ESE: Hs = 1.75m; Dir = 105°; T = 8.09sec, Inshore: Hs = 1.45; Dir = 95°; T = 8.08sec and probability = 4%.

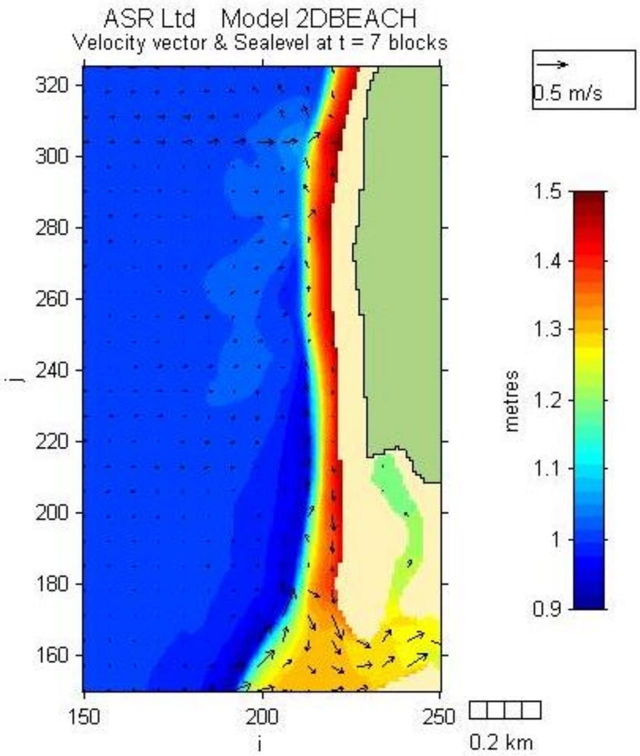


Figure 5.27 Current velocity vector and sea level for Offshore ESE: Hs = 2.75m; Dir = 105°; T = 8.18sec, Inshore: Hs = 2.25; Dir = 95°; T = 8.08sec and probability = 1%.

5.5.6 Limitations

Firstly it should be noted that although numerical models can provide great insight into the complex dynamics of the coastal environment, results should be regarded as indicative rather than absolute, with close comparison to measured data recommended (Dean and Dalrymple, 2002). Several limitations of the current study should be noted. Firstly boundary conditions were extracted for a single location in the middle of the open boundary from the Swan runs. This condition was then applied along the whole input boundary. However in reality the wave angle and wave height is varied along this boundary, especially waves from a south westerly direction which undergo a great degree of refraction and diffraction around Cape St Francis. Easterly waves arrive more parallel to the open boundary except along the headland where refraction causes a lower angle of incidence.

The result of this uniform boundary condition is that during south westerly swell the wave angle in the northern half of the grid is over overestimated. Thus longshore currents along the northern half of the grid may be overestimated. In addition variation in wave height along the boundary due to the large degree of refraction during south westerly swells is not accounted for; therefore the longshore wave height gradient is not simulated during these conditions. During easterly swells the wave angle along the southern boundary is well aligned but the wave angle along the southern 1/3 of the boundary is overestimated. This means the angle of wave incidence along the point will be overestimated, possibly leading to overestimation of longshore currents (Figure 5.28).

The results should be treated as preliminary and indicative of general trends and processes rather than absolute definitive answers, with the emphasis on the existing processes and the effects of different features in this complex environment.

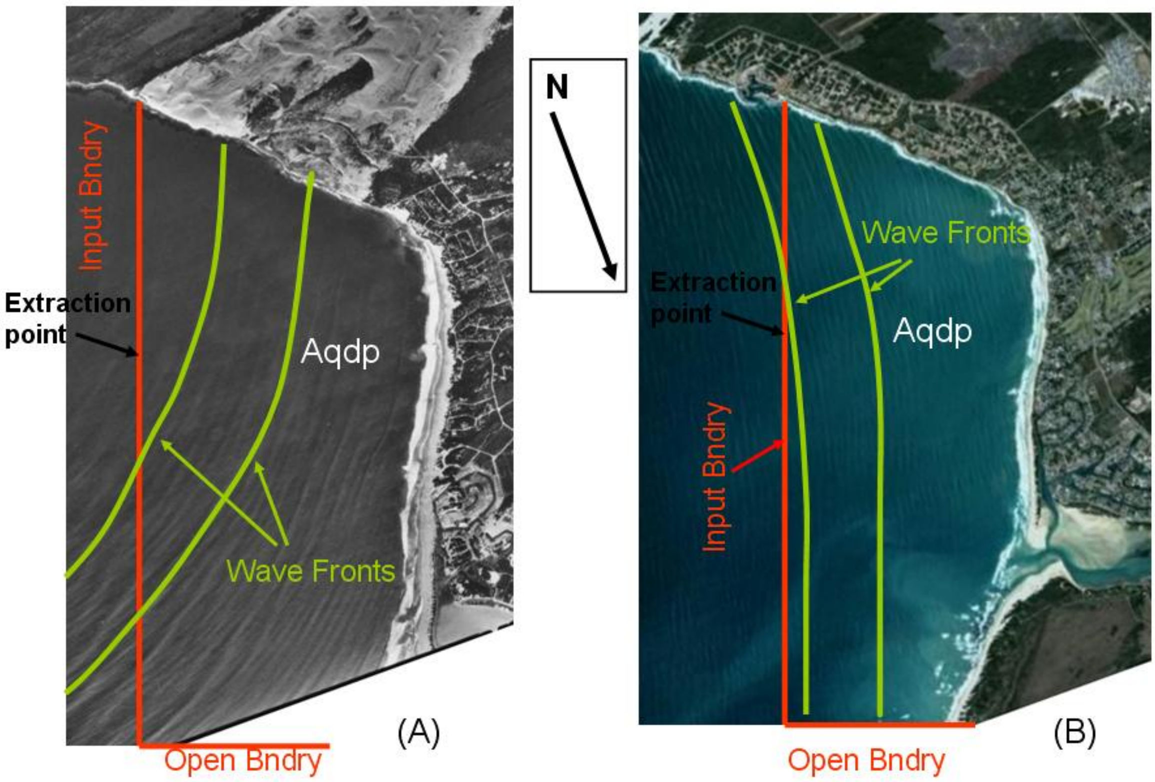


Figure 5.28 Aerial photographs showing angle of wave fronts within St Francis Bay and the location of 2DBEACH input boundary and swan output extraction point. For south westerly (A) and easterly (B) offshore swell directions.

5.6 Discussion and Conclusions

Longshore transport calculations conducted by Mead et al. (2006) suggest a discontinuity to net transport direction either side of Umzuwethu reef, with net transport in a south westerly direction to the south of Umzuwethu and net transport marginally north easterly to the north of Umzuwethu. This was in agreement with previous calculations conducted by presented in

Bickerton and Pierce (1987) and WPR (1993). Simulation of wind driven currents showed that the dominant south westerly winds drive relatively weak north easterly currents out of the bay. Although these currents alone may be too weak to suspend sediment, sediment suspended by wave action could then be transported. Considering the fine grain size found within St Francis Bay this process could well account for a slow transport of sand out of St Francis Bay to the north east. This process could account for the large losses measured in the offshore region (10 – 15 m water depth). Recent research by Black *et al.* (2008) of the sediment dynamics of monsoonal beaches in India suggests that wind driven currents are critical for sediment transport along the Kerala coast where a net annual transport of 178 000 $m^3.yr^{-1}$ was calculated for the inner shelf at depths >8m out to +\- 2km offshore.

In order to investigate the hydrodynamics of St Francis bay in more detail further modelling was conducted by the author, firstly NOAA WW3 hind-cast wave data was used as boundary conditions for the 3rd order wave refraction model SWAN (Booij *et al.*, 2004) using a large bathymetry grid extending to +/- 100m depth offshore of Cape St Francis. Offshore data from the Aquadopp deployment period was modelled and a good agreement between measured and modelled data was achieved. Subsequently the long term offshore wave climate was used as boundary conditions and 'steady state' simulations were conducted to transform the long term offshore NOAA Wave Watch 3 wave climate to the inshore in St Francis bay. All conditions with greater than 0.51% probability were used to create a representative wave climate representing 96% of the full climate, which was used to drive the numerical model 2DBEACH over a smaller grid.

Analysis of this hydrodynamic modelling provided added insight into the behaviour of waves and currents within St Francis bay under different wave conditions. Certain bathymetric features were identified and their effects and significance evaluated. Comparison with aerial photographs allowed verification of significant offshore flow in the South Western corner of the bay immediately adjacent to Huletts Reef.

The results of the detailed 2DBEACH hydrodynamic modelling agree with previous calculations and modelling results which concluded that strong unidirectional longshore currents occur along the headland due to the oblique angle of wave incidence and the close to parallel angle of wave incidence along the beach leads to weak longshore currents of variable direction. However this detailed modelling allowed greater insight into the dynamics and processes occurring in St Francis Bay, which suggest a relatively high degree of complexity governed by several main elements. Key elements controlling the hydrodynamics are: the fact that the St Francis Bay beach is bounded by a hard headland to the south, small scale nearshore features like Huletts Reef and Anne Avenue reef which effect local hydrodynamics, the large feature known as Umzawethu Reef has a major influence on the beach altering waves and currents, leading to the creation of a large salient in its lee which gives the St Francis Bay beach its characteristic “dog leg” plan form. In addition the ancient Kromme river valley causes defocusing of wave energy.

What is clear is that little longshore transport is evident along St Francis Bay Beach, with erosion occurring due to cross-shore transport due to large waves from a Southerly to Easterly direction and factors such as the predominant alongshore wind-driven currents transporting sand to the north east and out of the bay.

The next step would be to investigate the sediment transport within St Francis Bay in more detail by conducting sediment transport modelling. However it is important to note that In order to have confidence in sediment transport modelling, verification is required, and this can be achieved by modelling periods between bathymetric surveys, using sediment traps or measuring build up against sand trapping features or structures.

6 REEF DESIGN AND ASSESSMENT OF FUNCTIONAL PERFORMANCE

6.1 Introduction

As discussed in previous chapters, little longshore transport is evident along St Francis Bay Beach, with erosion occurring due to cross-shore transport due to large waves from a Southerly to Easterly direction. Sand is transported to the north-east out of the bay by predominant alongshore wind-driven currents. Thus the previously recommended solution of multiple groynes (Entech, 2002a) would not have been effective in this environment. Groynes are effective in longshore dominant beach environments where they act as a barrier and sand accumulates on the updrift side, however they are ineffective in cross shore dominant environments and can actually exacerbate erosion by increasing offshore currents (Basco and Pope, 2004). In addition local residents were opposed to groynes for aesthetic and amenity reasons. According to the USACE (2006) detached breakwaters offer the most effective protection against cross-shore erosion, with the modification of wave rotation in the design of MPR's, these structures can also reduce the chronic north-easterly movement of sand.

Reef design and assessment of functional performance included a combination of empirical calculations and numerical modelling. Several factors were assessed to determine the best location for the placement of a multi-purpose reef including the distance from the beach that a reef should be placed, effective dissipation of waves, wave rotation/attenuation (i.e. modifying the waves without breaking them), and shoreline response. During these exercises, the primary aim was promoting beach protection with the secondary aim of creating a high quality surfing break.

Three numerical models from the 3DD Suite of Coupled Models were used: 3DD, WBEND and 2DBEACH. Modelling involved extracting boundary conditions from the regional model simulation outputs for input into the local grid. Reefs were incorporated into the local grid via the support module of the 3DD Modelling Suite (Black, 2001). Simulations were then undertaken and the outputs were assessed for factors responsible for beach protection, namely dissipation, rotation and salient formation as described by Black *et al*. (2001). In addition the circulation patterns behind the reefs were assessed according to recent research findings by Ranasinghe et al. (2006). Empirical predictions and preliminary numerical modelling, conducted by Mead *et al.* (2006) on planar bathymetry using 2DBEACH was used to assess the long-term shoreline response to preliminary reef designs. Further hydrodynamic modelling using 2DBEACH was conducted to assess the impacts of the reefs on the nearshore hydrodynamics with specific attention to changes in nearshore currents and the creation of four cell salient forming circulation patterns described by Ranasinghe *et al.* (2006).

6.2 The Design Process

Empirical calculations were conducted to assess the optimal reef size and location. Several reef designs were tested with WBEND, 3DD and 2DBEACH. A range of tests were undertaken to assess factors such as distance offshore, level of wave energy dissipation and wave rotation/attenuation, with a range of design boundary conditions. The conditions most likely to cause erosion were used as boundary conditions for testing dissipation, these included mean and storm wave events, wave directions, and tidal ranges from mean lower low water (MLLW) to spring high tide (SHT) with storm surge. The inshore wave climate developed in the previous chapter was also used as input boundary conditions for 2DBEACH modelling to assess circulation and salient formation. The alongshore size of the reef was governed by a combination of factors that related to the length of coast to be protected and the distance of the reef offshore. The major findings and recommendations derived from these various modelling exercises and empirical calculations are presented in this Chapter.

6.3 Design Bathymetry Grid

The inshore bathymetry used for the modelling and reef design process was constructed from a combination of recent bathymetry and beach profile data. Bathymetric data was collected by the author during a series of surveys between December 2005 and June 2006 (described in chapter 4). The most recent beach profile data was collected by Maarschalk and Partners Inc. during October 2006. These data sets were combined, gridded in Surfer ® 7 using the kriging interpolation method with a cell size of 5m and rotated 200° CCW for numerical modelling purposes, Figure 6.1 below. This grid was then converted into a 3dd model bathymetry grid as shown in Figure 6.2.

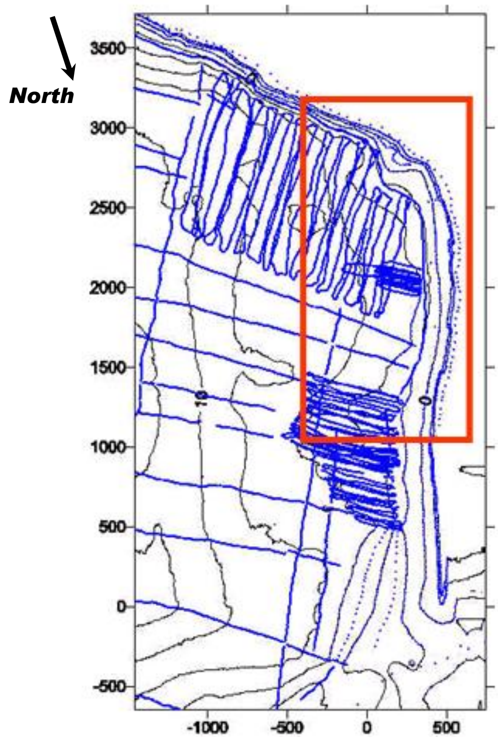


Figure 6.1 Profile data used to generate inshore bathymetry, rotated 200 counter-clockwise, contour values are in meters. The red box indicates the section of the beach selected for the proposed reef sites.

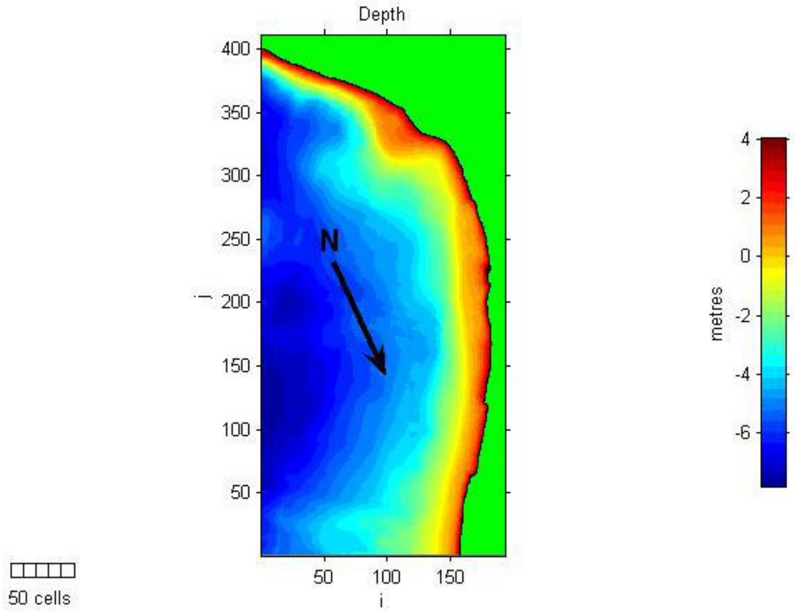


Figure 6.2 Final inshore bathymetry grid used for reef modelling and design. The grid has been rotated 200 degrees counter clockwise for modelling purposes.

"Batools", in the 3DD support module (Black, 2000) allows the investigator to describe a reef design by coordinate position of the start of the main contour (the reef crest), depth of the main contour (which can be made to vary along each section of the reef), orientation, curvature and length of particular reef sections, and reef face gradient (which can also be varied along the sections of the reef and can be linear or convex). The designed reefs are 'superimposed' onto a bathymetry template and then converted to a single bathymetry grid for model tests.

6.4 Offshore Reef Location

The offshore location of a multipurpose reef is a critical design consideration. Numerical and physical modelling studies have shown the sensitivity of the beach response to distance between the reef and the beach (Black, 2003; Ranasinghe *et al*., 2006: Ranasinghe and Turner, 2006). The basic relationship is that reefs placed too close to the shoreline tend to have an erosive effect on the beach whereas reefs placed further offshore will shelter the beach and allow the beach to accrete. Black (2003) suggests that reefs placed offshore at a distance 2 to 4 times the longshore length of the reef would have the greatest sheltering effect. Ranasinghe *et al*. (2006) predict shoreline accretion based on the ratio between the reef distance offshore (S_a) and the surf zone width (SZW), (S_a/SZW). For situations where this ratio is greater than 1.5 net shoreline accretion is predicted, while erosion is predicted where this ratio falls below 1.0.

This relationship described in Ranasinghe et al. (2006) was first used for preliminary design quantities – namely offshore distances of 150, 175, 200, 225 and 250 m, with alongshore reef width of 100 m. The surf zone width probability was extracted from 2DBEACH modelling of the statistical inshore wave climate described in chapter 4. The probability of width of surf zone was compared with the different distances offshore and the results indicate that only the closest positions (150 m) falls within between the erosion and accretion boundary for 1% of the time. Results are shown in Table 6.1 below.

Table 6.1 Calculation of erosion or accretion depending on reef distance offshore (S_a) and surf zone width (SZW) probability according to relationship defined by Ranasinghe *et al.* (2006).

		$S_{a\ (m)}$				
Probability (%)	**SZW (m)**	**150**	**175**	**200**	**225**	**250**
100	**5.66**	26.49	30.91	35.32	39.74	44.15
90	**32.56**	4.61	5.37	6.14	6.91	7.68
80	**40.58**	3.70	4.31	4.93	5.54	6.16
70	**48.60**	3.09	3.60	4.12	4.63	5.14
60	**57.10**	2.63	3.07	3.50	3.94	4.38
50	**64.17**	2.34	2.73	3.12	3.51	3.90
40	**70.78**	2.12	2.47	2.83	3.18	3.53
30	**78.80**	1.90	2.22	2.54	2.86	3.17
20	**88.24**	1.70	1.98	2.27	2.55	2.83
10	**96.73**	1.55	1.81	2.07	2.33	2.58
1	**115.61**	1.30	1.51	1.73	1.95	2.16

Therefore according to Black (2003) a reef of 100m longshore length should be placed at distance of between 200-400m offshore of mean sea level to create the greatest sheltering effect. And according to empirical relationships defined by Ranasinghe *et al*. (2006) the reef should be placed at a distance of > 150 m offshore in order to induce accretion for the wave climate experienced at St Francis Bay beach.

6.5 Reef Design

Figure 6.3 and Figure 6.4 present the computer-designed positions for three reefs at St. Francis Bay. Considering the results of empirical calculations presented in the previous section, the reefs were positioned at +/- 225m offshore of mid tide. The alongshore width of the reef was +/-100 m. The asymmetric plan shape, with a longer northern ‘arm’, was aimed to provide greater wave dissipation during south easterly and easterly swells and provide additional sediment retention through wave rotation (detailed below). The crest height was set to chart datum. Each individual reef would have a volume of ~15,000 m^3 above the seabed, and cover an area of ~5,000 m^2. St Francis Bay has some unique characteristics required special attention in the design process. The inshore wave climate is relatively variable in terms of wave height but fairly consistent in terms of direction. The following sections describe the preliminary findings of reef design testing.

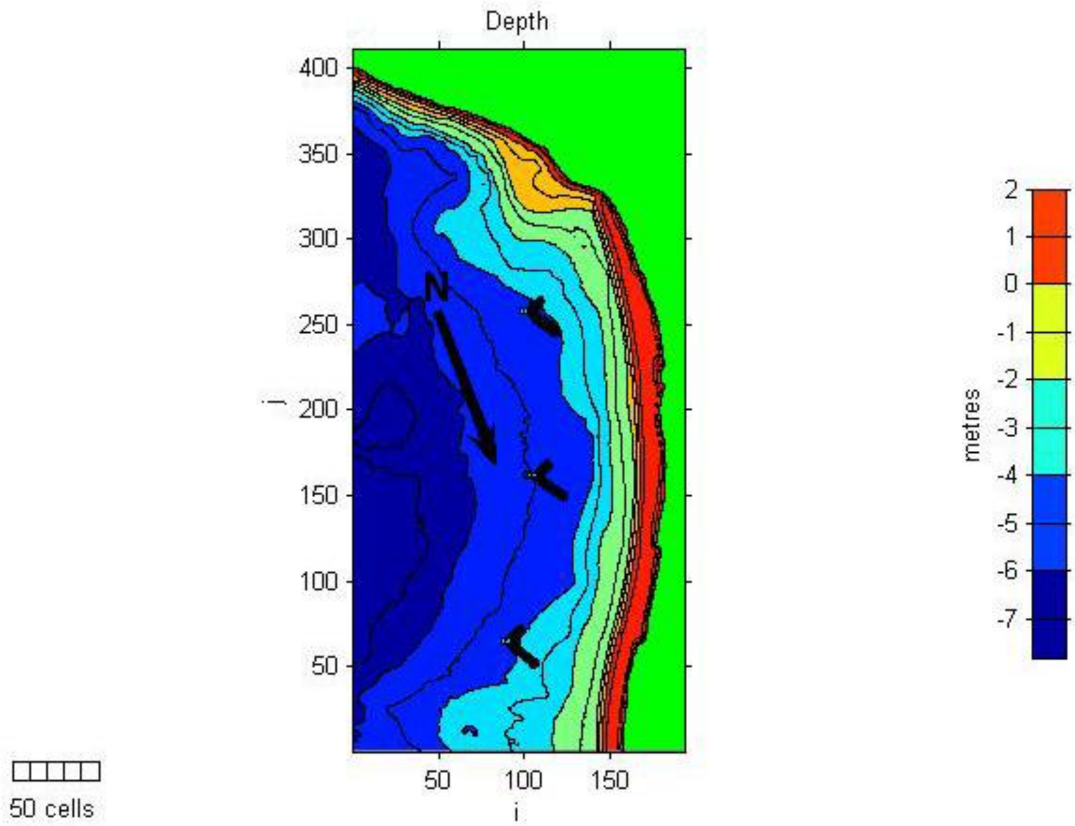


Figure 6.3 Location map of the St. Francis Bay reefs – on the design bathymetry rotated 200° CCW for numerical modelling.

Figure 6.4 Location map of the St. Francis Bay reefs superimposed on a Google Earth Image (2004).

6.6 Wave Dissipation

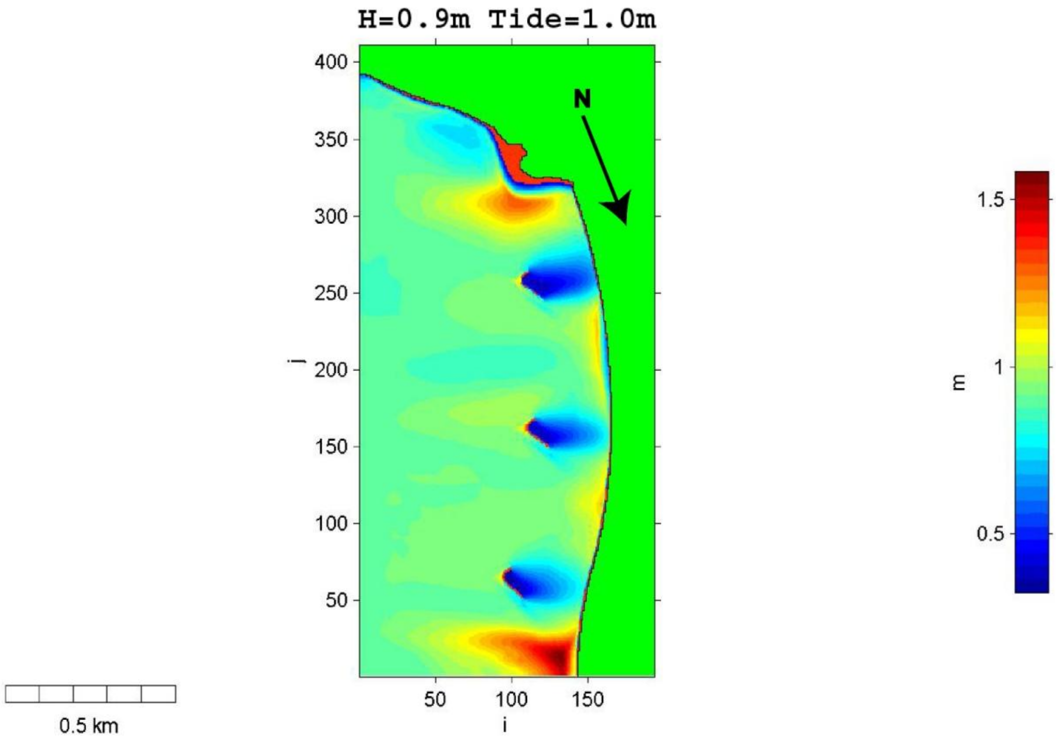
Investigation of wave energy dissipation aspects of reefs at St. Francis Bay (WBEND) confirmed that the distance of ~200 m offshore was required to ensure that the reef was beyond the 'normal' surf zone during significant storm events. ASRMDI data was extracted offshore of St. Francis Bay for an 8 year period, from February 1998 to February 2006. The 1, 5, 10, 25, 50 and 100 year return period storm events were calculated for eight directional bins using ASR MDI Matlab ® toolbox. A transformation parameter was applied to this offshore data to find the relevant swell heights at the inshore location during the above mentioned storm swell events (Table 6.2).

Table 6.2 Significant swell heights at 1, 5, 10, 25, 50 and 100 year return periods, grouped into directional bins for offshore location and transformed to the inshore location.

	Return Period (years)											
Directional	1	5	10	25	50	100	1	5	10	25	50	100
Bins	**Offshore Swell Height (m)**						**Inshore Wave Height (m)**					
45	2.2	2.7	2.9	3.2	3.4	3.6	1.5	1.8	1.9	2.1	2.3	2.4
90	4.7	5.7	6.1	6.7	7.1	7.6	3.2	3.8	4.1	4.4	4.7	5.0
135	5.0	6.2	6.8	7.5	8.1	8.7	3.3	4.2	4.5	5.0	5.4	5.8
180	5.0	5.7	6.1	6.5	6.8	7.1	3.3	3.8	4.0	4.3	4.5	4.7
225	5.7	6.3	6.5	6.8	7.0	7.2	3.8	4.2	4.3	4.5	4.7	4.8
270	3.7	4.8	5.3	5.8	6.2	6.6	2.5	3.2	3.5	3.9	4.2	4.4
315	2.1	2.5	2.7	2.9	3.1	3.3	1.4	1.7	1.8	2.0	2.1	2.2
360	1.3	1.5	1.6	1.7	1.8	1.8	0.9	1.0	1.1	1.1	1.2	1.2
Combined	6.4	7.3	7.7	8.2	8.6	9.0	4.2	4.9	5.1	5.5	5.7	6.0

From previous studies (Bickerton and Pierce 1988; CSIR, 1992; WPR, 1993) and modelling studies during the feasibility study phase (Mead et al. 2006) as presented in chapter 0 and 0, it was evident that large short period storm swells from the easterly and south easterly quarters, with a relatively direct approach, were the most significant within the bay and responsible for the most dramatic and acute erosion events. WBEND wave refraction modelling was conducted in order to investigate wave height reduction and sheltering effects of the reefs during different swell and tidal conditions. The largest wave heights are found in return period swell events from the south easterly direction bin (135°) therefore these were selected for modelling purposes. Special attention is paid to the large, short period storm waves during high water levels as these scenarios allow the highest degree of wave energy to reach the shore and therefore the most acute erosion. Figure 6.5 a and b wave height plots clearly shows how wave energy is dissipated by a submerged reef showing the wave shadow zone for mean tide and SHT for the average swell experienced at St. Francis Bay of

0.9 m wave height. Figure 6.6 illustrates the wave height reduction in the lee of the reefs for the 10 year return period storm event with swells of 4.5 m within the bay at Mean Sea Level (MSL), Spring High Tide (SHT) and SHT + storm surge water levels. Figure 6.7 is the Ubed3 parameter output of WBEND which shows the area where the waves will break or the width of the surf zone, indicated by the brown area. The cases chosen here indicate that the reefs are located beyond the surf zone during the 10 year return period storm swell events for SHT and SHT + storm surge water levels. The bathymetry grids have been rotated 200° counter clockwise for use in the numerical models. As discussed in section 4.6, the most common direction for waves reaching the nearshore in to St Francis Bay is from an ESE direction (average direction of 119°).



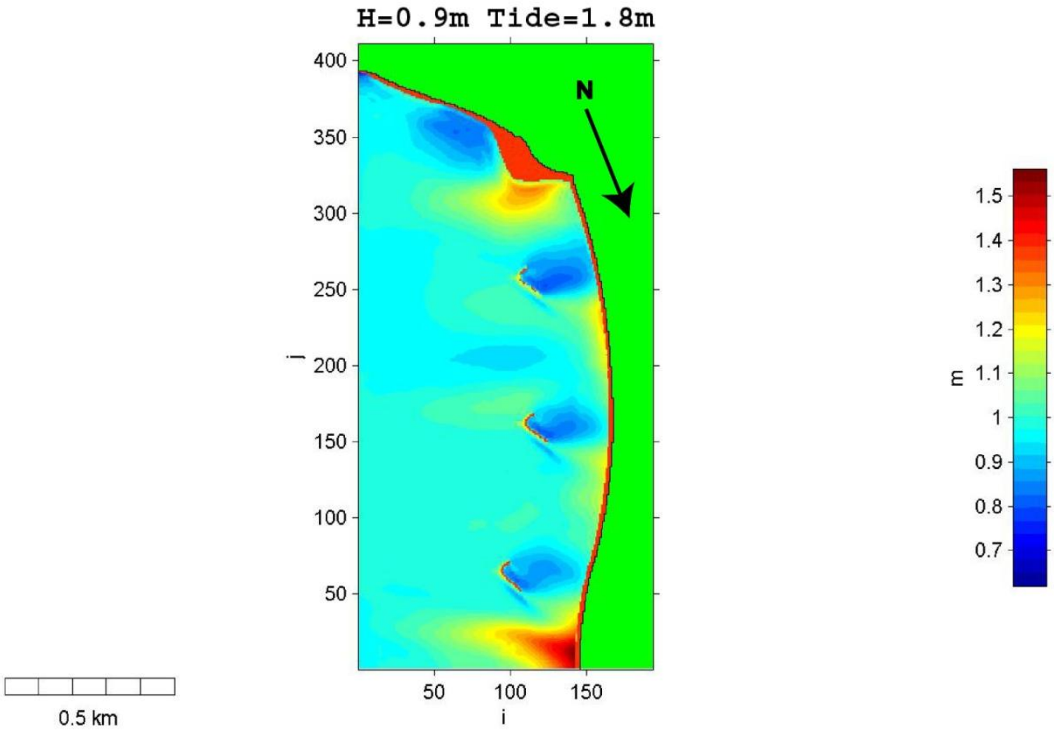
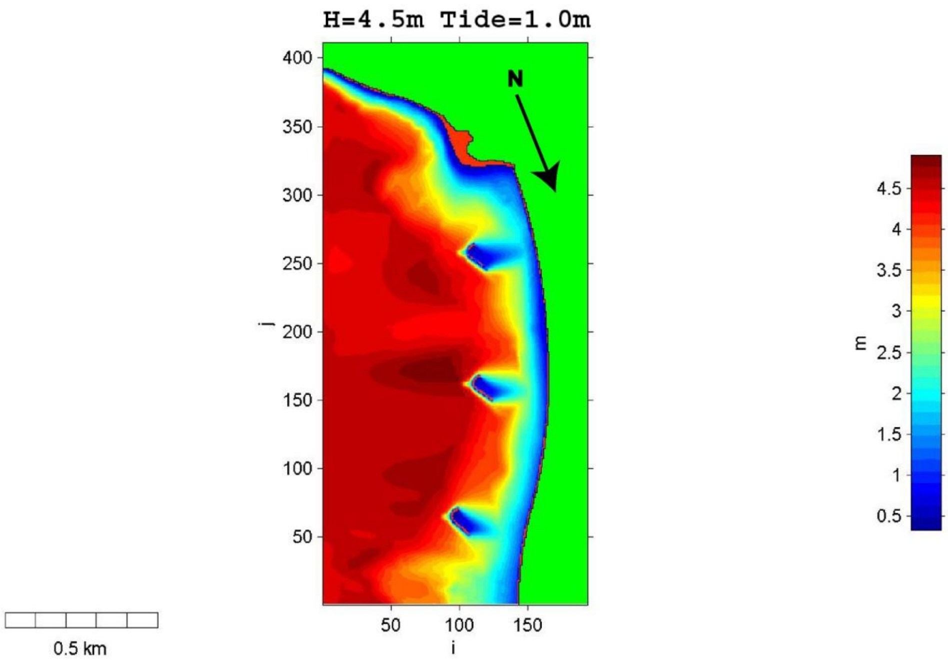
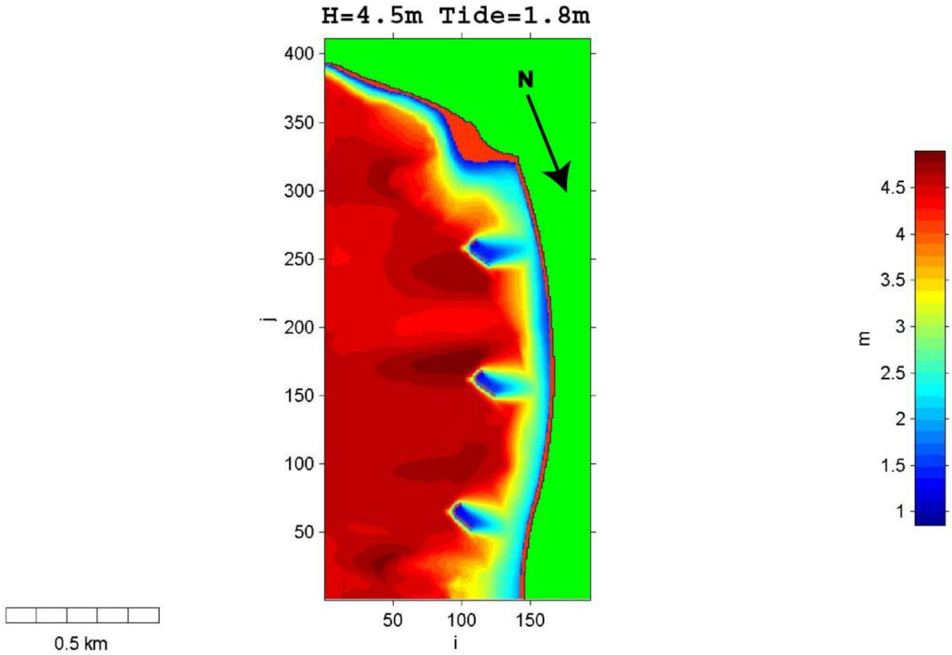


Figure 6.5 H=0.9m, direction of 110°, above-MSL and below-SHT, illustrating favourable levels of wave height attenuation in the lee of the reefs.



a



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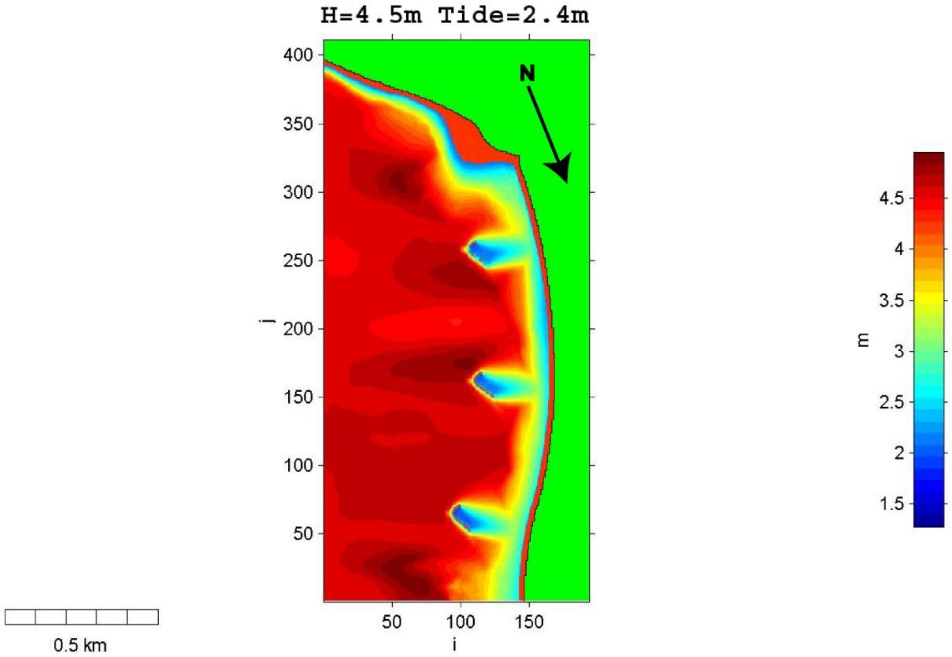
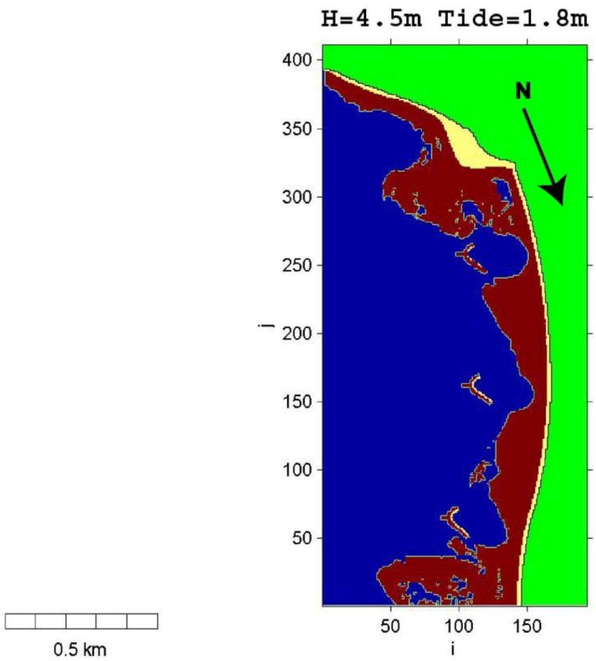


c

Figure 6.6 Wave shadowing due to an offshore reef during 10 year return period storm event, H=4.5m T=9 sec, at a - MSL, b - SHT and c - SHT + storm surge tidal levels. Storm waves associated with extreme high tides (bottom figure) are responsible for acute erosion events as the waves break closer to the beach during these events. The reefs show an excellent ability to reduce wave height during these conditions.



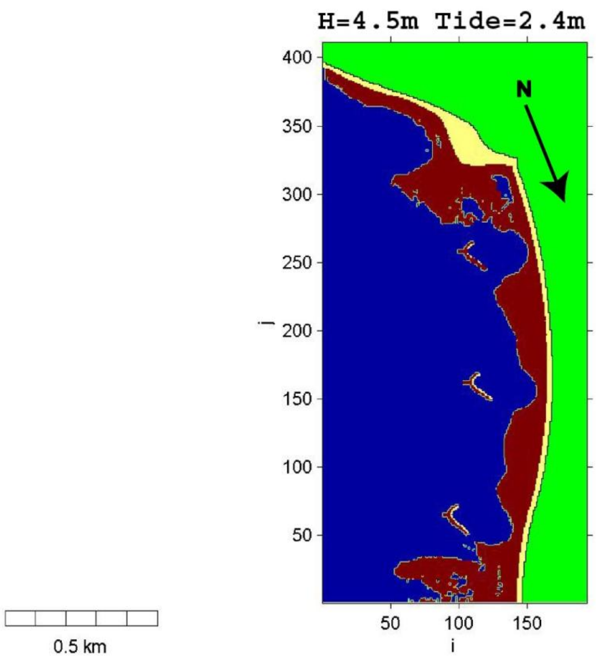


Figure 6.7 The reef location was determined to be outside of the surf zone during 1 in 10 year return period storm wave events for tidal levels: SHT (above) and SHT + storm surge (below). The area of wave breaking is the brown area (surf zone). The shape of the reef is highlighted because waves will be breaking over the reef.

6.7 Wave Rotation

Wave rotation (refraction) can be used as an effective means of sand retention during periods when waves pass over the reef without breaking. Wave rotation refers to redirecting waves so that when they reach the beach and break they modify the longshore component of wave energy flux that generates alongshore currents and removes sand from the beach (Black and Mead, 2001). At St Francis Bay the waves need to be rotated to a more southerly direction to induce sediment retention in the bay.

The 3DD Boussinesq model was utilized for the investigation of wave rotation, since this model best predicts refraction and diffraction of waves. Figure 6.8 shows an idealised schematic of wave rotation over a submerged MPR.

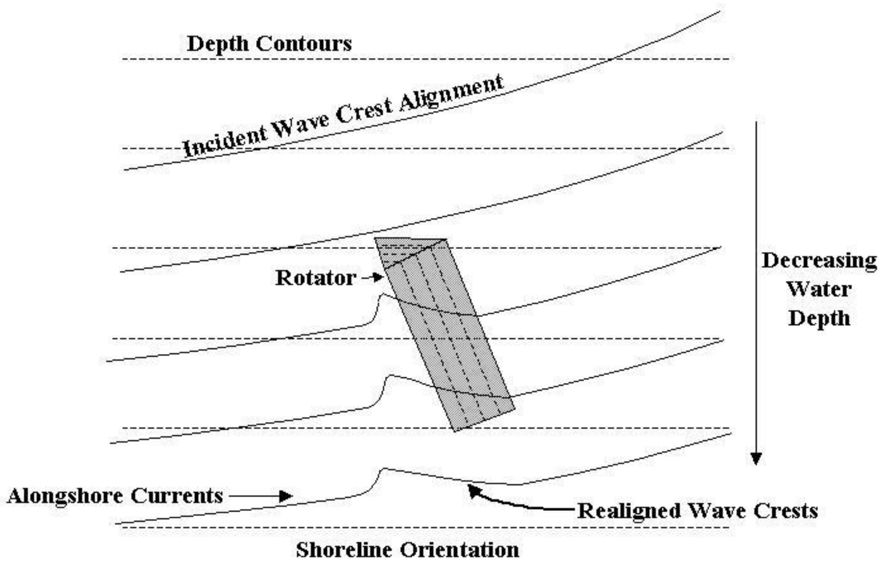


Figure 6.8 Idealised schematic of wave rotation due to a submerged multi-purpose reef (Black and Mead, 2001).

Previous modelling investigations have shown that with only a single-sided reef waves tend to refract up the back of the reef and distort the wave crest, as well as rotate it in a more northerly direction, thereby actually increasing wave driven currents (Figure 6.9) (Borrero et al., 2006). Rotation in the opposite direction is required to lessen the wave-driven current and stabilize the beach. To compensate for this undesired feature, a short reef 'arm' is required – in the present case, the short southern arm was incorporated from the first design (e.g. Figure 6.10). As a result of this feature, waves are unable to refract onto the back of the reef, thus an increase in the northerly direction of the wave crest does not result. Using this information the initial design reef shapes were of a "candy cane" type shape with a long right hand section and short left hand arm. This initial design proved robust, providing all of the desired effects of coastal protection through rotation and dissipation and exhibiting desirable peel angles from a surfing perspective as described in the following chapter.

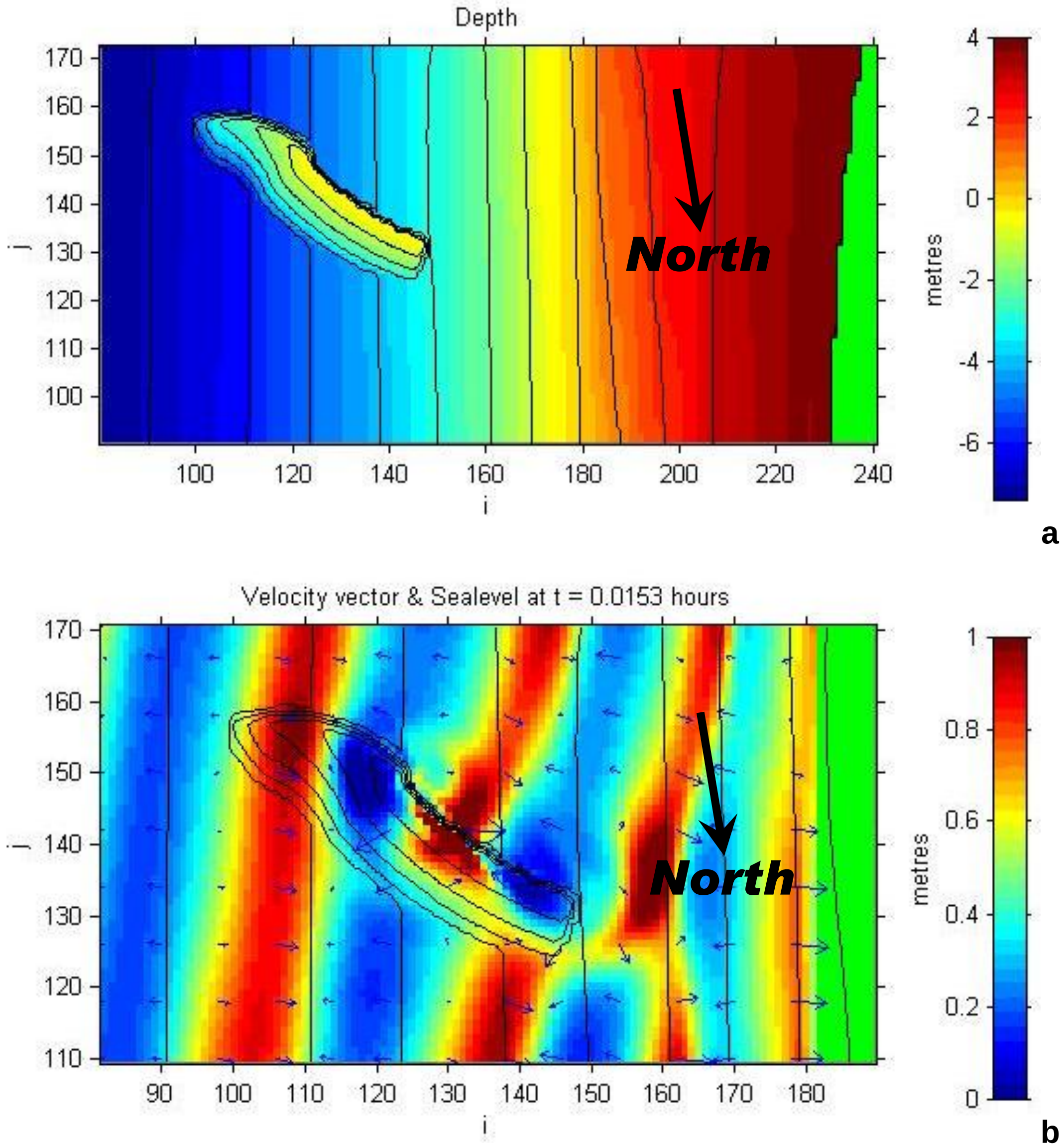
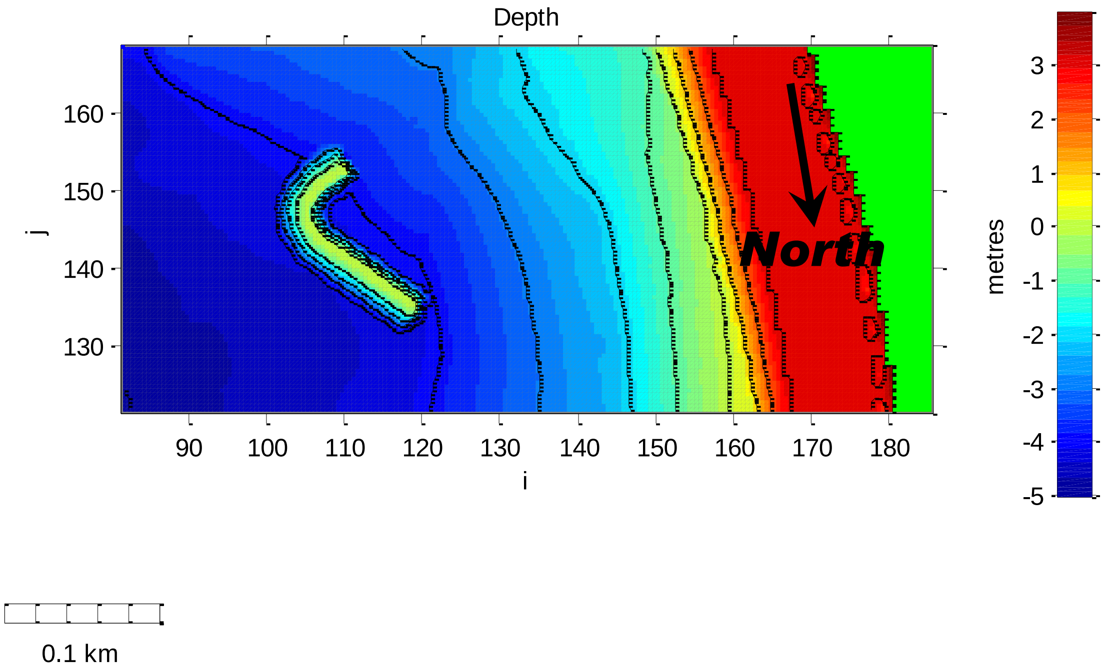
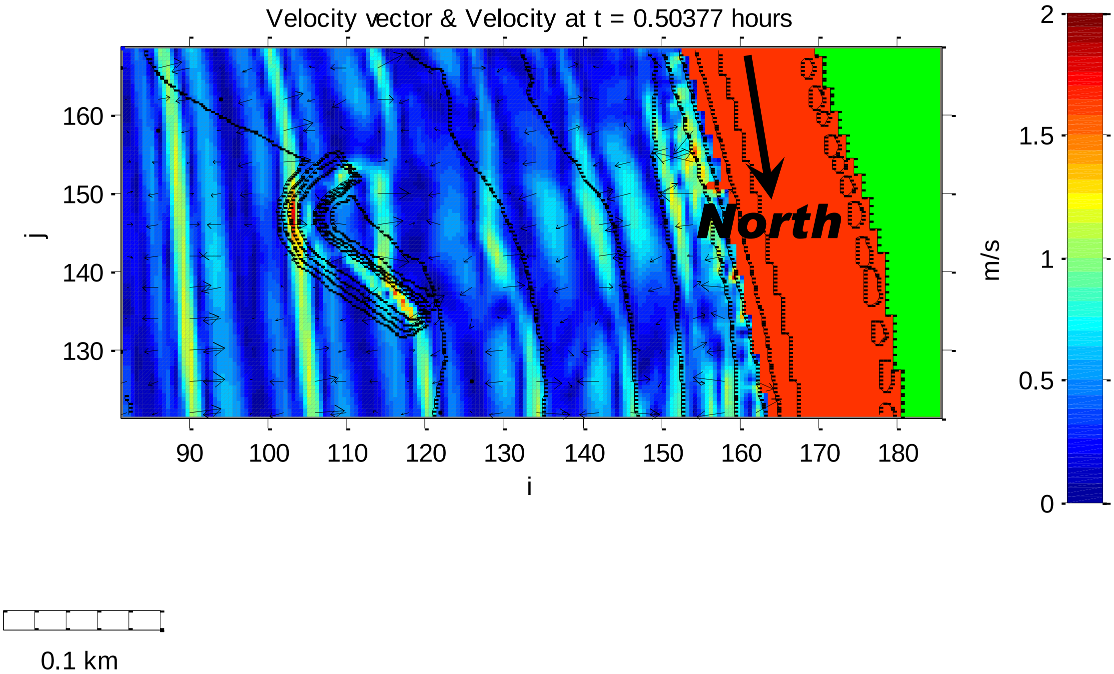


Figure 6.9 a and b– a single sided reef tested during previous modelling (Borrero *et al.*, 2006). Note the tendency for wave crests to rotate clockwise around the offshore end. This would drive currents to the north, opposite of what is desired for shore protection.



a



b

Figure 6.10 First simple 'candy cane' shape reef showed good wave rotation but from a surfing perspective resulted in an undesirable close out section at the nose of the reef.

As the relatively small wave climate of the St Francis Bay site means that waves will often pass over the reef without breaking. This design provides beach protection through wave rotation without excessive wave focusing in the lee of the reef.

6.8 Salient Formation

On sandy shores, natural reefs and islands create wider beaches, termed salients[2] (Fig. 4.10) and tombolos[3] (Fig. 4.11), due to sediment deposition in their lee. While manmade structures have previously been built offshore to afford coastal protection, a thorough understanding of salient formation and impacts has often been incomplete resulting in over-design and negative impacts in the aesthetic and amenity value of the coast. A series of studies at the Centre of Excellence in Coastal Oceanography and Marine Geology at Waikato University identified new concepts for the formation of salients[2] and tombolos[3] and methods to predict the shoreline response in the presence of offshore obstacles of known dimensions (Black and Andrews, 2001a&b). These studies complimented other work in the Artificial Reefs Program, and allowed for the creation of structures that emulate the natural way that offshore reefs protect the coast.

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[2]A salient is a build up of sand in the lee of an offshore structure that *does not* attach to the structure that formed it and so enables sediment to bypass between the obstacle and the shore and is therefore less likely to cause erosion on the adjacent coastline (Komar, 1998).

[3] A tombolo is a build up of sand in the lee of an offshore structure that *does* attach to the structure that formed it, blocking sediment movement alongshore and thus usually resulting in erosion of the downcoast shoreline (Komar, 1998).

Figure 6.11 A salient sand feature in the lee of a submerged reef (Lakes Beach, Noraville, Australia). (From Black and Andrews, 2001a).

Figure 6.12 A tombolo sand feature in the lee of an emerged reef.

For coastal protection, reefs that lead to salient formation are preferred (e.g. Black *et al*., 1997; Black *et al*., 2000 a&b) because the gap between the offshore reef and the shore still allows alongshore transport of sediment, unlike a tombolo, which effectively acts as a groyne and leads to negative down-coast impacts (Bush *et al*., 1996). Alternately, submerged structures too close to the coast can cause erosion due to the circulation patterns that are created (Black, 2003; Ranasinghe *et al*., 2006). Thus, the position of a reef offshore in relation to its dimensions and the existing met-ocean conditions must be determined by a number of methodologies.

Over 350 natural cases of offshore coastal protection, such as presented in Figure 6.11, were identified on the New Zealand and eastern Australian coastlines from aerial photographs (Andrews, 1997). To confidently amalgamate the recreational and coastal protection aspects, accurate predictions of outcomes prior to construction of offshore reefs are required, including the expected adjustments of the beach (Black and Andrews, 2001a). Care is required both to optimize the benefits of the structures and to minimize or eliminate any negative shoreline impacts (Black, 1999; Black and Andrews, 2001a). On the Gold Coast in Queensland, Australia, an offshore submerged reef, designed by ASR Ltd, has achieved coastal protection by salient formation with no down coast impact (Figure 6.13).

Figure 6.13 The Gold Coast multi-purpose reef was designed with a primary function of erosion control and secondarily to produce high-quality surfing waves. The notations are provided by John McGrath of the Gold Coast City Council (Mead et al. 2006).

6.8.1 Empirical Predictions

The shape of the salient that forms in the lee of an offshore reef can be predicted using empirical equations (Black and Andrews, 2000a; Andrews, 1997). At St Francis Bay, calculations using the preliminary reef dimensions are worked through below to predict the level of coastal protection that each offshore reef would provide.

The longshore width of the reef (*B*) and the distance between the reef and the undisturbed shoreline (*S*), indicate that the reef would form a salient. Salients form when:

$$\frac{B}{S} < 2.00 \qquad \text{(Equation 6.1)}$$

Next, by substituting the reef dimensions into the salient equations (Equation 6.2 and Equation 6.3) of Andrews (1997) and Black and Andrews (2001a), the geometry of the salient can be predicted. The average salient amplitude for offshore reefs is given by,

$$\frac{X}{B} = 0.498\left(\frac{B}{S}\right)^{-1.268} \qquad \text{Equation 6.2}$$

where *X* is equal to S - Y_{off}, which is the distance between the undisturbed shoreline and the reef (S), minus the length of the shore normal between the undisturbed shoreline and offshore extremity of the salient (Y_{off}). Salient basal width is given by,

$$\frac{Y_{off}}{D_{tot}} = 0.125 \qquad (\pm\ 0.020)\ \text{Equation 6.3}$$

where, D_{tot} is the total length of shoreline affected. From these equations, using the results from the calculations described above, for a reef of B = 100 m and S = 225 m the predicted salient is a maximum of 85 m cross-shore at the widest point, tapering down to zero accretion some 343 m in each direction alongshore. However, the alongshore length is normally reduced to allow for 10% of the across width (since it asymptotes to zero), which results in an alongshore length of approximately 617 m in this case. The width of the salient refers to the distance moved offshore by the beach isobaths.

6.8.2 Model Predictions

Beach evolution modelling was undertaken with Model 2DBEACH (Black and Rosenberg, 1992a) to assess the shoreline response of preliminary reef designs at St. Francis Bay. 2DBEACH is a non-linear numerical circulation model for irregular waves, containing five coupled simulations of physical processes: 1) wave height transformation, 2) wave angle refraction, 3) wave dissipation due to breaking and friction, 4) radiation stress-driven circulation and 5) sediment transport.

In this phase the reefs were added to a planar bathymetry and the model runs over long periods with varying wave and tide conditions to predict the long-term sedimentary response. The modelling is particularly focused on the development of the salient at the shoreline. These predictions effectively bring together all the hydrodynamics occurring in response to a reef (wave heights, wave angles, current speed and direction, wave set-up, etc.) and provide predictions of beach response. 2DBEACH has capacity to predict features such as rip currents, sand bar movement, beach transformations, storm erosion and the build-up of beaches after storms.

Initial 2DBEACH Modelling conducted as part of the feasibility study (Mead et *al.*, 2006) adopted the following boundary conditions:

Wave heights:	Mean of 0.9 m and range of +/- 0.5 m
Tidal levels:	MSL +/- 0.8 m
Mean of 0.15 Angles:	Mean = 5^o (relative to design grid) range = +/- 12^o
Horizontal eddy viscosity:	1 m^2s^{-1}
Horizontal eddy diffusivity:	2 m^2s^{-1}
Breaking criterion:	0.78
Roughness length:	0.5 m
Wave friction factor:	0.01

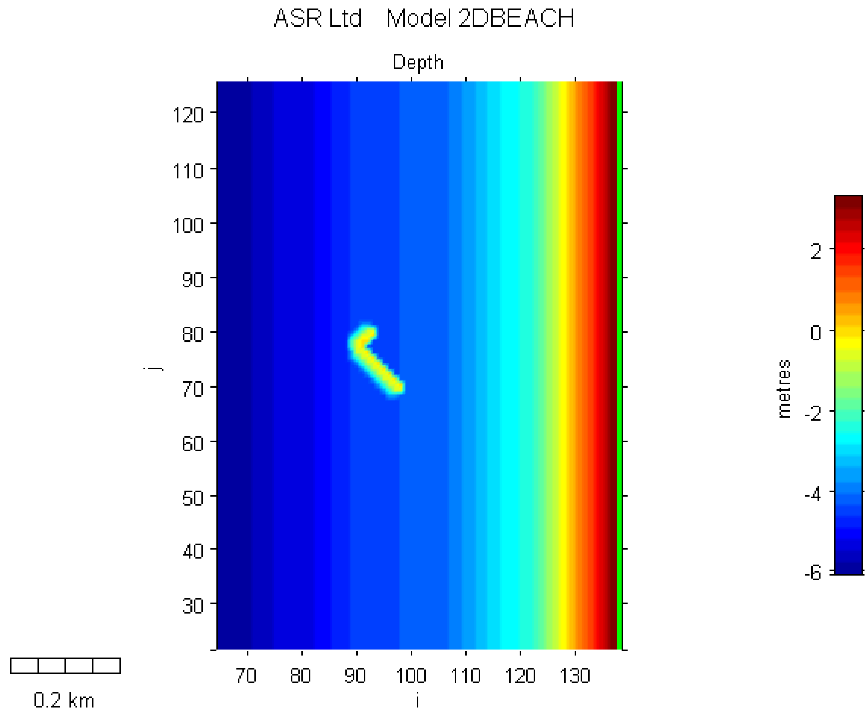


Figure 6.14 A seabed/beach profile was taken from the inshore numerical modelling grid and multiplied to produce a planar beach bathymetry used for 2DBEACH evolution modelling. A single reef was positioned offshore (B=100 and S=225) and model simulations were allowed to run for 234 days (Mead et *al.*, 2006).

The size of the salient predicted using 2DBEACH shown in Figure 6.15 was 74 m maximum width and 535 m alongshore, slightly smaller than that of salient predicted by empirical equations. Past experience has shown that the empirical predictions of salient size are generally greater than the model predictions. The four cell circulation system critical to salient formation (e.g. Black, 2003; Ranasinghe *et al*., 2006)) are shown in Figure 6.16. Ranasinghe et al. (2006) found that the strongest salients occur when the circulation pattern in the lee of the reef consists of two pairs of counter rotating gyres. The shoreward pair rotates such that the sand is swept in to the lee of the reef by the supportive currents. If reefs are placed to close to the shore, only one set of circulation cells is present and the resulting strong currents directed towards the beach diverge at the beach and compress the surf zone leading to erosion (Black and Mead, 2007).

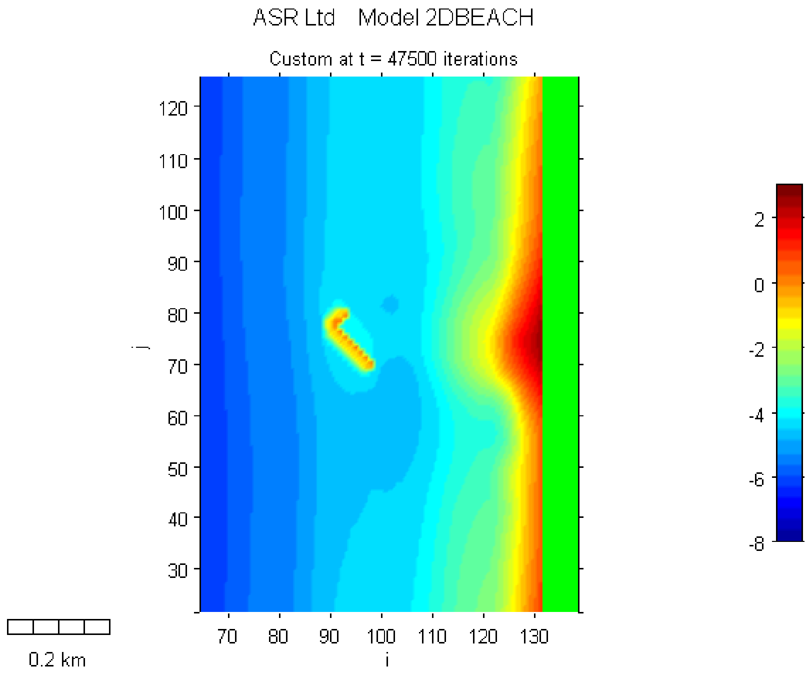


Figure 6.15 Salient evolution in the lee of the generic St Francis Bay Reef (Mead *et al.*, 2006).

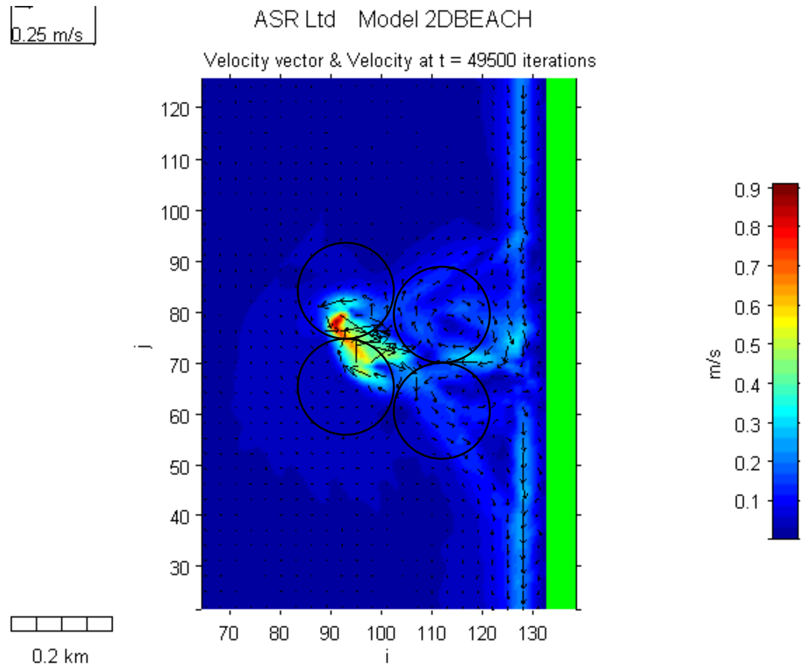


Figure 6.16 Wave-driven currents around a generic St Francis Bay reef that aid salient formation (Mead *et al.*, 2006).

6.9 Detailed Hydrodynamics

6.9.1 Bathymetry

In order to investigate the effect of the reefs on the nearshore hydrodynamics in more detail, further numerical modelling was conducted by the author using 2DBEACH (Black and Rosenberg, 1992a). The two southern most reefs were added to the actual bathymetry, positioned at +/- 225m offshore of MSL with the crest level set to chart datum as shown in Figure 6.17.

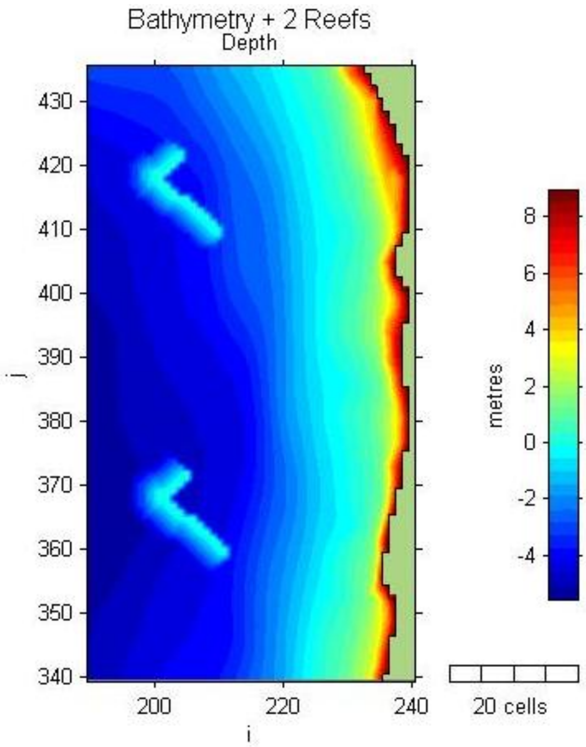


Figure 6.17 Close up of bathymetry for the south west corner of St Francis bay with two reefs located 225m offshore of MSL, cell size of 10m, rotated 200° for modelling purposes.

6.9.2 Modelling

The wave climate used in section 5.5.3 was run over the same bathymetry grid with reefs in position some 225m offshore of MSL, allowing comparison of hydrodynamics under different wave conditions. Velocity differences were computed between the currents over the control bathymetry and currents over the bathymetry with reefs. A selection of cases representing 51% of the inshore wave climate, are presented and discussed in the following Figure 6.18 to Figure 6.25 with particular reference to changes in nearshore circulation and likely impacts on sediment transport and salient formation according to Ranasinghe *et al.* (2006).

Under predominant offshore medium size SW waves which occur 33% of the time offshore of Cape St Francis, the resulting small waves reach the 2DBEACH boundary at a direction of 135° and lead to weak longshore currents in a north easterly direction, reefs exhibit very little effect on waves or wave driven currents, during the highest frequency of occurrence (17%) very minor changes to currents are predicted by the model (Figure 6.18). Slightly stronger wave driven currents are experienced on the reef, with minor changes to currents at the beach under the slightly bigger offshore SW waves occurring 16% of the time as shown in Figure 6.19 .

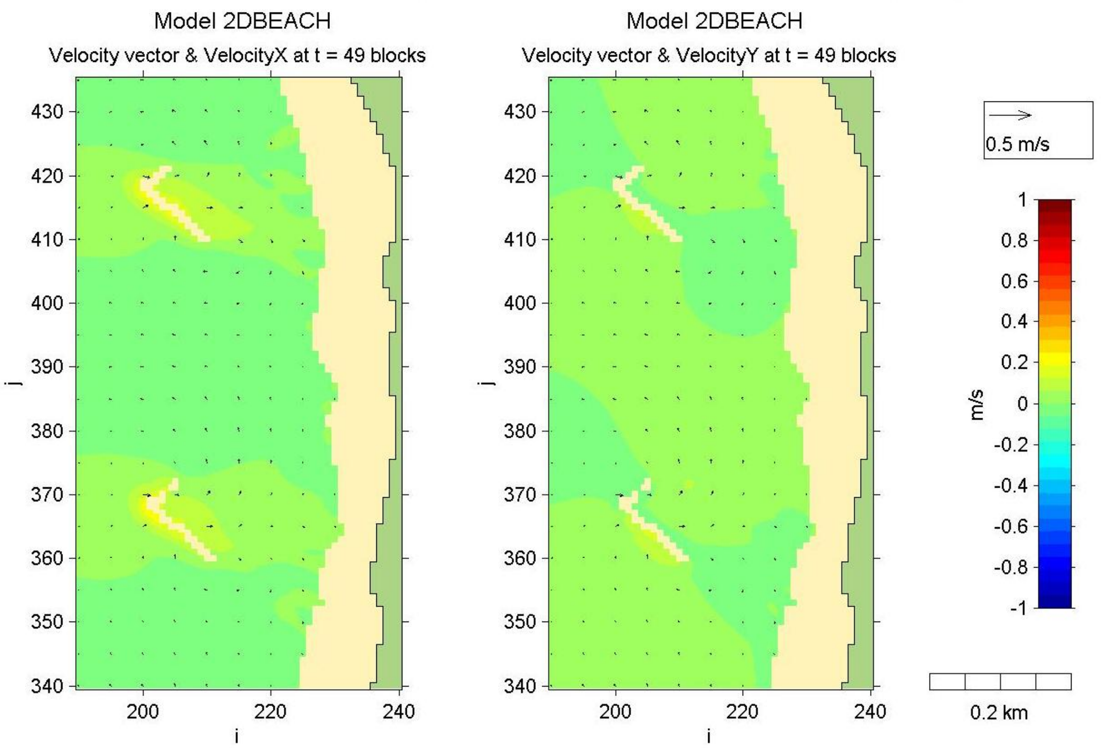


Figure 6.18 Current velocity vector and difference in X direction (left) and Y direction (right), for offshore SW waves: Hs = 1.75m; Dir = 225°; T = 11.14sec, Inshore: Hs = 0.42m; Dir = 135°; T = 11.91sec probability = 17%.

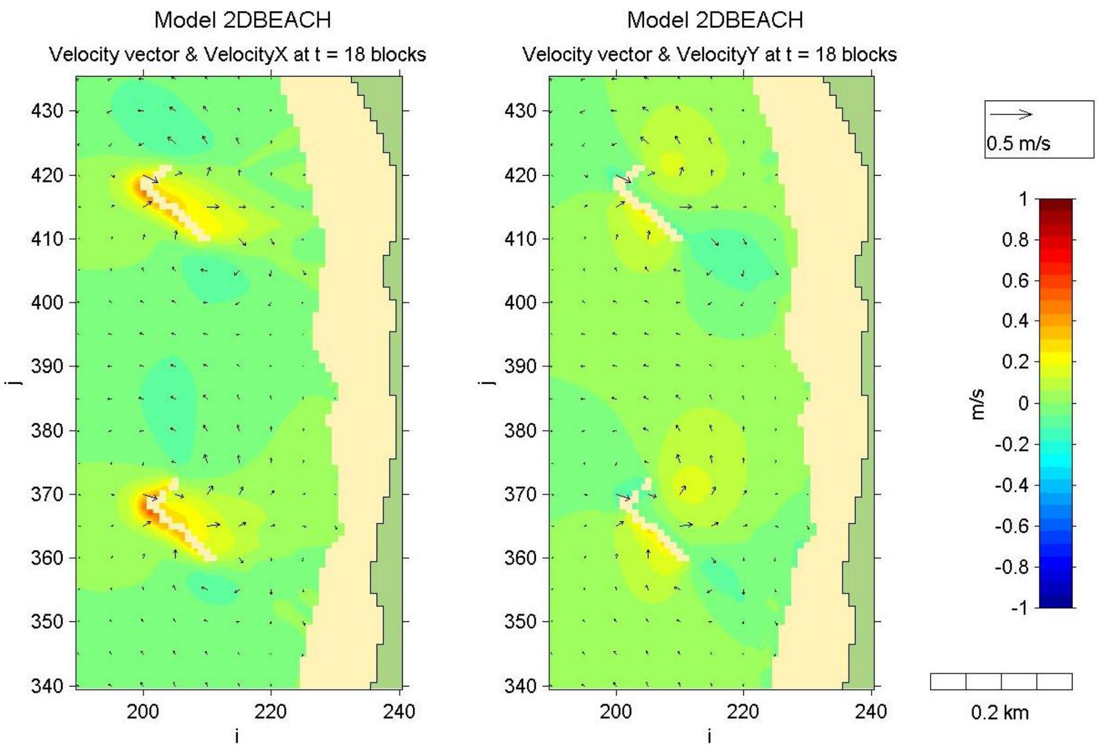


Figure 6.19 Current velocity vector and difference in X direction (left) and Y direction (right) for offshore SW: Hs = 2.25m; Dir = 225°; T = 11.53sec, Inshore: Hs = 0.56m; Dir = 135°; T = 11.91sec and probability = 16%.

Large offshore waves from the SW experience a great degree of result in medium size waves inshore with a direction of 135° at the 2BEACH model boundary. Modelling results in Figure 6.20 below indicate that these conditions result in relatively strong wave driven currents over the reefs. These currents diverge behind the reefs and retroflect forming the first set of circulations cells as described by Ranasinghe *et al.* (2006). Inshore longshore currents at the beach are deflected offshore behind the reefs, dissipating beyond the surf zone. Although not creating the exact four cell circulation described by Ranasinghe *et al.* (2006) the alteration in longshore currents will definitely effect beach morphology behind the reef, most likely leading to salient formation in the lee of the reefs slightly to the south.

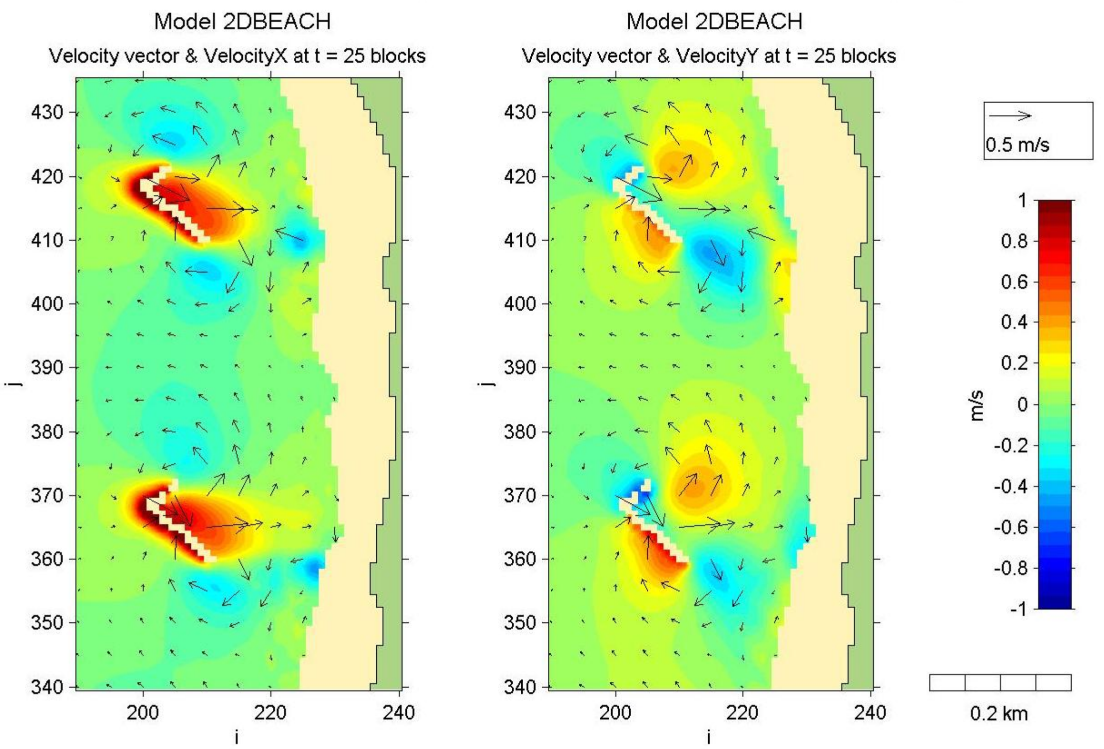


Figure 6.20 Current velocity vector and difference in X direction (left) and Y direction (right), for offshore SW waves: Hs = 4.25m; Dir = 225°; T = 12.69sec, Inshore: Hs = 1.27m; Dir = 135°; T = 11.91sec and probability = 1%.

Medium size offshore waves from the SSW result in small inshore waves with a direction of 135° at the 2DBEACH boundary. Modelling results presented in Figure 6.21 below indicate the formation of moderate wave driven currents over the reefs quite pronounced in the +ve X direction. This will lead to increased water levels in the lee of the reef. Retroflection of these wave driven currents and the formation of a relatively weak first set of circulation cells is evident in the velocity vectors and Y velocity difference plot (left). Minor changes in currents are experienced closer to the beach, with evidence of nearshore convergence (Velocity Y difference plot) and offshore flow behind the reefs (Velocity X difference plot). Sediment will most likely be deposited in areas of low currents, midway between the beach and reefs slightly to the north.

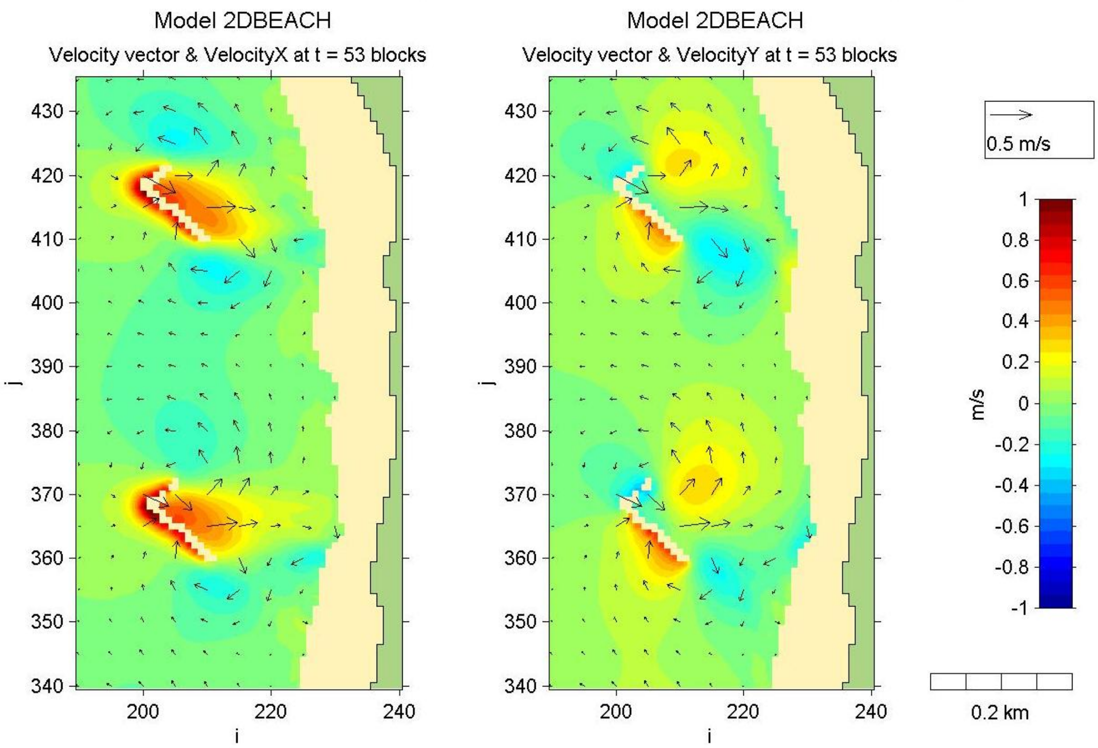


Figure 6.21 Current velocity vector and difference in X direction (left) and Y direction (right), for offshore SSW: Hs = 1.75m; Dir = 195°; T = 10.33sec, Inshore: Hs = 0.74m; Dir = 135°; T = 10.47sec and probability = 8%.

Medium size offshore waves from the SSE result in medium sized waves inshore with a direction of 125° at the 2DBEACH model boundary. Modelling results presented in Figure 6.22 below indicate the formation of moderate wave driven currents over the reefs which would lead to increased water levels in the lee of the reefs, as indicated in Velocity X difference plot (left). Retroflection of these wave driven currents and the formation a moderately pronounced first set of circulation cells is evident in velocity Y difference plot (right). As with the previous scenarios, in the nearshore longshore currents are altered with some deflection seawards behind the reefs as shown in velocity X plot (left), nearshore currents are deflected to the SW behind the southern reef (top) . Sediment will most likely be deposited in areas of low currents, midway between the beach and reefs slightly to the north.

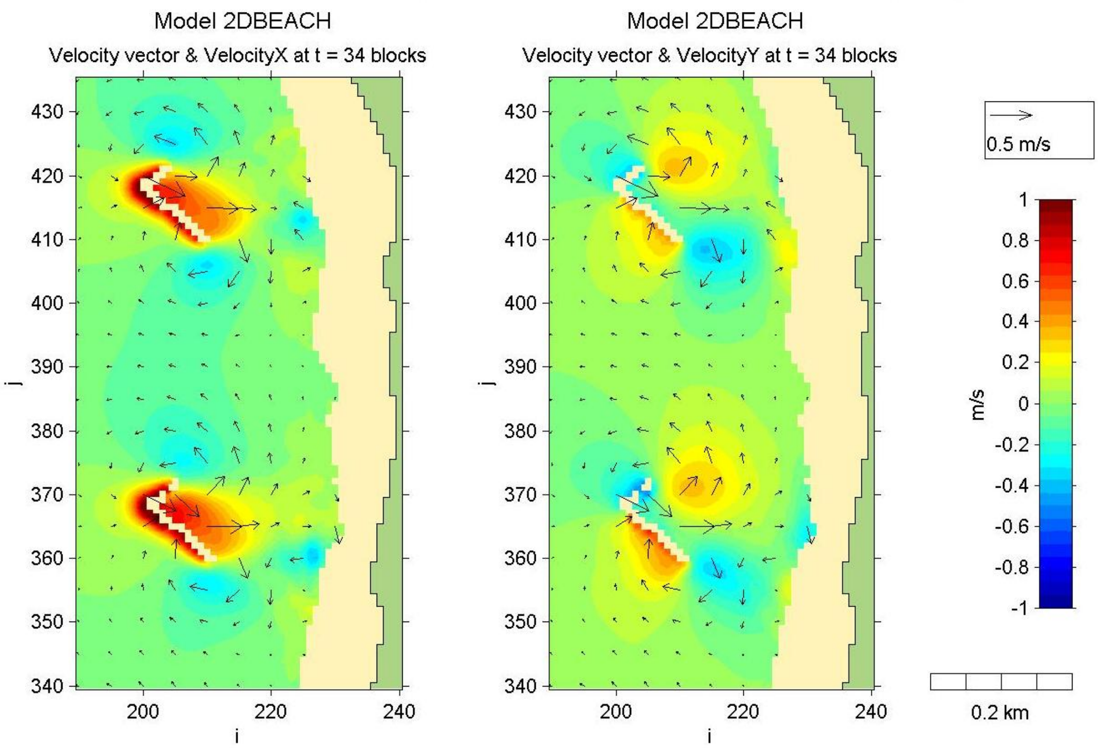


Figure 6.22 Current velocity vector and difference in X direction (left) and Y direction (right), for Offshore SSE: Hs = 1.75m; Dir = 165°; T = 9.24sec, Inshore: Hs = 1.07m; Dir = 125°; T = 9.20sec and probability = 2%.

Medium size offshore waves from the SE result in medium sized waves inshore with a direction of 115° at the 2DBEACH model boundary. Modelling results presented in Figure 6.23 below indicate the formation of moderate wave driven currents over the reefs most pronounce in the positive X. Retroflection of these wave driven currents and the formation a moderately pronounced first set of circulation cells is shown in the velocity Y difference plot. In the nearshore some deflection seawards behind the reefs is evident in velocity X plot and changes in longshore currents form the second set of circulation cells. These conditions are most likely to induce changes in nearshore circulation with resultant salient formation at the shore behind the reefs.

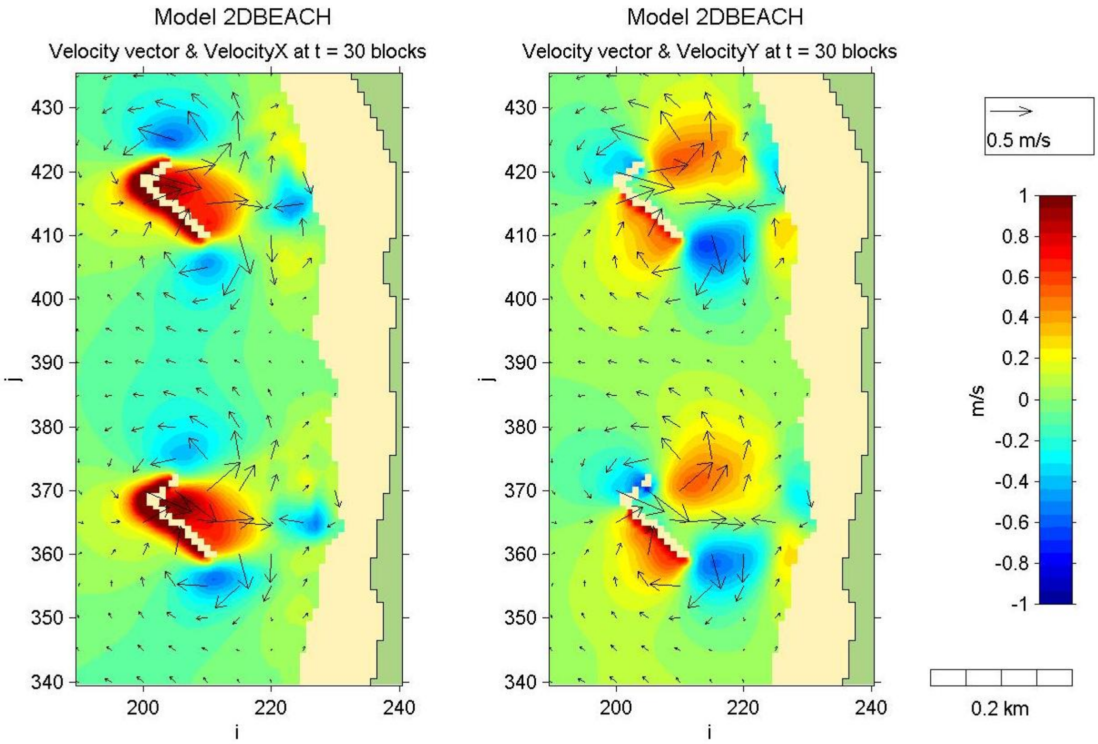


Figure 6.23 Current velocity vector and difference in X direction (left) and Y direction (right), for Offshore SE: Hs = 1.75m; Dir = 135°; T = 8.88sec, Inshore: Hs = 1.33; Dir = 115°; T = 9.20sec and probability = 2%.

Small to medium size offshore waves from the ESE result in above average size waves inshore within St Francis Bay with a direction of 95° at the 2DBEACH model boundary. Modelling results presented in Figure 6.24 below indicate the formation of strong wave driven currents over and in the lee of the reefs (velocity X plot). Strong retroflection of these wave driven currents (velocity Y plot) leads to the formation a pronounced first set of circulation cells. Nearshore longshore currents are strengthened behind the reefs, with some deflection seawards behind the reefs (velocity X plot). The nearshore currents converge behind the reefs (velocity Y plot) flow offshore and turn outwards completing well pronounced four cell circulation system. Therefore model results suggest that, under these wave conditions circulation behind the northern reef will be most likely to lead to salient formation.

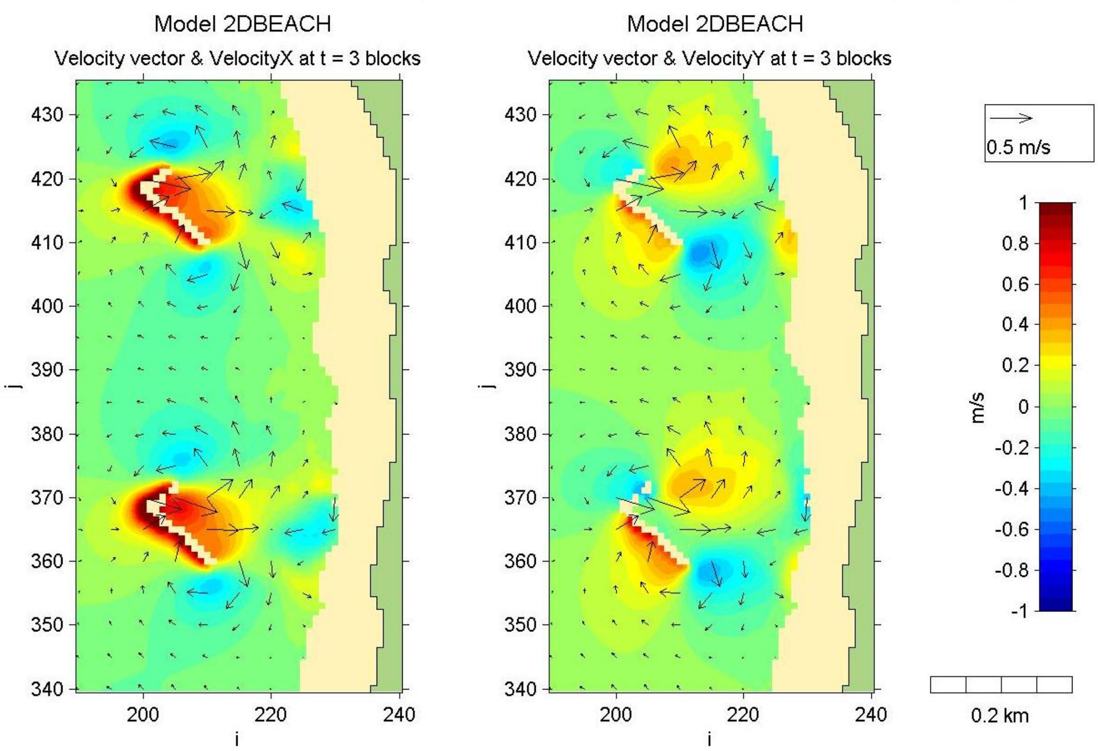


Figure 6.24 Current velocity vector and difference in X direction (left) and Y direction (right), for Offshore ESE: Hs = 1.75m; Dir = 105°; T = 8.09sec, Inshore: Hs = 1.45; Dir = 95°; T = 8.08sec and probability = 4%.

Medium size offshore waves from the ESE result in relatively large waves within St Francis Bay, with a direction of 95° at the 2BEACH model boundary. Modelling results presented in Figure 6.25 below indicate the formation of very strong wave driven currents over and in the lee of the reefs (velocity X plot). Strong retroflection of these wave driven currents (velocity Y plot) leads to the formation a very pronounced first set of circulation cells. Nearshore longshore currents are strengthened behind the reefs, with deflection seawards behind the reefs (velocity X plot) and the convergence of longshore currents behind the reefs completing well pronounced four cell circulation systems. Therefore model results suggest that under these wave conditions circulation behind the northern reef will be most likely to lead to salient formation, however if these currents are too strong erosion may result.

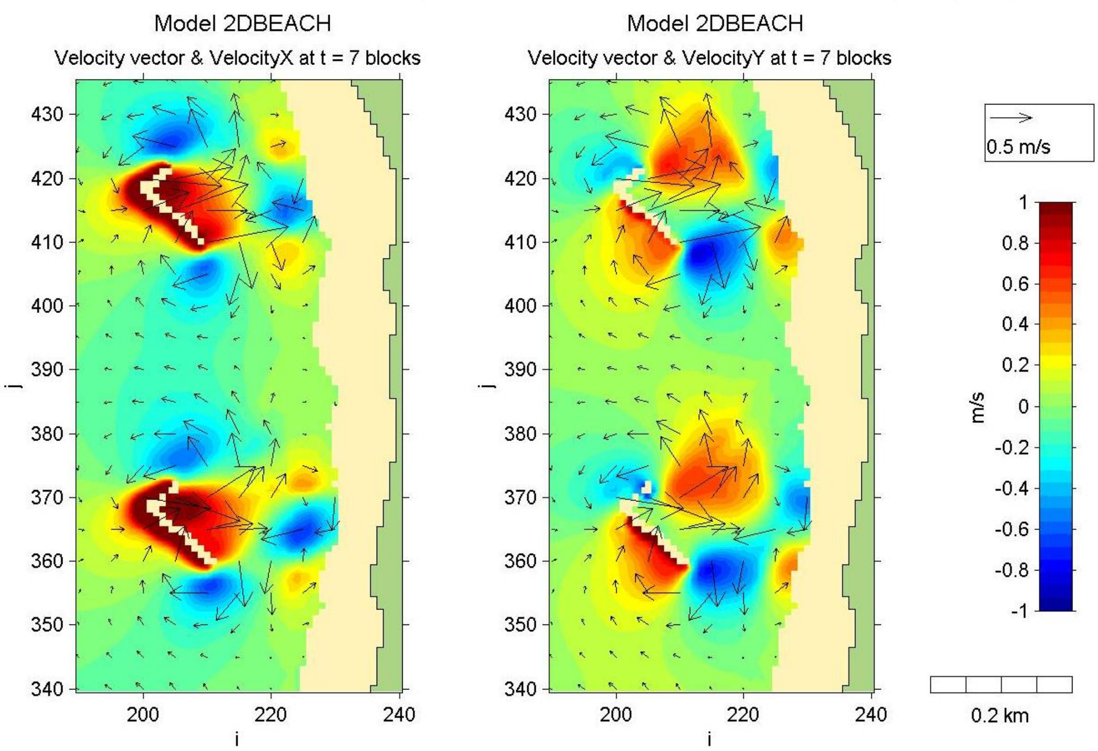


Figure 6.25 Current velocity vector and difference in X direction (left) and Y direction (right), for offshore ESE: Hs = 2.75m; Dir = 105°; T = 8.18sec, Inshore: Hs = 2.25; Dir = 95°; T = 8.08sec and probability = 1%.

In summary, the predominant medium size waves from a south westerly direction result in small waves in the nearshore at St Francis Bay. Modelling results indicate that during small wave conditions within the bay, minor changes in nearshore circulation occur. This is due to the depth of the reef crest (chart datum) and the tidal level (1m above CD). However waves larger than 0.7m start to break and drive wave driven currents on the reefs. The desired four cell circulation is evident when waves are average to above average size (>1m). Offshore swell directions from SE to ESE result in more distinct four cell circulation behind the reefs. This could be attributed to the shape and orientation of the reefs, with waves from SE to E direction arriving more directly to the longer northern arm.

6.10 Summary and Conclusions

Reef design involved a combination of empirical calculations and numerical modelling. Firstly empirical relationships defined by Black (2003) and Ranasinghe *et al.* (2006) were used to calculate the optimal distance offshore for reef placement. According to Black (2003) reefs should be placed at a distance offshore 2-4 times greater than the longshore length of the reef. Therefore for a reef of +/-100m longshore length, the reef should be placed 200-400m offshore for optimal sheltering. Using the probability of surf zone width and several distances offshore, results predicted accretion for all distances tested (150, 175, 200, 225 m) except for the closest distance (150m) for which erosion was predicted for SZW conditions experienced 1% of the time. 175m fell on erosion and accretion boundary and accretion was predicted for all positions greater than 200m offshore. As volume and cost increase with depth it was decided that a position 225m offshore of MSL was satisfactory in order to be located beyond the surf zone for a majority of the time and minimize reef volume.

Three numerical models from the 3DD Suite of Coupled Models were used for the reef design and assessment of the functional performance (primarily sand retention/coastal protection) – 3DD, WBEND, and 2DBEACH. Several factors were assessed to determine the functionality of multi-purpose reefs, including effective dissipation of waves, wave rotation/attenuation (i.e. modifying the waves without causing breaking), salient formation and nearshore circulation.

In order to assess the effectiveness of the reefs to dissipate wave energy, offshore return period wave statistics were transformed to the inshore of St Francis Bay. Due to the orientation of St Francis Bay, offshore waves from the south easterly quarter result in the largest waves inshore of St Francis Bay, this confirmed the results presented in previous studies (Bickerton and Pierce, 1988; CSIR, 1992; WPR, 1993). These being the most extreme return period wave conditions were considered the most appropriate to investigate the reefs effectiveness to dissipate waves. WBEND outputs were assessed using two variables, wave height and surf zone width. Modelling was conducted using return period waves from the offshore south easterly direction bin (135°) at a range of tidal levels. During high tides greater wave energy is allowed to reach the beach resulting in greater erosion. As has been evident in St Francis Bay where the most acute erosion has occurred when large waves from the SE have occurred in conjunction with equinox tides. The reefs showed good wave dissipation and sheltering for conditions from mean wave and tides (Hs=0.9 m and tide= 1m) up to 1:10 year return period waves under the highest possible tides Hs = 4.5 m and tide = 2.4m, spring high tide 1.8m + storm surge 0.6m). Under the same critical 1:10 year wave conditions with tide set at spring high (1.8m) and spring high + storm surge (2.4m) the reefs were found to be beyond the surf zone creating a large reduction in surf zone width behind the reef.

Wave rotation (refraction) can be used as an effective means of sand retention during periods when waves pass over the reef without breaking. Wave rotation refers to redirecting waves so that when they reach the beach and break they modify the longshore component of wave energy flux that generates alongshore currents and removes sand from the beach. At St Francis Bay the waves need to be rotated to a more southerly direction to induce sediment retention in the bay.

The Boussinesq model 3DD was utilized for the investigation of wave rotation, since this model best predicts refraction and diffraction of waves. Previous modelling investigations have shown that with only a single-sided reef, waves tend to refract up the back of the reef and distort the wave crest, as well as rotate it in a more northerly direction, thereby actually increasing wave driven currents (Borrero *et al*., 2006). Rotation of wave fronts towards a more south westerly direction is required to lessen longshore wave-driven currents and stabilize the beach. To compensate for this undesired feature, a short reef ‘arm’ is required – in the present case, the short southern arm was incorporated from the first design. As a result of this feature, waves are unable to refract onto the back of the reef and an increase in the northerly direction of the wave crest does not result. Using this information the initial design reef shapes were of a “candy cane” type shape with a long right hand section and short left hand arm.

The relatively small wave climate of the St. Francis Bay site means that waves will often pass over the reef without breaking. Modelling results indicate that the final reef design provides significant wave rotation without excessive wave focusing in the lee of the reef. From a surfing perspective measured peel angles were within desired range for high quality surfing waves (detailed in the following chapter).

Several processes acting on an offshore reef are responsible for the creation of a salient. According to recent studies, the primary way that an offshore reef creates a salient is by wave sheltering, although the previously promoted method of wave diffraction and nearshore circulation (e.g. Hsu and Silvester, 1990; Pilarczyk and Zeidler, 1996) is also be part of the mechanism in some cases (Black and Andrews, 2001b; Black, 2003; Ranasinghe et al., 2006), and refraction resulting in re-alignment of wave crests can also play a significant role (Mead and Black, 2002). The shape of the salient that forms in the lee of an offshore reef can be predicted using empirical equations (Black and Andrews, 2000a; Andrews, 1997).

From the results of empirical equations defined by Black and Andrews (2001), the predicted salient at St. Francis Bay is a maximum of 85 m cross-shore at the widest point, tapering down to zero accretion some 343 m in each direction alongshore. However, the alongshore length is normally reduced to allow for 10% of the across width (since it asymptotes to zero), which results in an alongshore length of approximately 617 m in this case. The width of the salient refers to the distance moved offshore by the beach isobaths.

Beach evolution modelling was undertaken with Model 2DBEACH (Black and Rosenberg, 1992a) to assess the shoreline response of reef designs at St. Francis Bay over planar bathymetry. In this phase, the model was run over long periods with varying wave and tide conditions to predict the long-term sedimentary response. The modelling was particularly focused on the development of the salient at the shoreline. 2DBEACH has capacity to predict features such as rip currents, sand bar movement, beach transformations, storm erosion and the build-up of beaches after storms. Thus, this modelling exercise provided further evidence to support the offshore location (Mead *et al.*, 2006).

The size of the salient predicted using 2DBEACH is 74 m maximum width and 535 m alongshore, slightly smaller than that of salient predicted by empirical equations. Past experience has shown that the empirical predictions of salient size are generally greater than the model predictions. Behind the reef a four cell circulation system is present, which according to Ranasinghe *et al.* (2006) is deemed to be a significant factor controlling salient formation (Mead *et al*., 2006).

Further detailed hydrodynamic modelling using 2BEACH provided good insight into the nearshore dynamics of St Francis Bay and good evidence of the effect of the reefs in interrupting longshore currents and creating the desired four cell circulation in the lee of the reefs, as described by Ranasinghe *et al*., (2006).

Predominant medium size waves from a south westerly direction result in small waves in the nearshore at St Francis Bay. Modelling results indicate that during small wave conditions within the bay, minor changes in nearshore circulation occur. This is due to the depth of the reef crest (chart datum) and the tidal level (1m above CD). However waves larger than 0.7m start to break and drive wave driven currents on the reefs. The desired four cell circulation is evident when waves are average to above average size (>1m). Offshore swell directions from SE to ESE result in more distinct four cell circulation behind the reefs. This can most likely be attributed to the shape and orientation of the reefs, with waves from SE to E direction arriving more parallel to the longer northern arm. Combined with the good degree of dissipation during SE and E swell directions responsible for most of the erosion, this provides good evidence of the effectiveness of this reef design to protect St Francis Bay beach. Sediment deposition is expected in regions of low current velocity and erosion in areas of high velocity. When waves break on the reef strong wave driven currents running down the reef arms and into the lee will result erosion of these areas and the creation of large holes inshore of each arm of the reef as has been measured and modelled for the Mount Manganui MPR in New Zealand (Black and Mead*,* 2007). Accretion will be likely in the lee of the Reefs where nearshore currents converge.

It is important to note that the mechanisms believed to be responsible fro salient formation are most likely to vary in relative significance depending on the particular site characteristics. For example strong salient response has been found inshore of Kapiti Island, which is located some 10's of kilometres off New Zealand's west coast, in the order of 1000 surf zone widths offshore. Therefore Black and Mead (2007) propose that the mechanism responsible for salient formation cannot exclusively be the result of wave-induced counter-rotating gyres, as theorised by Ranasinghe *et al.* (2006). Rather salient formation is the result of: wave sheltering, wave crest rotation, wave breaking on the reef reducing the set-up of water levels at the beach in its lee. Counter rotating vortices cited by Black (2003) and Ranasinghe *et al.* (2006) are cited as being an indicator of salient formation, while the several other factors discussed above are of significance (Black and Mead, 2007).

The combination of numerical modelling results provides very good evidence that an offshore multi-purpose reef can effectively protect St Francis Bay Beach through wave dissipation, rotation and nearshore circulation and can therefore be used to retain sand at St. Francis Bay Beach in the form of a salient and create a high quality surfing break. The offshore end of the reef lies in approximately 4.5 m of water while the inshore end lies in approximately 4 m of water. The crest depth of the reef has been set at chart datum (CD), 1.04 m below mean tide level (MTL). The alongshore width of the reef is ~100 m, and it is likely that the final reef design will be asymmetric with a longer northern arm. From a surfing perspective this will create a longer right hand breaking wave and shorter, faster left hand breaking wave. However physical modelling tests conducted in the next chapter include detailed assessment and refinement of reef design from a surfing and construction perspective.

7 PHYSICAL MODELLING

7.1 Introduction

In order to amalgamate computer design, construction constraints and surfing wave quality a series of scale model laboratory tests were conducted. The tests were undertaken in ASR's wave basin where a 1:35 scale model of the reef was built. A range of wave heights and tide levels were used to simulate a variety of realistic wave scenarios. The wave quality was photographed and recorded on video. Once a favoured reef shape was determined, the scale reef design was surveyed allowing measurement of orthogonal gradients and the calculation of wave breaking intensity for the different sections of the reef. In order to allow better qualitative assessment the reef was rebuilt at a 1:25 scale which allowed better visual assessment by participants in the experiments. Lastly data from capacitance wave gauges located before and after the reef was compared and used to measure wave height transformation over the reef at the different tidal levels and wave heights over the experiment.

7.2 Wave Basin Design

The dimensions of the wave basin used for physical modelling testing was 8.5 m x 4.5 m, with maximum water depths of 0.6 m. Waves were generated from a water-filled compartment spanning the width of the pool. A heavy steel container was raised and lowered using an electric winch to form the waves (Figure 7.1). The generator was operated using a control box which could switch between manual and automatic and allowed for the adjustment of timing for both the starting and holding of the generator at preset levels. Wave heights between 0.02 and 0.20 m could be generated easily and consistently. This type of wave generator created solitary waves, which have the same characteristics as those that shoal and break on the coast. Thus the system was considered very suitable for design tests of multi-purpose reefs.

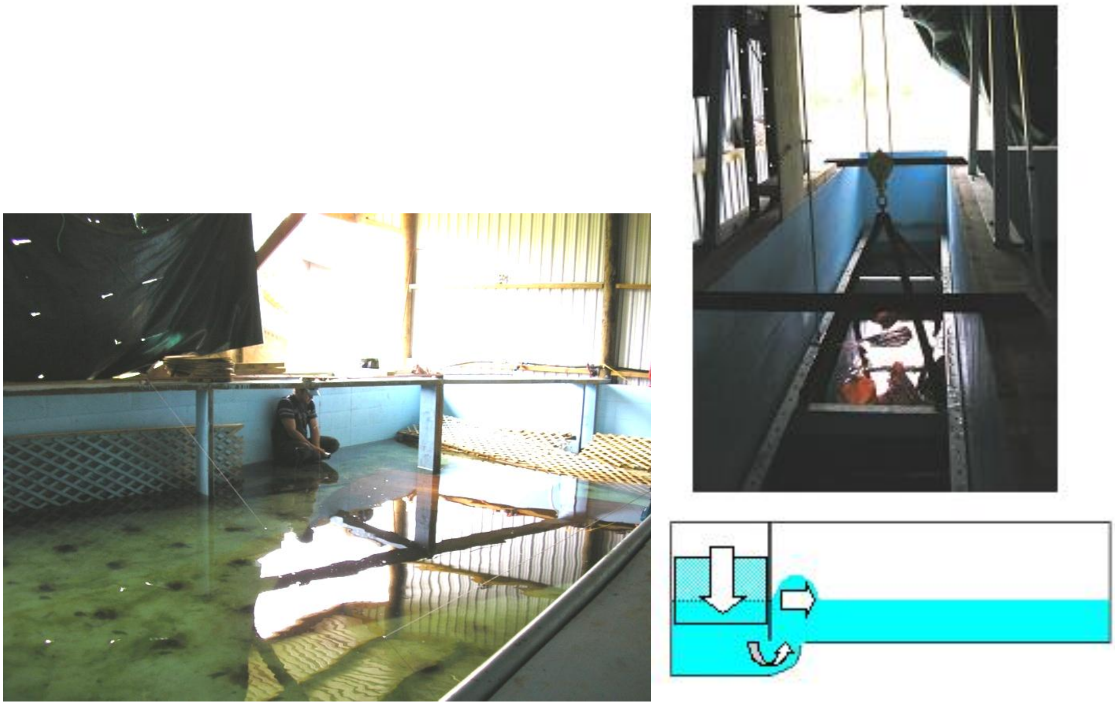


Figure 7.1 Clockwise from left: The wave basin (above) Wave generator (top right) with schematic of side view showing how a volume of water is expelled to produce a wave (bottom right).

7.3 Model Reef Design

The 1:35 scale model reef was built from sandbags that were fabricated to scale to represent the individual bag units. The first modification to the computer designed shape was altering the nose of the reef from the rounded shape used in the initial numerical modelling tests. This initial shape caused a large and undesirable close-out section across the front of the reef. To maximize its surfing function, a MPR should ideally be V-shaped in plan, with the apex pointing toward the predominant wave direction (Pattiaratchi 1999; Black and Mead 2001a). Therefore the apex of the reef was given a sharper shape with the two arms of the reef meeting square to each other. Additional focusing was provided by widening the outside of the nose of the reef, allowed the wave to initiate breaking without surging or sucking dry. The second half of the longer right-hand arm was also modified by orientating this section outwards by 5º, because this section was orientated more towards the wave, the reef was widened at this section, to ensure wave breaking. An ‘aerial ‘photo of the 1:35 scale reef design used for physical modelling is shown in Figure 7.2 below.

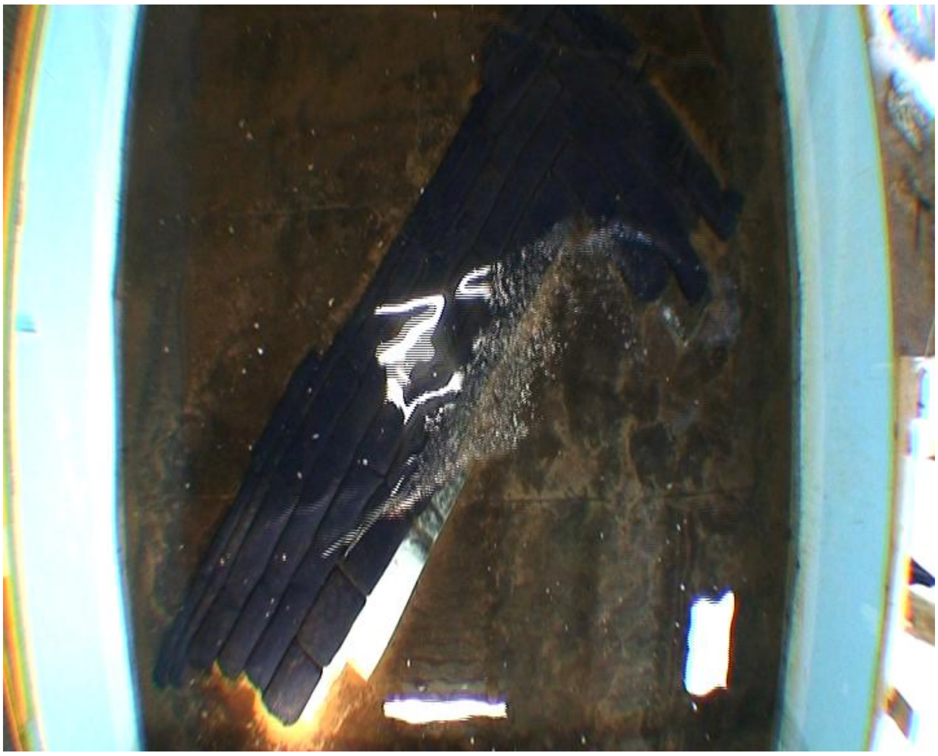


Figure 7.2 Frame from aerial video imagery of wave breaking on 1:35 scale reef used for physical model testing, the nose of the reef has been modified to a sharper ‘V’ shape to improve surfing wave conditions and create a more feasible construction shape.

7.4 Peel Angles

The peel angle (α) describes the line of the white-water as the wave breaks and determines the speed of the surfing ride (Figure 7.3). Surfers prefer to travel across the unbroken part of the wave, racing the breaking section as the wave moves shoreward. Zero peel angle refers to a “close-out” which is too fast for riding (all the wave breaks simultaneously as commonly observed on beaches with uniform longshore bathymetry), while 90^{o} is a “fat” or slow wave with no longshore translation of the breaking section (most commonly seen on reefs where the end of the white-water travels directly inshore, parallel with the crest normal). Since wave breaking is depth-dependent (e.g. the rule of thumb is that a wave will break when the water wave height:depth ratio is 0.78), the bathymetry has the major influence on the peel angle (swell peakiness and wave period are secondary factors (Hutt, 1997 in Mead *et al*., 2006). Surfers ride waves as they move shore-wards, either riding right or left as the wave peels, therefore waves are termed right or left hand breaks respectively.

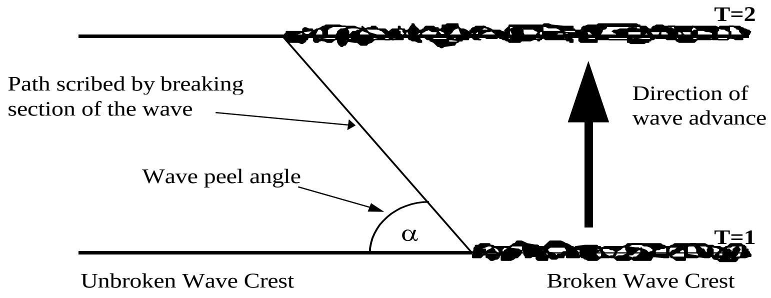


Figure 7.3 Schematic diagram of the wave peel angle showing movement of the breakpoint during an increment of time (Hutt, 1997 in *Mead et al.*, 2006)).

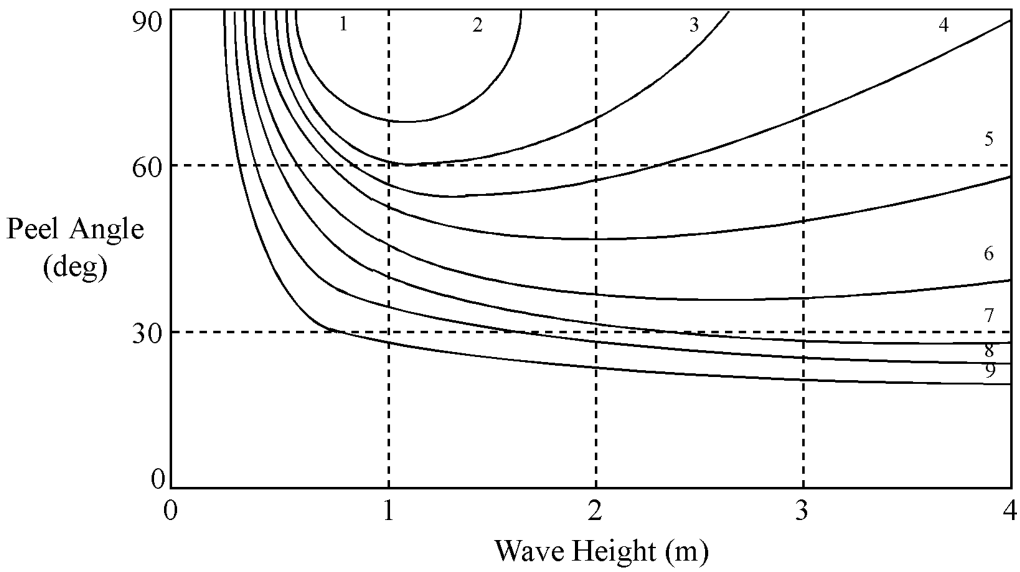


Figure 7.4 Classification of surfing skill rated against peel angle and wave height. (Hutt *et al.*, 2001).

Surfing skill for a particular break can defined by peel angle and wave height according the classification scheme shown in Figure 7.4 developed by Hutt *et al.* (2001). Generally rating 1-3, 4-6, and 7-9 represent beginner, intermediate and expert surfers respectively.

During the preliminary design and functional assessment of reefs for St Francis Bay, peel angles were measured from model outputs generated with WBEND and 3DD (e.g. Figure 7.5). As noted in above, the peel angles were designed to cater to surfers with skill levels of 4-7 (intermediate to expert surfers). In the present case, considering the common wave heights that are occur at St Francis Bay Beach, peel angles of 45-65° provide the appropriate peel angles (Mead *et al.*, 2006).

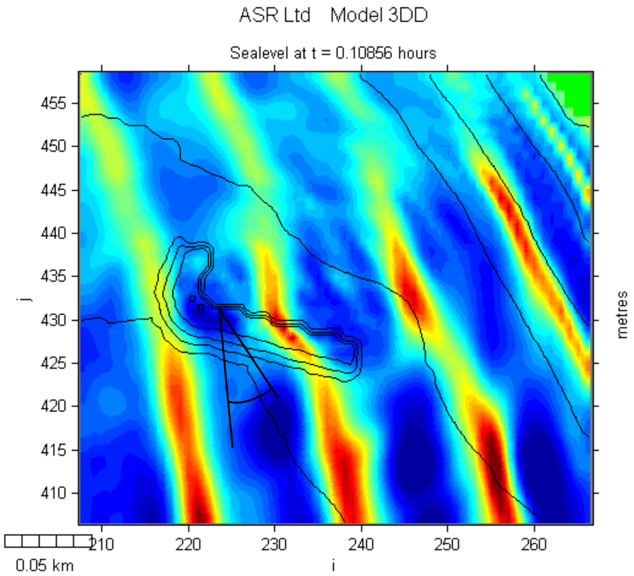


Figure 7.5 Example of a model output used to measure wave peel angles down a preliminary design (Mead *et al*., 2006).

To further refine the wave peel angles on the reef physical modelling tests were conducted. The reef model was tested for a range of wave heights and water levels designed to mimic the expected wave climate. Wave heights were measured with 2 capacitance wave gauges that were calibrated before the series of tests. Wave sizes ranged between 0.5 and 3.2 m at prototype scale (1.5 to 11 cm at model scale). The water level was varied to simulate spring low tide (MSLW), mean sea level (MSL) and spring high tide (MSL) water levels.

The individual waves were grouped in to 4 wave height bins: 1m (0.75 – 1.25m), 1.5m (1.25 – 1.75m), 2m (1.75 – 2.25m) and 2.5m (2.25 – 2.75m). Of these, the best cases for each bin were selected for more detailed video analysis of wave peel angles and break quality. This was done by using video taken by a camera mounted above the reef. The video was exported to individual frames and then loaded into image editing software where a mark could be placed in the image over the breaking point at each successive frame in the video. An example of this technique is shown in Figure 7.6 below.

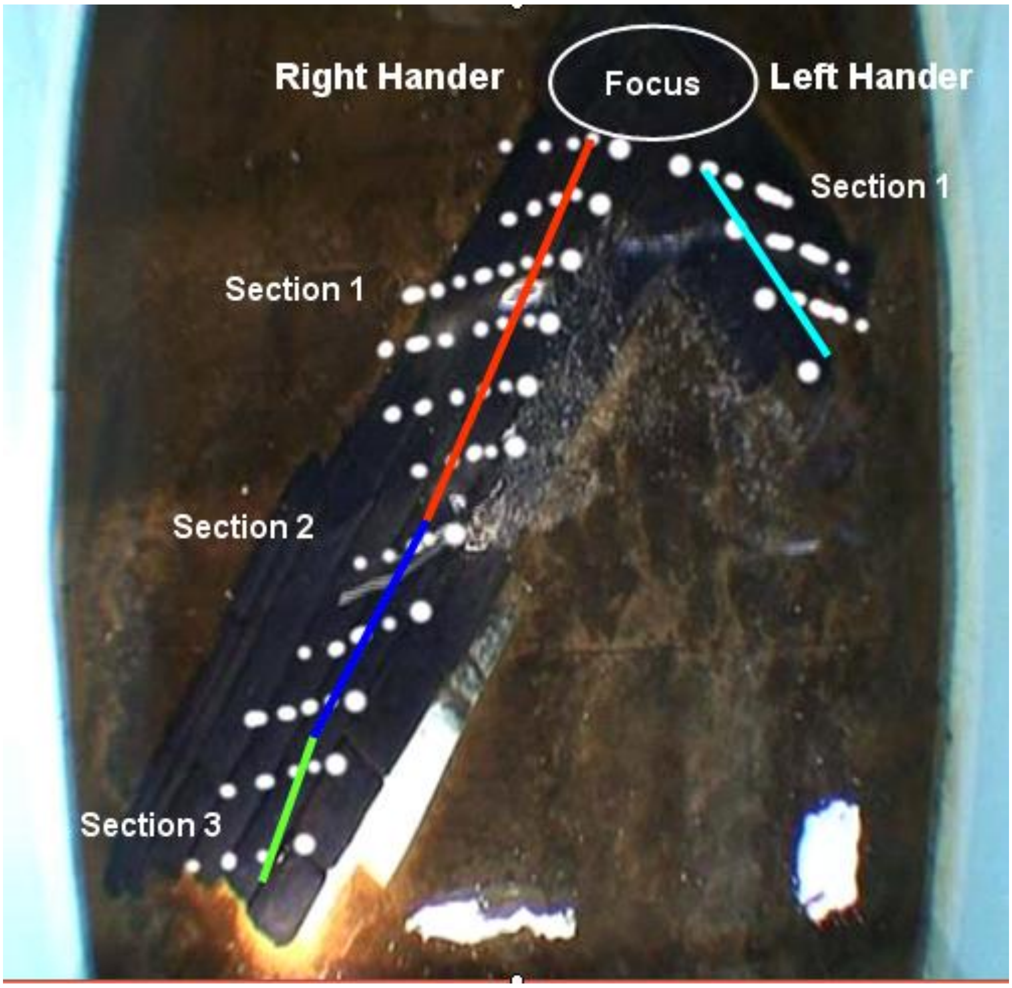


Figure 7.6 Video analysis of the peel angle over the model reef bathymetry. Larger white dots indicate the location of the breaking point, smaller white dots indicate the 'wall' of the breaking wave. Three sections were differentiated in the right hander and 1 section in the left hander.

From the video analysis, 3 separate sections were identified along the right-hander and 1 sections along the left hander, these sections were defined by analyzing peel angles along the reef, Figure 7.6 shows the first 50m of the right hander is defined by moderate peel angles ~ 65°, followed by a faster peel section 2 which is about 30 m long with a peel angle of ~45° and the wave slows down at the end for the last 20m where section 3 is defined by a peel angle of ~55°. The left hander Figure 7.7 is defined by one fast breaking section of 30m, with a nominal peel angle of ~ 45°. The different wave heights were tested at the 3 tidal levels: spring low tide (SLT); mean sea level (MSL); spring high tide (SHT).

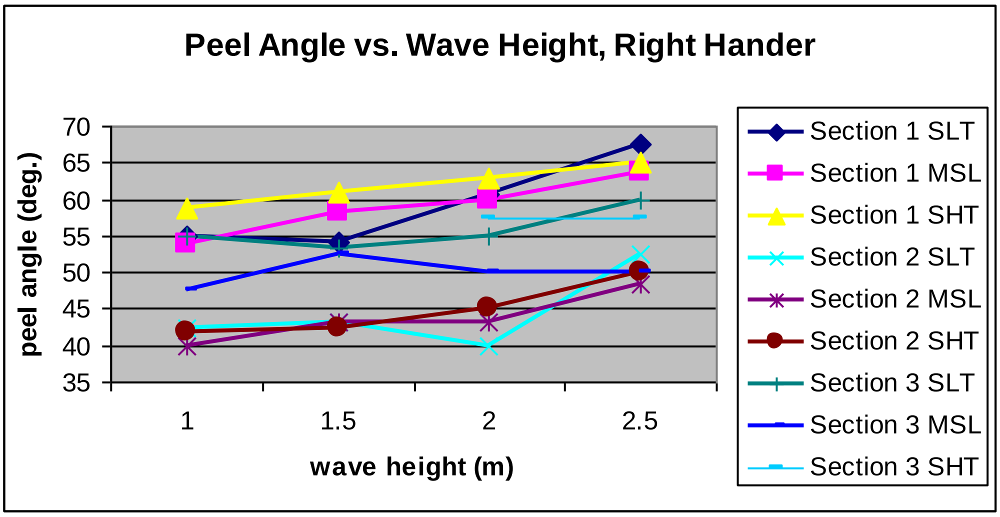


Figure 7.7 Wave peel angles degrees (deg.) for the right-hand side of the St. Francis Bay Reef for different wave heights and tidal levels.

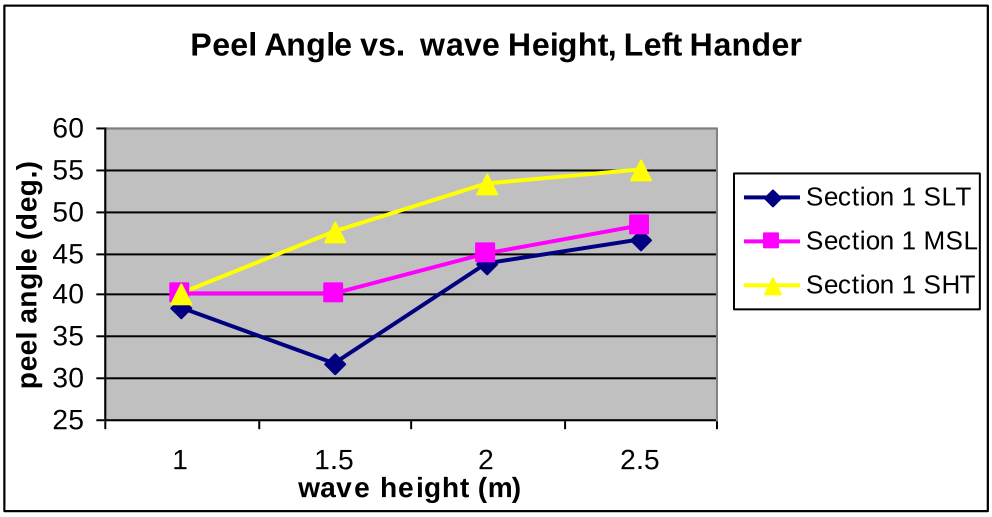


Figure 7.8 Wave peel angles degrees (deg.) for the left-hand side of the St. Francis Bay Reef, for different wave heights and tidal levels.

After analyzing these data it is evident that the peel angle on section 1 and 2 of the right hander and section 1 of the left hander show a consistent trend towards an increasing peel angle with increased wave height. Some variability in peel angle is noted for section three at the end of the right hander. All sections exhibit good consistency in peel angle for different tidal scenarios.

7.5 Wave Breaking Intensity

Although the Irribarren number gives a rough indication of wave breaking intensity, with reasonable differentiation between the three main breaker types plunging, spilling and surging breakers. However studies have shown that they do not well differentiate the transition between breaker categories and specially the differences between plunging waves clearly definable from a surfing perspective. Longuet Higgins (1982 in Mead and Black 2001b) demonstrated that the cubic curve gave a good description of the forward face of a plunging wave viewed in profile (parallel to the crest). Mead and Black (2001b) conducted cubic curve fitting analysis of 48 images from 23 different surf breaks, resulting in the development of a more reliable classification scheme for wave breaking intensity from a surfing perspective, as presented in Table 7.1 below.

Table 7.1 Classification schedule of surfing wave breaking intensity. (Source – Mead and Black, 2001b)

Intensity	Extreme	Very High	High	Medium/high	Medium
Vortex Ratio	1.6-1.9	1.91-2.2	2.21-2.5	2.51-2.8	2.81-3.1
Descriptive Terms	Square, spitting	Very hollow	Pitching, hollow.	Some tube sections	Steep faced, but rarely tubing
Example Break	Pipeline, Shark Island	Backdoor, Padang Padang	Kirra Point, Off-The-Wall	Bells Beach, Bingin	Manu Bay, Whangamata
Example Break Wave Profile					

With respect to reef profile gradients, the reader needs to be aware that the gradient determining wave breaking intensity is the gradient calculated along the direction of wave travel, not the maximum local gradient down the reef face (defined above). The wave travel gradients have been called "wave orthogonal gradients" in research publications (e.g. Black, 2001; Mead and Black, 2001b).

Surfing waves must peel, which is accomplished by orienting the reef at an angle, almost normal to the wave crest (e.g. Fig. 5.5). Thus, as designed, the waves on St Francis Bay reef approach at a glancing angle over much of the reef. Consequently, the orthogonal gradients are less than the steepest gradients down the reef face slope.

In order to quantify wave breaking intensity on the different sections identified, orthogonal gradients were calculated for the different sections of the reef. This allowed the vortex ratio to be calculated using the linear relationship between wave vortex ratio and orthogonal seabed gradient defined by Mead et al. (2001) in Equation 7.1 below:

$$Y=0.065X + 0.821 \qquad \text{Equation 7.1}$$

Where X is the orthogonal seabed gradient and Y is the vortex ratio, used to describe wave breaking intensity from a surfing perspective. The orthogonal gradient, vortex ratio and breaking intensity description for the different sections identified along the reef are presented in Table 7.2 below.

Table 7.2 Orthogonal gradients, vortex ratios and breaking intensities for the different sections identified on the reef.

Section	Gradient (%)	Vortex Ratio	Breaking Intensity
Take Off	16	1.86	Extreme
Right 1	19	2.06	Very High
Right 2	17	1.93	Extreme/Very High
Right 3	23	2.32	High
Left 1	12	1.6	Extreme

The results of this physical modelling exercise from a surfing perspective is that the take off will be of 'square and spitting' classified as extreme intensity. Section 1 of the right-hander will consist of a moderately fast peeling 'very hollow' section classified as 'very high' breaking intensity roughly ~ 50m long. Followed by section 2, a fast peeling 'square and spitting' barrel section of 'extreme' breaking intensity roughly 30 m long and finishing off with section 3, a slightly slower peeling 'pitching and hollow' section of 'high' breaking intensity of roughly 20m long. The left hander will consist of one short fast peeling, 'square and spitting' section of extreme breaking intensity.

7.6 Qualitative Assessment

In order to assess the wave breaking quality from a subjective perspective it was necessary to rebuild the reef at 1:25 scale. This increased scale allowed greater tolerance of minor irregularities in reef profile and more reliable visual observation. In these tests the right hander was observed by two assistants (experienced surfers/oceanographers) and rated on a scale of 1 to 10 with 10 being the best. The results of this test are shown in Figure 7.9. From this simple and highly subjective test we see the following trends as far as wave quality for surfing purposes. Waves appeared to perform best at all sizes at mean sea level while large waves performed well at spring high tide. Waves breaking at spring low tide were rated the lowest. These results are very encouraging, because most of the time water levels will be around MSL, providing us with high confidence that waves between 1 and 2.5m will break on the reef in such a manner as to provide high quality waves for surfing for a high percentage of the tides. Oblique angle photographs of waves breaking on different sections of the reef are shown in Figure 7.10 to Figure 7.12.

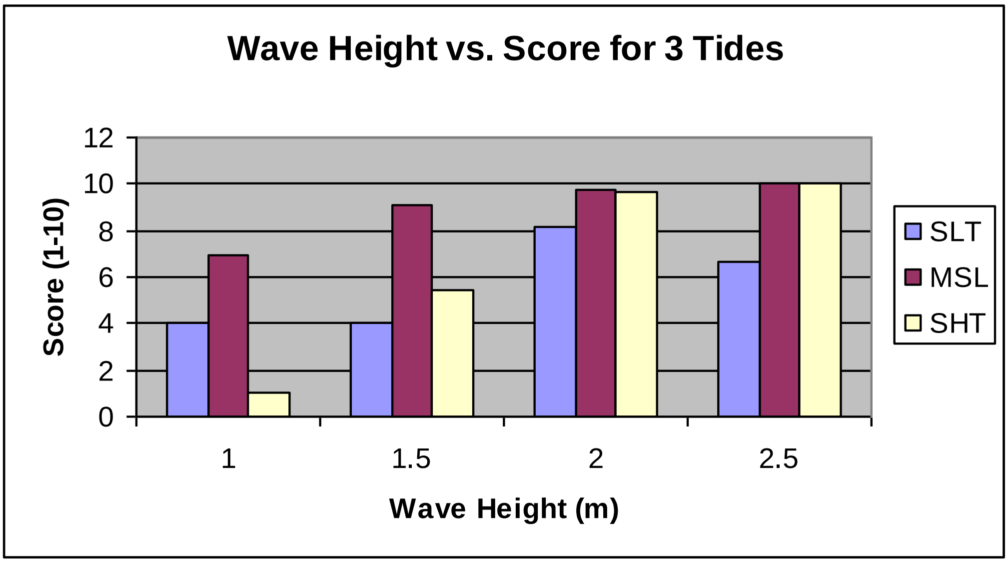


Figure 7.9 Results of a subjective wave quality rating assessment.

Figure 7.10 Image of wave breaking at the take-off area during model tests, the bag layout can be seen beneath the surface, as the wave peels left and right.

Figure 7.11 A plunging (tubing) wave, section 2 of the right hander.

Figure 7.12 A plunging (tubing) wave breaking on the shorter left-hander .

7.7 Wave Height Transformation

In order to assess the effectiveness of the reef in terms of energy dissipation, wave height before and after the reef was measured by means of two capacitance wave gauges. The wave gauges were installed for the duration of the peel angle and qualitative tests described above. The results showed good energy dissipation at MSL with the best results at SLT and the poorest dissipation at SHT, where under the smallest wave conditions a minor increase in wave height is found due to focussing as waves pass over the reef without breaking. At all tide levels the wave height transformation over the reef showed a similar close to linear trend with wave height reduction increasing with increasing wave height. Thus the reefs offer increasing protection with increasing wave height. This data is represented in Figure 7.13 below, where wave transformation is represented as a percentage of wave height after the reef in relation to wave height before the reef for the four wave height classes.

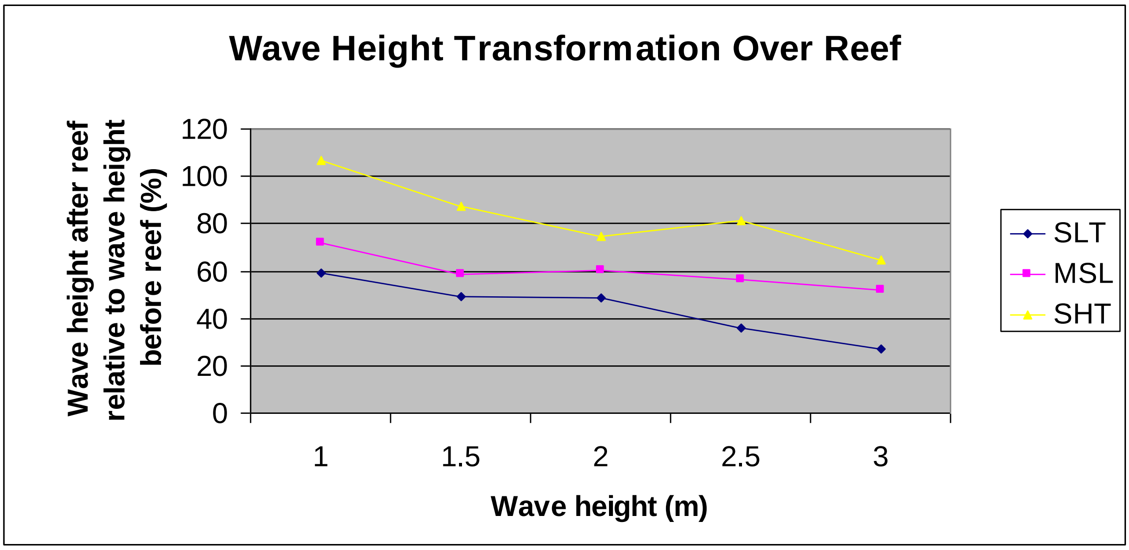


Figure 7.13 Wave height transformation over the reef, represented as a percentage of wave height after the reef relative to wave height before the reef for four wave height classes.

7.8 Summary and Conclusion

The laboratory modelling explored the wave breaking characteristics in the context of what a surfer would experience in the line-up and allowed assessment of construction limitations. The 1:35 scale model reef was built from sandbags that were fabricated to scale to represent the individual bag units.

The first modification to the computer designed shape was altering the nose of the reef from the rounded shape used in the initial numerical modelling tests. This initial shape caused a large and undesirable close-out section across the front of the reef. The nose of the reef was given a sharper shape with the two arms of the reef meeting fairly square to each other. This shape caused a desirable ‘A Frame’ peak at the take off. This refined nose shape is similar to that of Cables MPR in Western Australia (Pattiaratchi, 1999) and the Mount Reef in Mount Manganui, New Zealand (Black and Mead, 2007). Additional focusing was provided by widening the outside of the nose of the reef, allowed the wave to initiate breaking with out surging or sucking dry. The second half of the longer right-hand arm was also modified by orientating this section outwards by 5º, because this section was orientated more towards the wave, the reef was widened at this section, to ensure wave breaking.

During the preliminary design and functional assessment of reefs for St Francis Bay, peel angles were measured from model outputs generated with WBEND and 3DD. The peel angles were designed to cater to surfers with skill levels of 4-7 (intermediate to competent surfers) according to the classification scheme defined by Hutt *et al.* (2001). In the present case, considering the common wave heights that are occur at St Francis Bay Beach, peel angles of 45-65° provide the appropriate peel angles (Mead *et al.*, 2006).

Physical modelling tests allowed further detailed measurement of the wave peel angles on the reef. The reef model was tested for a range of wave heights and water levels designed to mimic the expected wave climate. From the video analysis, three separate sections were identified along the right-hander and one section along the left hander wave, these sections were defined by analyzing peel angles along the reef. Results indicate that the first 50m (section 1) of the right hander is defined by moderate peel angles ~ 65°, followed by a faster peeling section which is about 30 m long (section 2) with a peel angle of ~45° and the wave slows down at the end for the last 20m (section 3) with a peel angle of ~55°. The left hander is defined by one fast breaking section of 30m, with a nominal peel angle of ~ 45°.

Results indicate that the peel angle on section 1 and 2 of the right hander and section 1 of the left hander show a consistent trend towards an increasing peel angle with increased wave height. Some variability in peel angle is noted for section three at the end of the right hander. All sections exhibit good consistency in peel angle for different tidal scenarios.

Although the Irribarren number gives some indication of wave breaking intensity and is useful for defining breaking waves into 3 broad categories of plunging, spilling and surging, studies have shown that they do not well differentiate the transition between breaker categories specifically the sub-categories of plunging waves distinguishable from a surfer's perspective. Longuet Higgins (1982 in Mead *et al*., 2001b) demonstrated that the cubic curve gave a good description of the forward face of a plunging wave viewed in profile (parallel to the crest).

With respect to reef profile gradients, the reader needs to be aware that the gradient determining wave breaking intensity is the gradient calculated along the direction of wave travel, not the maximum local gradient down the reef face (defined above). The wave travel gradients have been called "wave orthogonal gradients" described in research publications (e.g. Black, 2001; Mead and Black, 2001b).

Surfing waves must peel, which is accomplished by orienting the reef at an angle, almost normal to the wave crest (e.g. Fig. 5.5). Thus, as designed, the waves on St. Francis Bay reef approach at a glancing angle over much of the reef. Consequently, the orthogonal gradients are less than the steepest gradients down the reef face slope.

In order to quantify wave breaking intensity on the different sections identified, orthogonal gradients were calculated for the different sections of the reef. Using frames from aerial video imagery the orthogonal angles were measured for the different sections, which were then used extract orthogonal profiles along orthogonal angles. Using the orthogonal angles the vortex ratio was calculated using the linear relationship between wave vortex ratio and orthogonal seabed gradient defined by Mead and Black (2001b)

The results of this physical modelling exercise from a surfing perspective is that wave breaking can be described as follows according the breaking intensity classification scheme defined by Mead *et al.* (2001): initially the wave breaks as an 'A-Frame' peak providing a ride left or right. The take off is 'square and spitting' classified as 'extreme' intensity. Section 1 of the right-hander is a moderately fast peeling (65°) 'very hollow' section classified as 'very high' intensity roughly ~ 50m long. Followed by section 2, a fast peeling (45°) 'square and spitting' barrel section of 'extreme' breaking intensity roughly 30 m long and finishing off with section 3, a slightly slower peeling (55°) 'pitching and hollow' section of high breaking intensity of roughly 20m long. The left hander consists of one short fast peeling (45°), 'square and spitting' section of 'extreme' breaking intensity.

According to the classification scheme, developed by Hutt *et al.* (2001), which relates surfer skill to wave height and peel angle, for all surfable wave heights on the reef, the peel angles on the right make this ride suitable for surfers of intermediate to advanced level of competence. The left hander is a short and fast hollow peeling wave suitable for intermediate advance surfers. Intuitively the right will be a slightly easier ride, with slightly slower and forgiving first section, giving the surfer a little extra time to position himself and gain speed for the fast barrelling second section, with the slightly slower third section allowing an easy ending to this ride. A surfer going left will have to make a steep take-off and immediately negotiate a short fast peeling 'square and spitting' section. The total ride length for the right and left hander will be in the order of 100 m and 30 m respectively.

8 HYDRODYNAMIC MODELLING OF THE KROMME ESTUARY

8.1 Introduction

The reduction of sediment supply to St Francis Bay beach, mainly attributed to the stabilisation of the large Santareme headland bypass dunefield, has led to chronic erosion of St Francis Bay beach over the last 30 years (WPR, 1993; McLachlan et al., 1994; La Cock and Burkinshaw., 1996; Illenberger and Burkinshaw, 1997). Since the 1990's beach front properties have been under threat and rock wall revetments have been constructed along much of St Francis Bay beach. The diminishing beach and continued threat to property poses a major threat to the economic future of this coastal holiday village.

As detailed in section 2.9.3 several technical studies have been conducted to investigate possible solutions to this erosion problem: WPR (1993), Entech, (2002a) and Mead *et al*. (2006). All investigations concluded that in order to restore the beach and its integral amenity value to this holiday resort town while at the same time protecting beach front properties, the implementation of a combination of coastal protection structures and beach nourishment would be required. The latest feasibility study conducted by Mead *et al*. (2006), recommends a hybrid solution involving:

- The construction of 3 (possibly4) Multi-Purpose Reefs (MPR's) offshore for shore protection and amenity enhancement.
- Beach Nourishment, in order to reinstate a wide sandy beach.
- Dune rehabilitation with appropriate indigenous plant species, in order to restore natural functioning foredune system.

This approach agrees with recommendations from Entech (2002a) with the difference being the use of MPR's offshore as opposed to multiple groynes suggested by Entech.

In terms of beach nourishment Entech (2002b) investigated several sand sourcing sites for beach fill including: The Kromme Estuary, Sand River dunefield (leading nose of the Oyster Bay dunefield), marina glades canal system and the municipal dump site. Of these areas the Kromme Estuary sandbanks were considered preferable (Entech, 2002b), with an estimated 600 000 m^3 of sand available from the extensive sand bank within the mouth on the southern bank.

In fact removal of sediment from the lower reaches of the Kromme Estuary can be considered beneficial as the lower reaches of the Kromme Estuary have become sediment loaded, with extensive shoaling effecting navigability negatively effecting recreational amenity value in terms of boating, sailing, waterskiing activities (Bickerton and Pierce, 1988)). In order to assess the suitability of the Kromme Estuary as a site for sediment extraction it is necessary to have a good understanding of the system and its dynamics. Although most research in the Kromme has been biologically orientated, several studies have included physical and chemical measurements. Schumann and de Meillon (1993) conducted a detailed investigation into the hydrodynamics of the Marina Glade canal system which included collection of water level and current data, but no measurements were conducted in the main channels of the estuary. Extensive sediment sampling was conducted by Reddering and Esterhuysen, (1983).

As described in detail in chapter 2 the Kromme Estuary extends 14 km inland, with a highly variable but permanently open tidal inlet, an average width of 80 m and average depth of 2.5m at low water ordinary spring tide. A large artificially vegetated sand spit extends from the southern bank, which has a tendency to push the mouth channel northwards. The tidal area of the Kromme is about 3km^2 and the greatest width of the tidal zone is 175m, inside the mouth behind the spit (Bickerton and Pierce, 1988)). Two large dams within the catchment area effectively reduce all freshwater input into the estuary, except during extreme flood events. Most months of the year the estuary is saline for the full 14 km, during the hot summer months high levels of evaporation result in hyper saline conditions in the upper parts of the estuary with values as high as 42 X 10 $^{-3}$ reported (Schumann de Meillon, 1993).

Beginning in the 1960's a system of canals and associated housing development has been developed on the southern bank near the mouth, this system is connected to the Kromme via two entrances. Tidal variation in the ocean is the predominant driving force of circulation within the estuary and associated canals. The sand banks and mouth configuration are highly variable and have a large influence on currents and water levels within the estuary and associated canal system. Evidently the lower entrance to the canals has been partially shut at times, resulting in restricted flows through this entrance (Schumann and de Meillon, 1993). This study concluded that current speeds were of sufficient magnitude to ensure circulation and flushing required in order to maintain low levels of sedimentation and acceptable water quality within the canal system. Volume of the canals is very small compared to the volume of the whole estuary.

The Kromme estuary is a flood tide dominant system. The flood tidal current flows at greater velocity over a shorter duration, while the ebb tidal current flows at a lower velocity for a longer duration (Schumann and De Meillon, 1993). The stronger currents associated with the flood tide result in higher levels of sediment transport into the estuary, with an estimated 13-27 X 10^3 m^3 p.a. being transported into the estuary, (Bickerton and Pierce, 1988) in Entech (2002c). Sediment carried in to the estuary by the dominant flood tidal currents is deposited in a the lower 4.5 km of the estuary with a large flood tidal delta (FTD) inside the mouth of the Kromme Estuary. This is a common feature in most flood tide dominated estuaries along the Eastern coast of South Africa, where sufficient longshore sediment supply exists (Reddering and Esterhuysen, 1983; Illenberger 1992). The lower Kromme estuary receives further sediment supply from the Sand River which drains the extensive Oyster Bay dunefield during flood events discharging sediment into the Kromme two kilometres from the mouth. From here sediment is distributed up and down the estuary by the flood and ebb tides, (Bickerton and Pierce, 1988)).

It is most likely that in the past this marine sediment accumulated in large sand banks in the lower 5 km of the Kromme estuary would have been periodically scoured out by large river flood events, (Reddering and Esterhuysen, 1983). However the construction of the Churchill (1943) and Mpofu (1983) dams with a collective storage capacity of 133 X 106 m^3 exceeding the Mean Annual Runoff (MAR) of 106 X 106 m^3 for the Kromme River catchment area (Bate and Adams, 2000), has eliminated the scouring potential of river flood events. Moderate sedimentation of the lower reaches of the Kromme Estuary has been observed (Reddering and Esterhuysen, 1983).

Results from sediment grain size and composition analysis confirm that the sediment accumulated in extensive sandbanks in the lower 5 km are is mainly of marine origin (Reddering and Esterhuysen, 1983), which is comparable in size and composition to that of sediment found on the beach and would therefore be suitable for the purpose of beach nourishment (Entech, 2002b). Although some concern has been expressed over the anoxic black colour below the surface, it is generally believed that this will bleach quickly once exposure to oxygen, sunlight and wave action on the beach and therefore is not considered to be a significant problem (Entech, 2002b).

The large FTD on the southern bank immediately within the estuary is considered a preferable source of sand for several reasons. Firstly it is a significantly large body of sand close to the mouth therefore it should be replenished effectively by sediment carried by the dominant flood tidal currents; secondly this environment is highly mobile and variable, therefore the organisms within this environment are highly adaptable; thirdly the proximity of this site to the beach results in short pumping distances, thus reducing pumping costs. Dredging and pumping from this location will cause far less inconvenience in terms of noise and dust and visual disturbance associated with trucking sand in from the Oyster Bay dunefield (Entech, 2002b).

Beach nourishment has gained popularity over recent years. This type of nourishment, where sand accumulated in an estuary mouth is pumped and discharged on an up-drift beach, using the natural processes of sediment transport on the beach and the natural sand trapping nature of the flood tide dominated estuary has been implemented at several locations internationally. Good examples of such projects are found at Noosa in Australia (Coughlin, 1989) and Narrowneck on the Gold Coast, as discussed in Chapter 3, where 1.3 X 10^6 m^3 of sediment was dredged from Broadwater seaway, hydraulically pumped and deposited on the beaches to the south from where it was spread down the beach by dominant northerly longshore transport (Boak *et al*., 2001). Not only was the beach environment widened considerably but deepening of the Broadwater channels led to improved navigation. As discussed in Chapter 3 this project included the construction of a large MPR offshore designed to maintain nourishment on the beach and improve surfing conditions, thus exhibiting several similarities with the proposed remediation for St Francis Bay beach.

Previous studies estimated that 600-1000 X 10^3 m^3 of sand could be extracted from the large FTD opposite the Huis River (CSIR, 1992; WPR, 1993; Entech, 2002b; Klages *et al*., 2002). The tidal area of the Kromme Estuary is about 3km^2 (Bickerton and Pierce, 1988). This translates into a tidal prism of some 3 000 000 m^3. Removal of 600 000 m^3 of sand from the existing sand banks between MSL and -2m MSL would lead to and increase in tidal prism of less than 10% (Entech, 2002b). However Entech (2002b) expressed some concern that the removal of such a large volume of sediment would lead to a temporary increase in tidal velocities through the mouth leading to scouring and deepening of the mouth. However they went on to suggest that a new equilibrium would be reached and sediment inflow from the sea would most likely reduce tidal exchange to current values.

In order to assess the impacts of this proposed sand extraction on the currents within the estuary and adjoining canal system, a Hydrodynamic Modelling exercise was carried out. The 3dimensional hydrodynamic and mass transport model 3DD (Black, 1999) was used to simulate flows in the estuary over several different sand extraction scenarios, This chapter describes the process of developing a model for the Kromme Estuary and presents the results and findings of this modelling exercise.

8.2 Fieldwork and Data Collection

8.2.1 Bathymetric data collection collation and processing

In order to conduct numerical modelling, detailed bathymetric data is required. As no bathymetric data was available for the Kromme Estuary a bathymetric survey of the lower estuary was undertaken. Survey data was then combined with digitized data from aerial photography in order to create a bathymetric grid for the entire Kromme Estuary.

The bathymetric survey of the lower section of the Kromme Estuary was conducted by the Author and Maarschalk and Partners on the 19 July 2006. Mapping of Sub-tidal areas was conducted onboard a 5m semi-rigid inflatable boat, with a single 90 hp outboard motor and centre mounted console. The boat was equipped with a 200 kHz single beam echo-sounder measuring depth (z) with an accuracy of +\-10cm this data was output simultaneously with GPS data to a Garmin GPSMap 78C Chartplotter via an NMEA 0182 data stream at a frequency 0.5Hz and recorded directly to lap top computer. The receiving antennae of a Leica Real Time Kinematic (RTK) Global Positioning System (GPS) measuring longitude and latitude and height (x,y,z) with an accuracy of +/- 10cm was mounted directly above the echo sounder transducer and this data was also recorded at 0.5 Hz directly to the systems data logger. Inter-tidal sand bank areas which were not accessible by boat were walked with the RTK GPS system (Figure 8.1and Figure 8.2).

Figure 8.1 Inter-tidal Sandbank below the road bridge being surveyed with RTK GPS system, with the semi-rigid inflatable boat used for survey of sub-tidal areas in the right of the frame.

Figure 8.2 Satellite image of the lower Kromme Estuary with bathymetric survey lines indicated in black and inter-tidal survey coverage in dark blue. The large flood tidal delta (FTD) can be seen within the mouth.

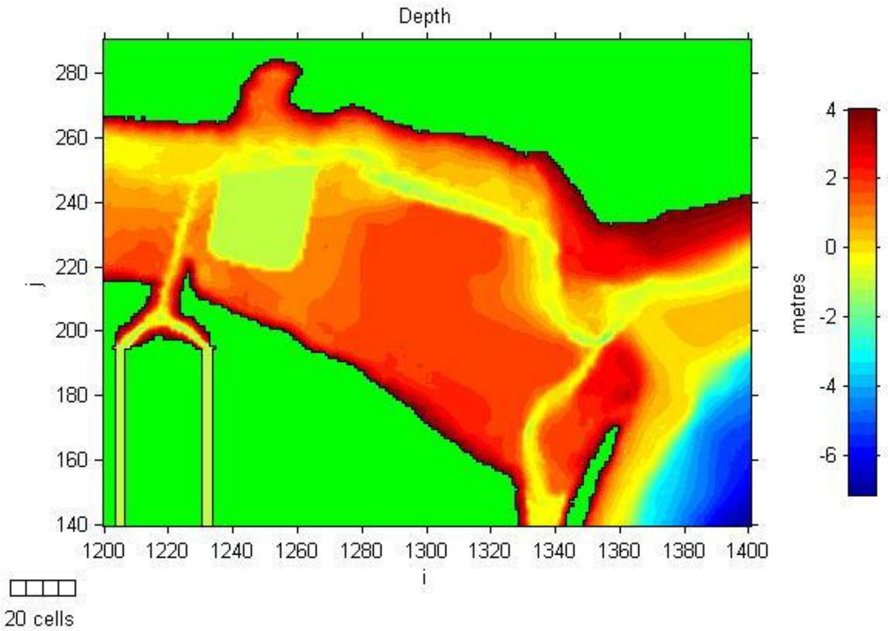
Bathymetric survey data was then processed as follows:

- Echo Sounder depth data (z) was combined with RTK GPS (xyz) data, by means of the common satellite time series in both data sets.
- Depth data was reduced to mean sea level by subtracting the RTK GPS height data, then further reduced to Chart datum.
- The data collected by walking the inter-tidal sand bank areas was simply reduced to chart datum.

Further coverage not included in the field survey was gained using the contouring package Surfer ™ (Golden Software). This process involved digitizing the boundaries and banks in the lower estuary and full bathymetry above the road bridge from satellite imagery. The barrier dune and offshore bathymetry was also digitized using a combination of beach profile data from May 2006 and offshore bathymetric data from the December 2005 Survey laid over satellite imagery.

The survey and digitized data was then combined and gridded in Surfer © at a cell size of 8 X 8 metres by means of the Kriging interpolation technique. This grid was then imported into the front end (FE) of the Numerical Model 3DD, where it was converted into 3DD bathymetry file format. The canal shape was digitized in Surfer and imported into AutoCAD ® where the area of the canal system was calculated this was combined with spot depth information to calculate the volume of the canal system. The volume of the canals is very small 0.15 million m^3 compared to the tidal prism of +/- 2 million m^3 for the whole estuary.

Using the Depth Change Function in the Front End of 3DD the bathymetry was edited, adding canal reservoirs and creating the Eastern boundary, further bathymetry grids were created to simulate different variations of dredging scenarios (Figure 8.3). The volume of these excavations was calculated using Volume Calculation Function in Surfer ©. The following volumes were excavated from the main sand bank by reducing simulated extraction areas to 1m below chart datum: 100 000m^3 , 300 000m^3, 600 000m^3 , in the following report these extraction scenarios are referred to as 100, 300 and 600 respectively. Two Variations of the 600 000m^3 excavation were also created: 600 + UECv1 where the bank was excavated through to the upper entrance to the canals and the whole upper entrance area was excavated down to 1m depth below chart datum and 600 + UECv2, where the main excavation was extended to the channel leading to the upper entrance to the canals but the confluence and entrance area near Shore road parking was left unaltered.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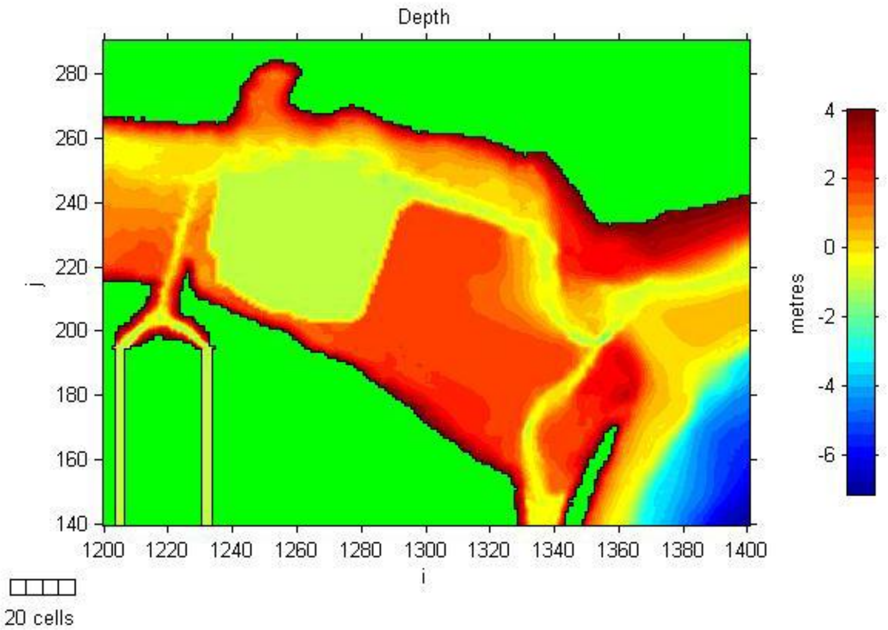
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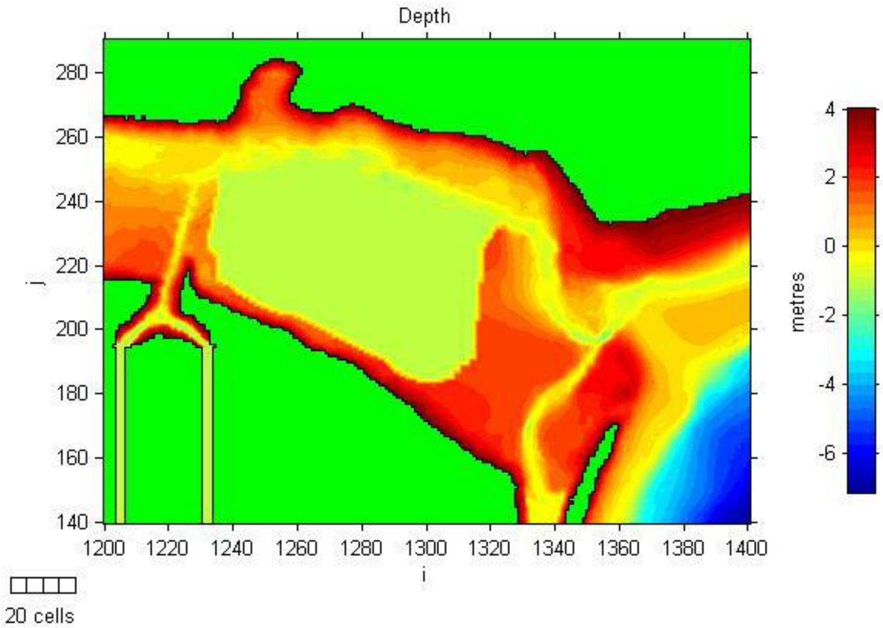
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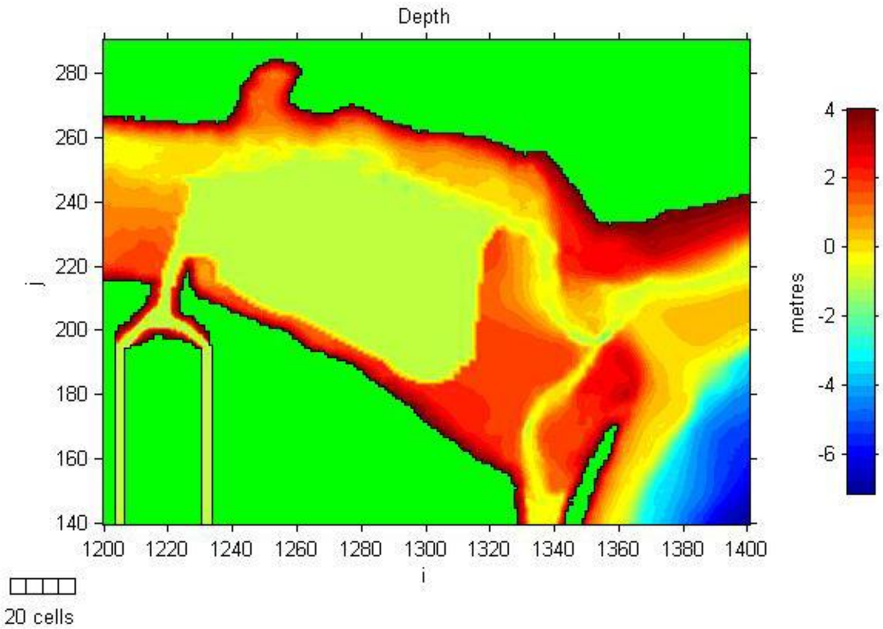
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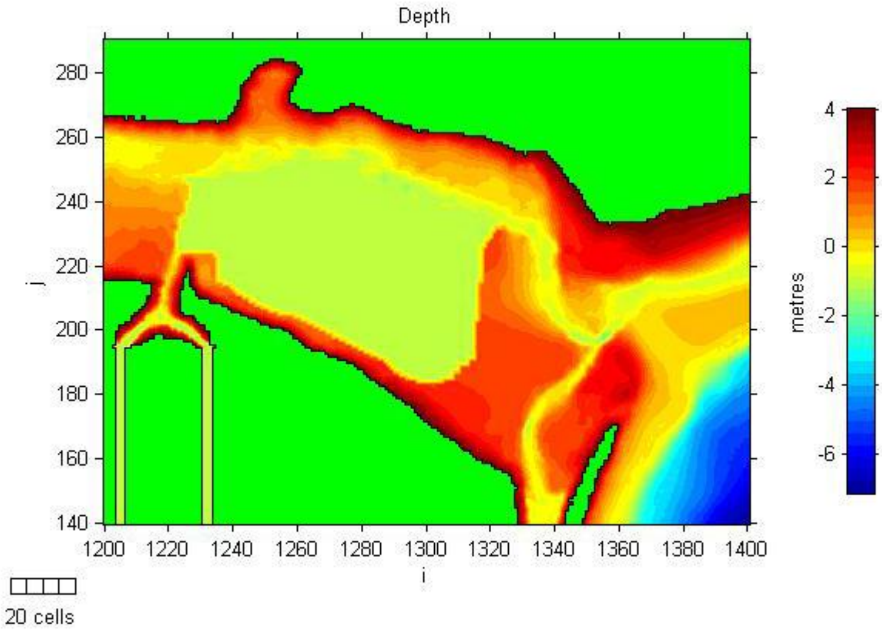


e

Figure 8.3 The five different sand extraction bathymetric scenarios: a) 100, b) 300, c) 600, d) 600+UECv1 and e) 600+UECv2, cell size 8 X 8m.

8.2.2 Tidal data analysis and calibration

Tidal data was required as input data to drive the numerical model 3DD. The best source of tidal data available was from Port Elizabeth Harbour some 77km east of St. Francis Bay (Figure 8.4), provided by the South African Navy Hydrographic Office (SANHO). To investigate the possible existence of phase discrepancies between tides at St. Francis Bay and those experienced at Port Elizabeth, sea level data collected by means of a pressure sensor mounted on a Nortek Aquadopp current profiler deployed in St. Francis Bay over a three month period from February to May 2006 (described in chapter 0) was compared with tidal data from the port of Port Elizabeth for the same time period (Figure 8.5). Tidal data at Port Elizabeth recorded at 3 minute intervals was averaged out to 1.5 hour intervals for comparison with tidal data from St. Francis Bay. The tidal phase and timing differences were found to be negligible, therefore it was concluded that Port Elizabeth tides would be suitable for use as a tidal boundary input for hydrodynamic modelling of the Kromme Estuary.

Figure 8.4 Location map showing Location of the Kromme Estuary and proximity between St. Francis Bay and Port Elizabeth harbour.

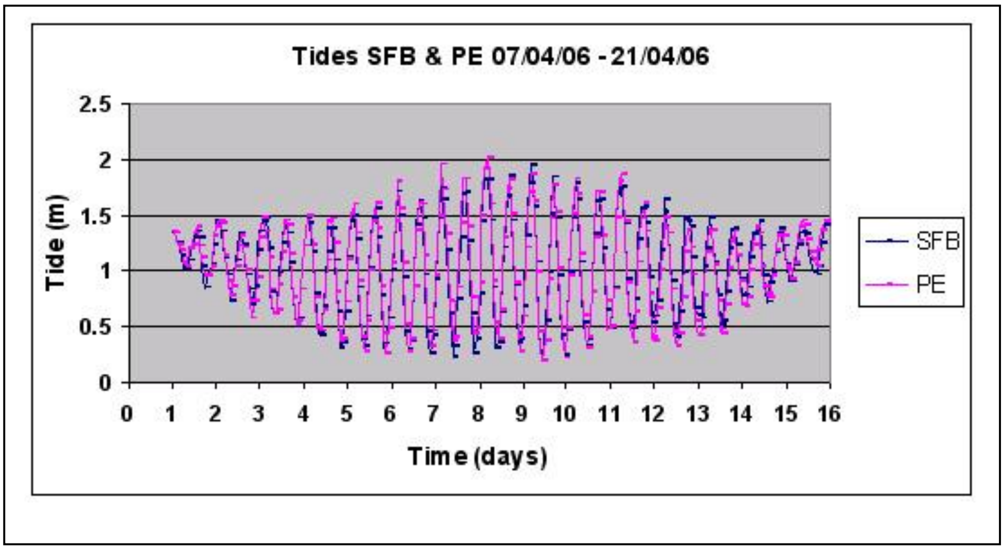


Figure 8.5 Comparison of tides at St. Francis Bay and Port Elizabeth for a 15 day period.

8.2.3 Current data collection, collation and processing

In order to calibrate the model outputs current flows were measured at 3 sites in the lower estuary. Two current meters were deployed at three places in the estuary over a two week period, 8-16 July 2006. The Nortek Aquadopp Current Profiler is equipped with a vertically mounted pressure sensor and three acoustic beams which measure current velocities and directions in ENU (East, North, Up) magnetic directions. The Aquadopp was set up to record data at a frequency of 1Hz at 30 minute intervals. The instrument was deployed on an especially built aluminium frame.

The Sensor data 6000 mechanical Current Meter measures current speed (m/s) and directional data (magnetic) and records 10 minute averaged readings to an internal memory storage device. The Sensordata was attached to a 60 kg mooring weight and held upright by a subsurface buoy.

The Aquadopp was first deployed at site 1 in the entrance to the Ski Canal, after one week the instrument was retrieved, data was downloaded and the Aquadopp was redeployed at site 3 in the main channel of the estuary near the road bridge week. The Sensordata 6000 current meter was deployed at the upper entrance to the canals (UEC) for the full two week period (See Table 8.1 and Figure 8.6)

Table 8.1 Estuary Survey Current Meter Locations July 2006

Site number and description	**Instrument type**	**Location (UTM LO-25)**	**Date deployed**	**Date retrieved**
(1) Ski Canal	Aquadopp	14842.702 E 3779813.122 S	08/07/06	15/07/06
(2) Upper Entrance to Canals	Sensordata 6000	15748.164 E 3779498.540 S	08/07/06	22/07/06
(3) Upper Estuary	Aquadopp	16959.705 E 3779497.461 S	16/07/06	22/07/06

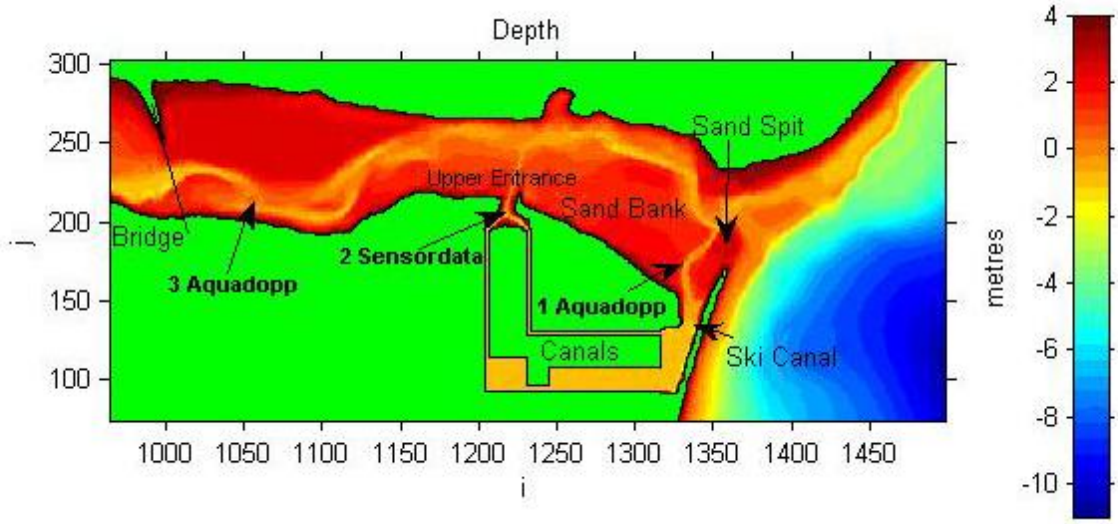


Figure 8.6 Bathymetry of Lower Kromme Estuary showing main features and locations of current meter deployments.

Once the instruments were retrieved, data was downloaded from both current meters and processed using Matlab ®: Data was converted into averaged 30 minute interval time series. Aquadopp data was resolved from Easting and Northing components of velocity and direction into the resultant direction and velocity. The Sensordata current speeds were converted from cm/s to m/s. Direction data from both current meters was then corrected for magnetic declination to True North.

8.3 Numerical modelling

8.3.1 Model Calibration

The Numerical model 3DD was run from the Eastern boundary of the grid (Figure 8.7) using smoothed tidal data from Port Elizabeth Harbour for this same time as the instrument deployment period (Figure 8.8). During the first model run the water levels of the estuary were initiated at an artificial uniform water depth, thus it was necessary to run the model for 6 hours to allow the model to assume realistic water levels. This condition was then used to 'hot start' all subsequent model runs. Current speed and direction data was extracted from the model output files at the locations of the current metres and compared graphically to measured current speed and direction data (Figure 8.9-Figure 8.11).

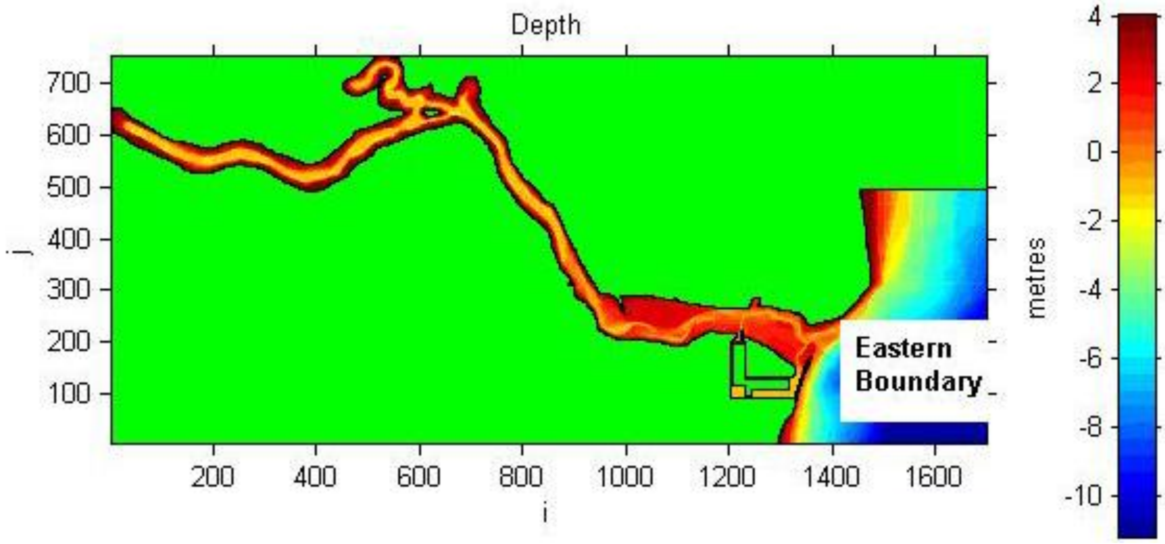


Figure 8.7 Bathymetric grid of the Kromme estuary and offshore area with eastern boundary open, cells 8 X 8 m.

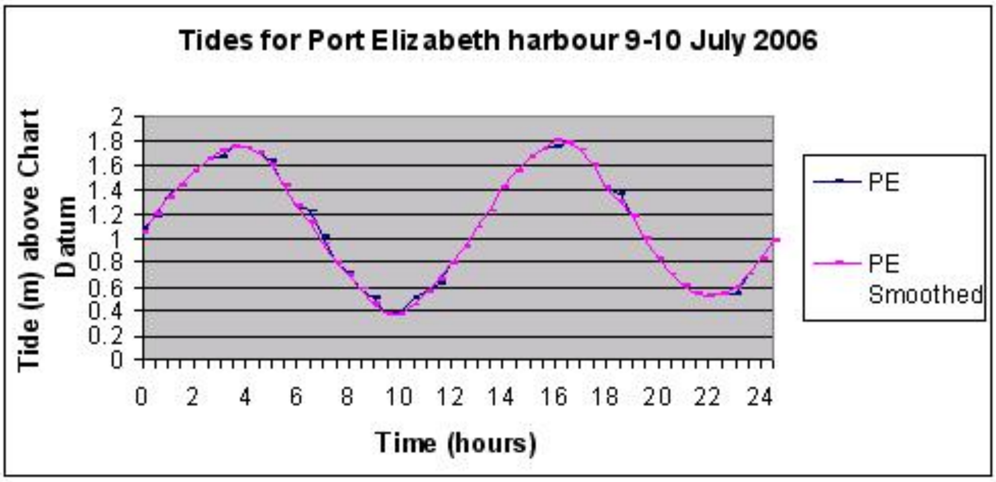


Figure 8.8 Tides from Port Elizabeth harbour, raw and smoothed for use as time series input at the eastern boundary to drive the hydrodynamic model 3DD.

Data from site 1 showed good calibration of speed and direction with a discrepancy in phase of 0.5 hours, most likely due to the lack of true bathymetric data for the canal system. Modelled output data was shifted by 0.5 hours to compensate for this (Figure 8.9). Directional calibration at site 2 was poor (Figure 8.10) due to the complex circulation at this location, situated at a 3-way split, however current speeds were reasonably calibrated. Calibration was highly satisfactory for both current speed and direction for Site 3 in the main channel of the Upper Estuary (Figure 8.11).

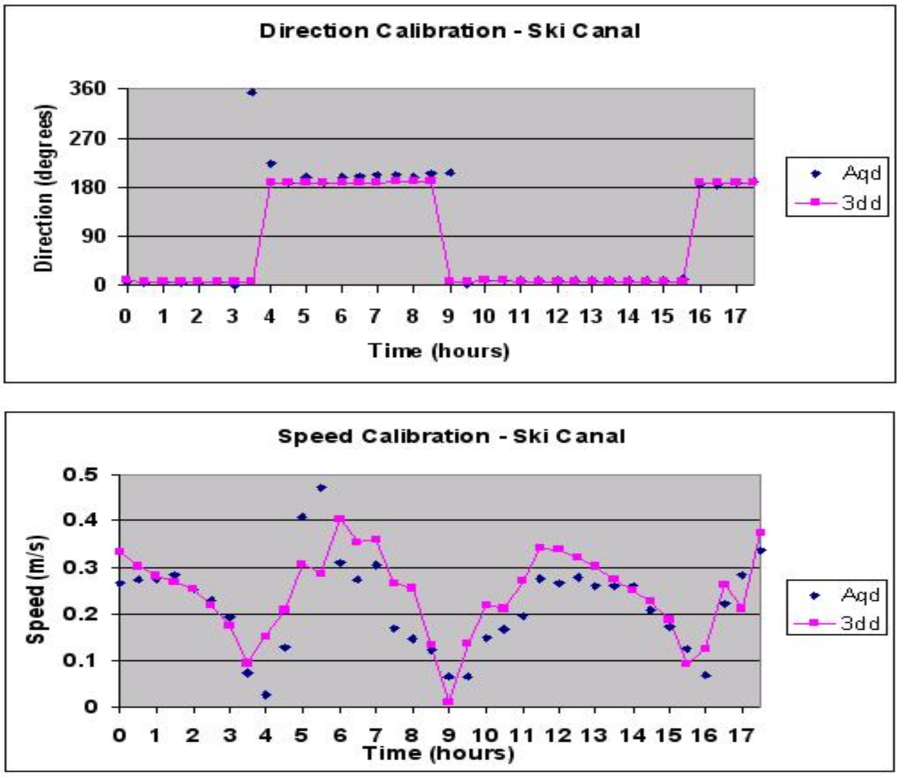


Figure 8.9 Site 1: Ski Canal, comparison of direction (top) and current speed (bottom) between measured Aquadopp data and 3DD model output.

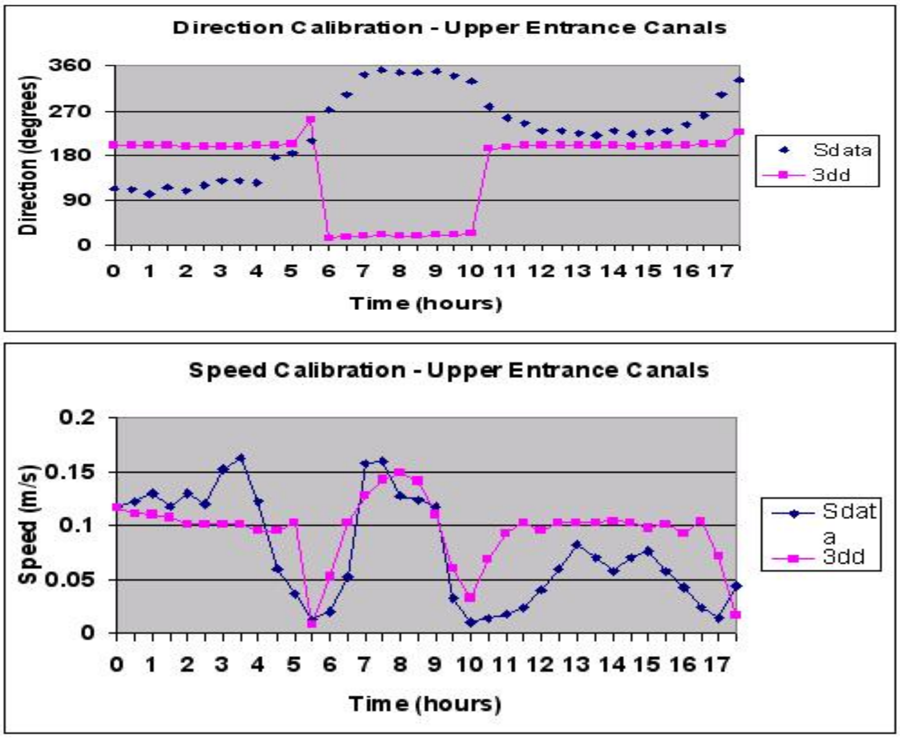


Figure 8.10 Site 2: Upper Entrance to Canals, comparison of direction (top) and current speed (bottom) between measured and 3DD output data.

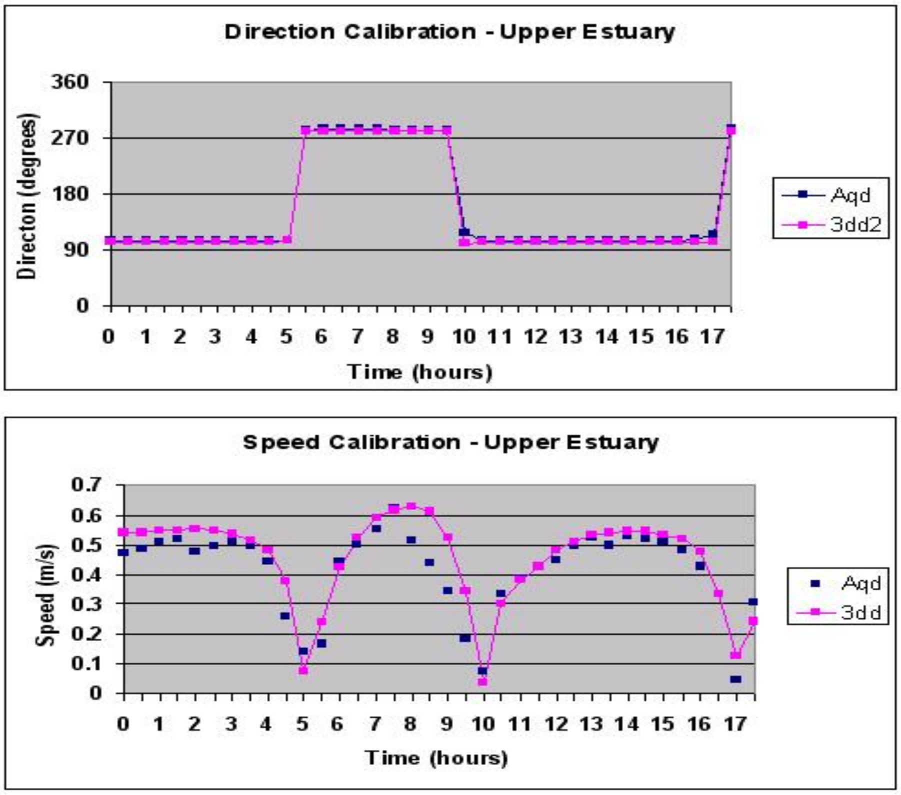


Figure 8.11 Site 3: Upper Estuary, comparison of direction (top) and current speeds (bottom) between measured Aquadopp and 3DD output data.

8.3.2 Modelling of Sand Extraction Scenarios

The model was then run from a hot start file 6 hours into the original model run output file, for a full tidal phase (12.5 hours) over the following bathymetries: Control, 100, 300, 600, 600+UECv1 and 600+UEC. Data was extracted at the instrument sites 1-3 and compared graphically.

Using the 3DD Front End, difference files were created between the control run and modelling over the different sand extraction bathymetries. This allowed the differences between model outputs of currents to be represented graphically using Plot3DD.

8.3.3 Results

By comparing current speed and direction data extracted at sites 1-3 for all the model runs over the different bathymetries, the following is evident:

- Current speeds are low in magnitude at the canal entrances, site 1 and 2.

- At Site 1 currents are fairly consistent in speed and direction through all model runs, with the only exception being 600+UECv1, where through excavation of the upper entrance and canal confluence area, the reduced resistance in this area leads to a phase shift of 0.5 hours experienced in speed and direction (Figure 8.12).
- Current speeds and directions at Site 2 are fairly consistent between measured and modelled data, with a slight reduction in speed directly related to increased sand extraction. 600+UECv1 once again shows the most difference with a phase shift and reduced current speeds during the flood tide. The 600 and 600+UECv2 scenarios are very similar, with slightly lower speeds than 600+UECv1 during the ebb tide (Figure 8.13).
- Site 3 in the main channel of the upper estuary shows almost no variation between the Control and the 5 extraction scenarios (Figure 8.14).

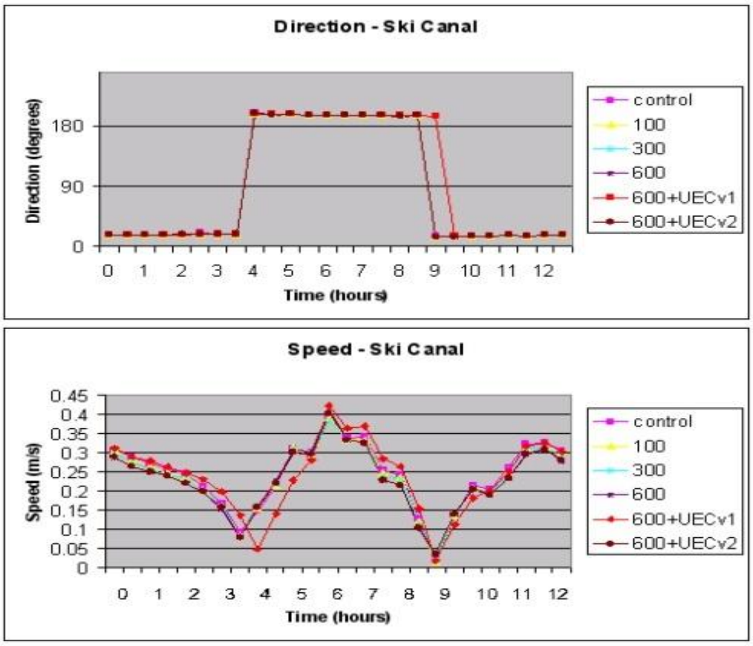


Figure 8.12   Site 1: Ski Canal, comparison of modelled current direction data (top) and current speed (bottom) for different sand extraction scenarios.

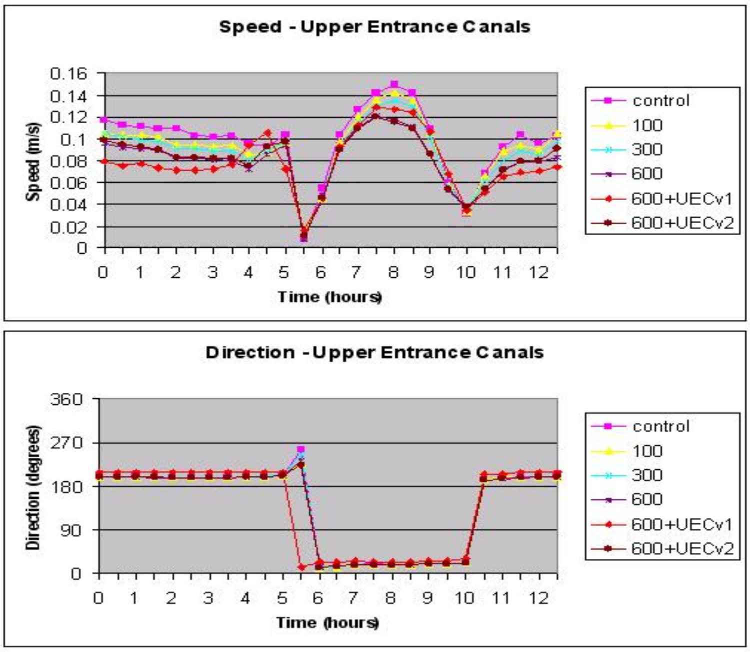


Figure 8.13 Site 2: Upper Entrance to Canals, comparison of modelled current direction data (top) and current speed (bottom) for different sand extraction scenarios.

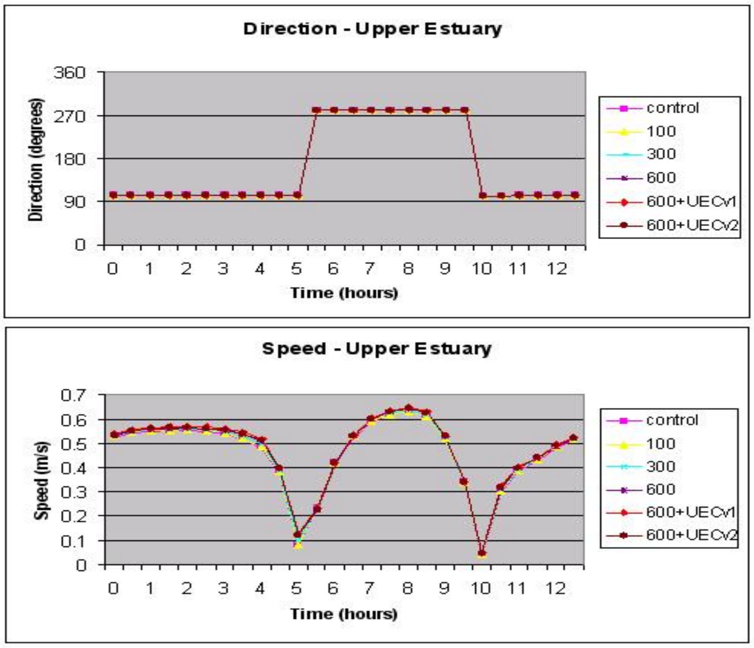
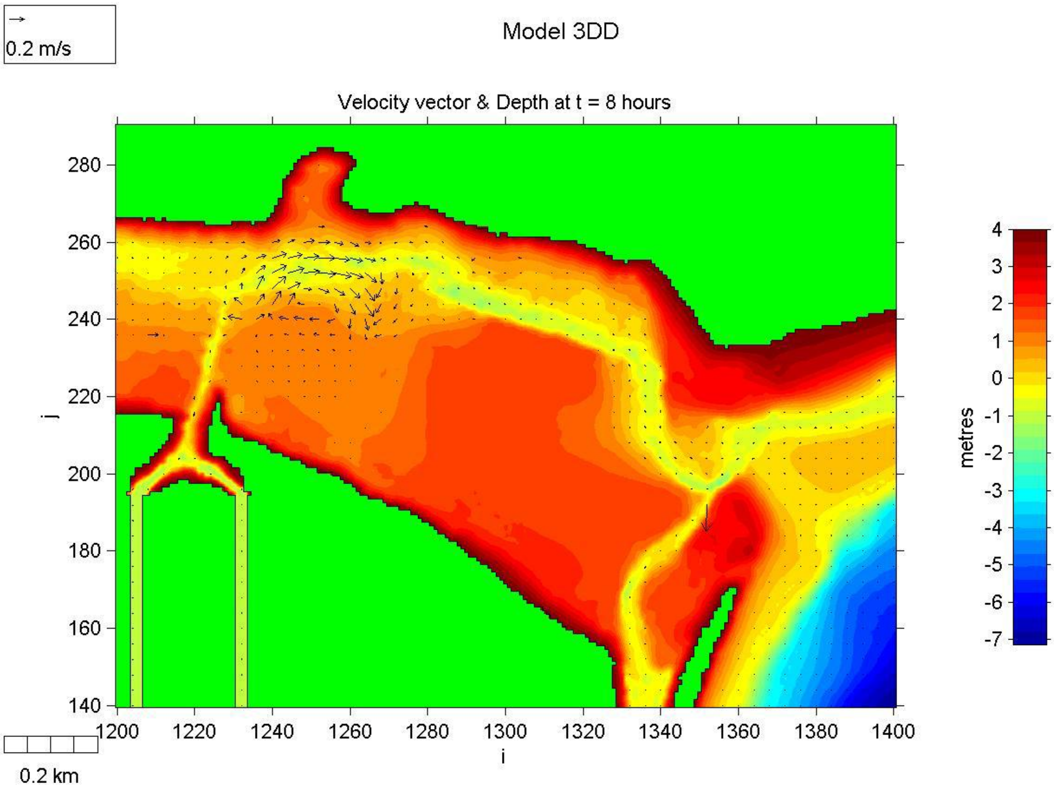


Figure 8.14 Site 3: Upper Estuary, comparison of modelled current direction (top) and current speeds (bottom) for different sand extraction scenarios.

Resultant velocities between the control and 5 different sand extraction scenarios are presented in Figures Figure 8.15 to Figure 8.19 with vectors showing the magnitude and direction of current velocity differences at peak flows of both ebb and flood tides. In all cases velocities over sand extracted bathymetry were subtracted from velocities over control bathymetry, so in effect the results present the magnitude and direction of reduction in current velocity.



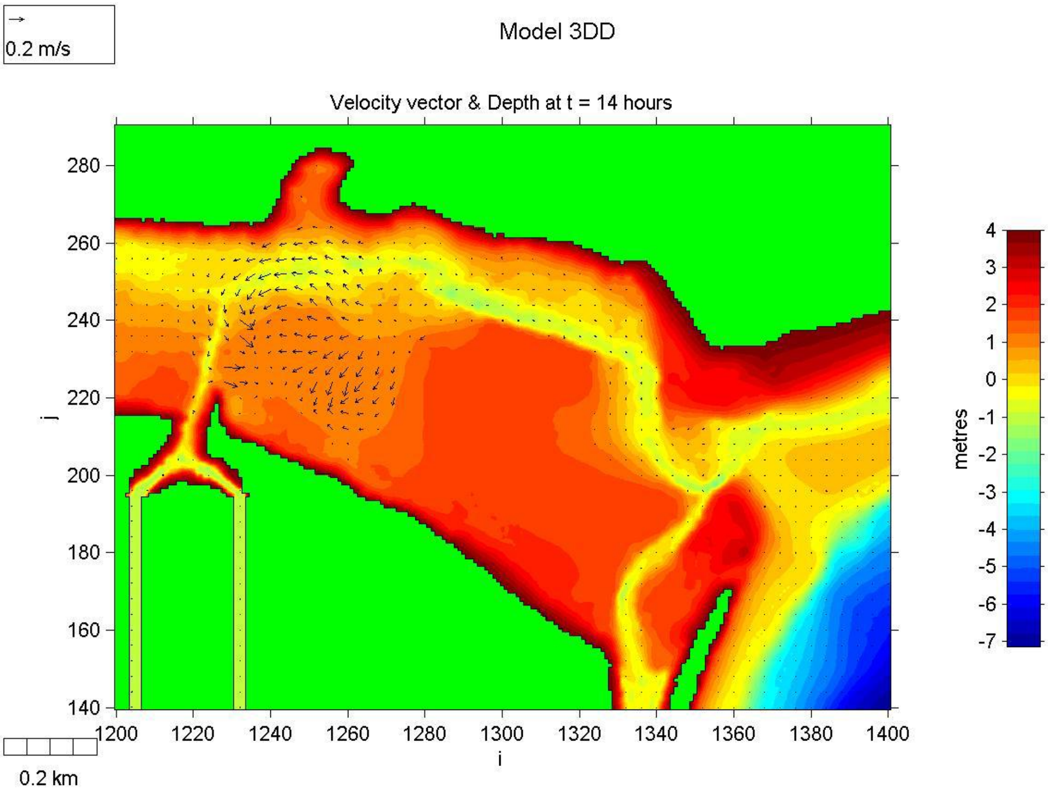
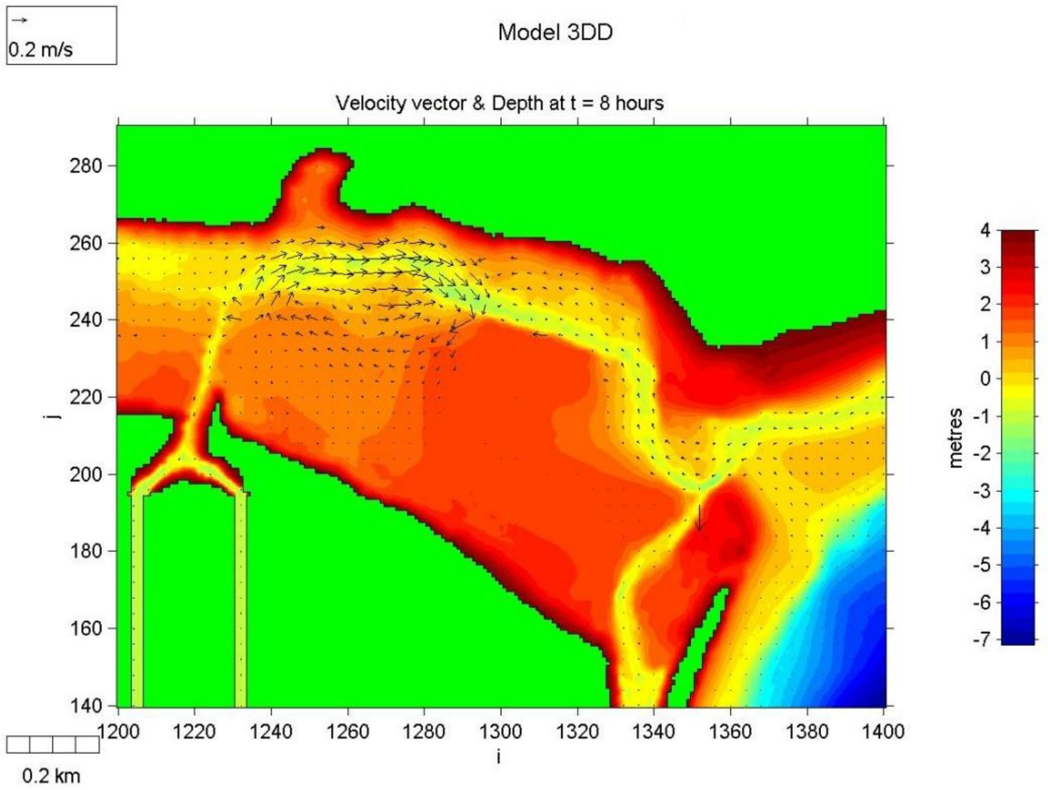


Figure 8.15 Difference in current velocity over 100 and control bathymetry during peak ebb tide flow (top) and peak flood tide flow (bottom).



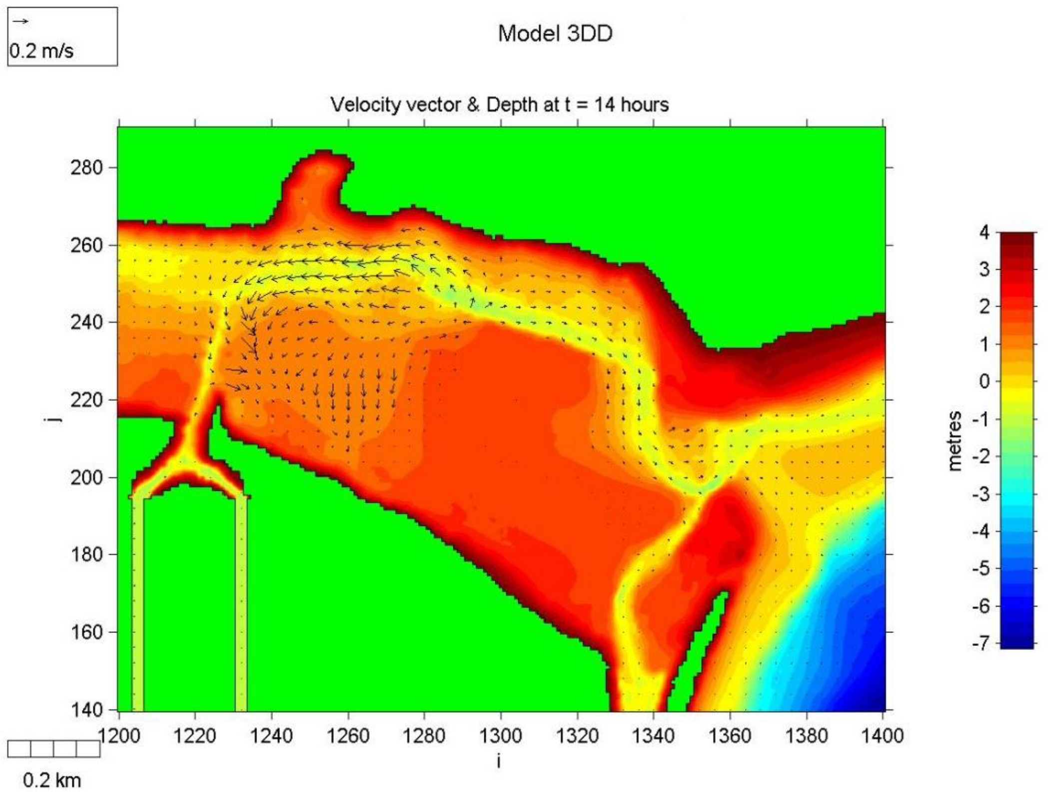


Figure 8.16 Difference in current velocity over 300 and control bathymetry during peak ebb tide flow (top) and peak flood tide flow (bottom).

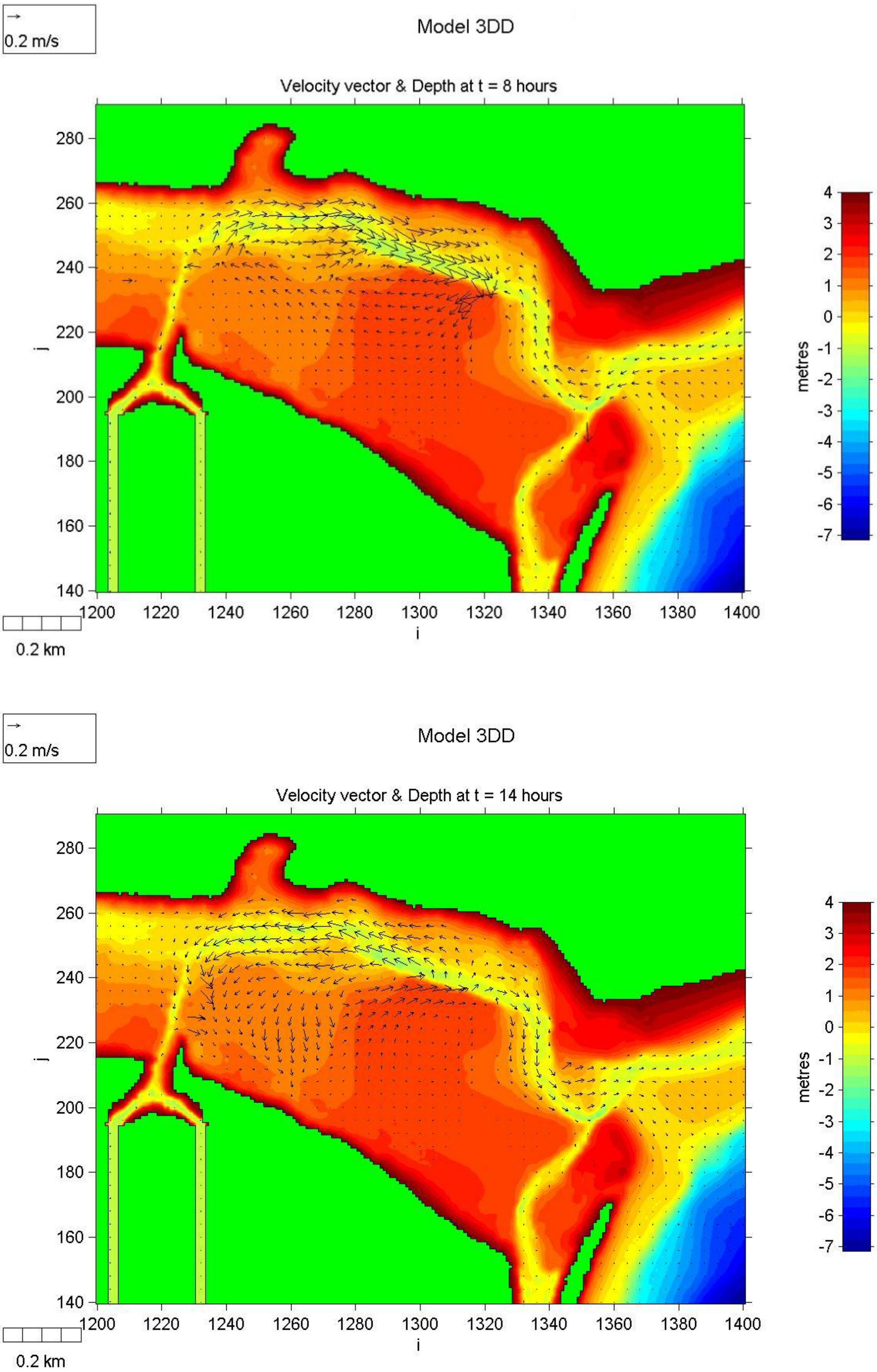
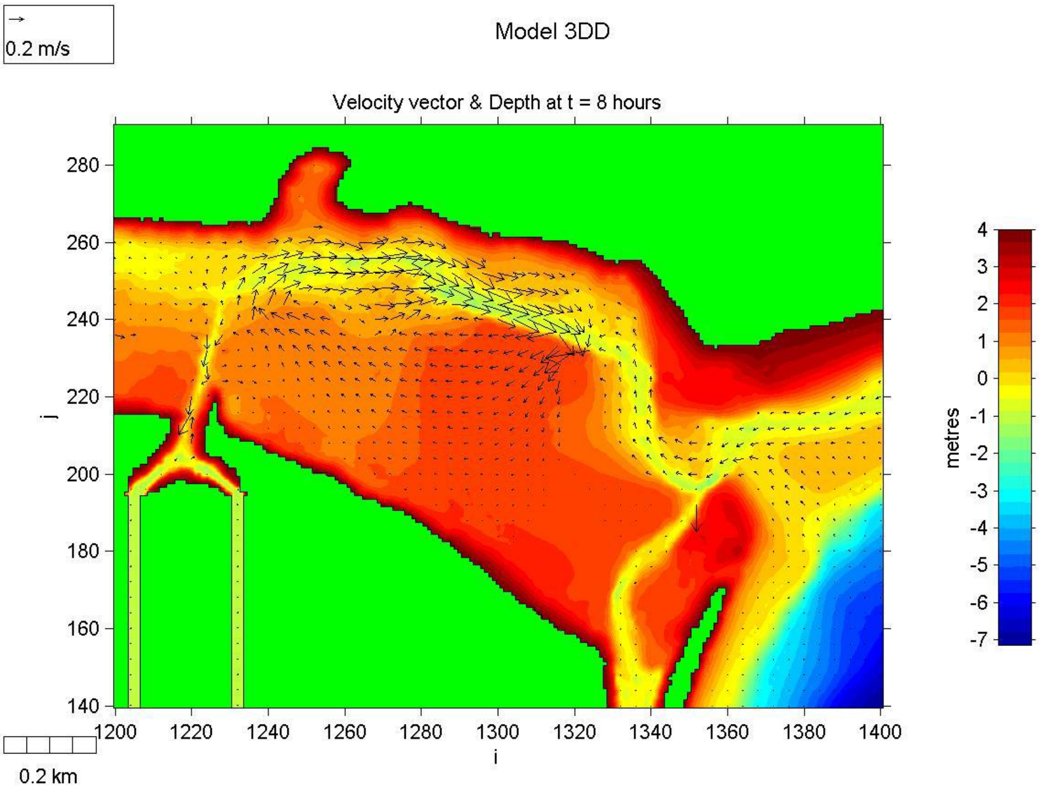


Figure 8.17 Difference in current velocity over 600 and control bathymetry during peak ebb tide flows (top) and peak flood tide flows (bottom).



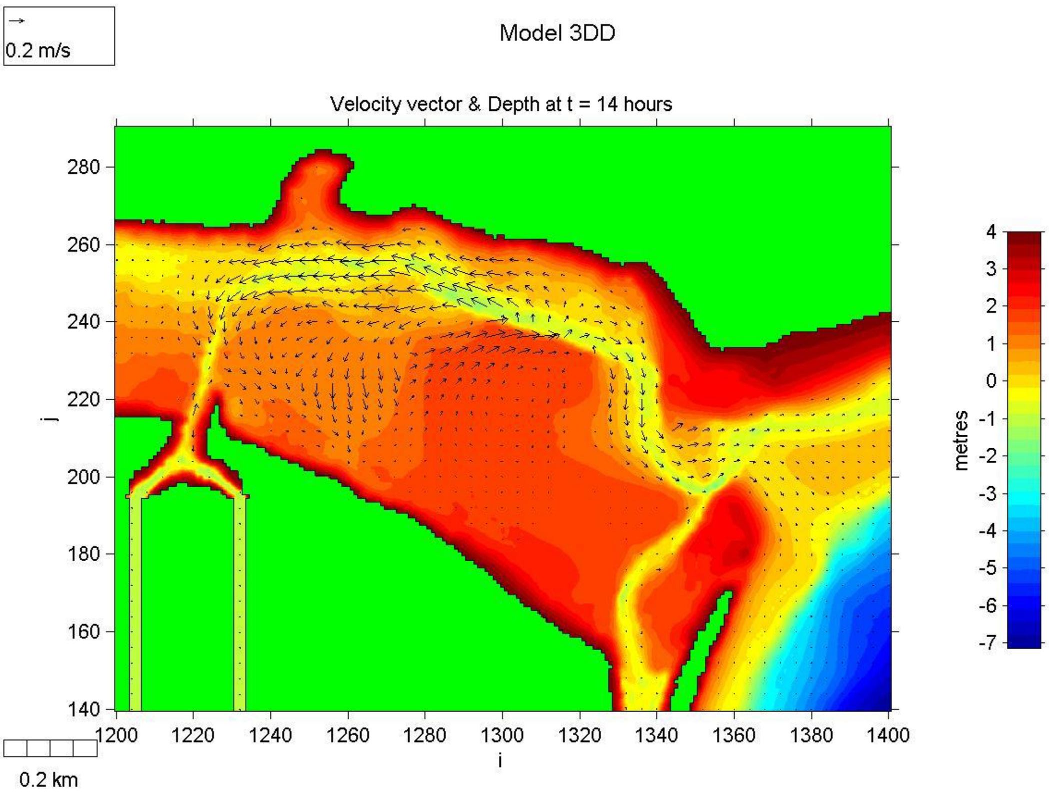
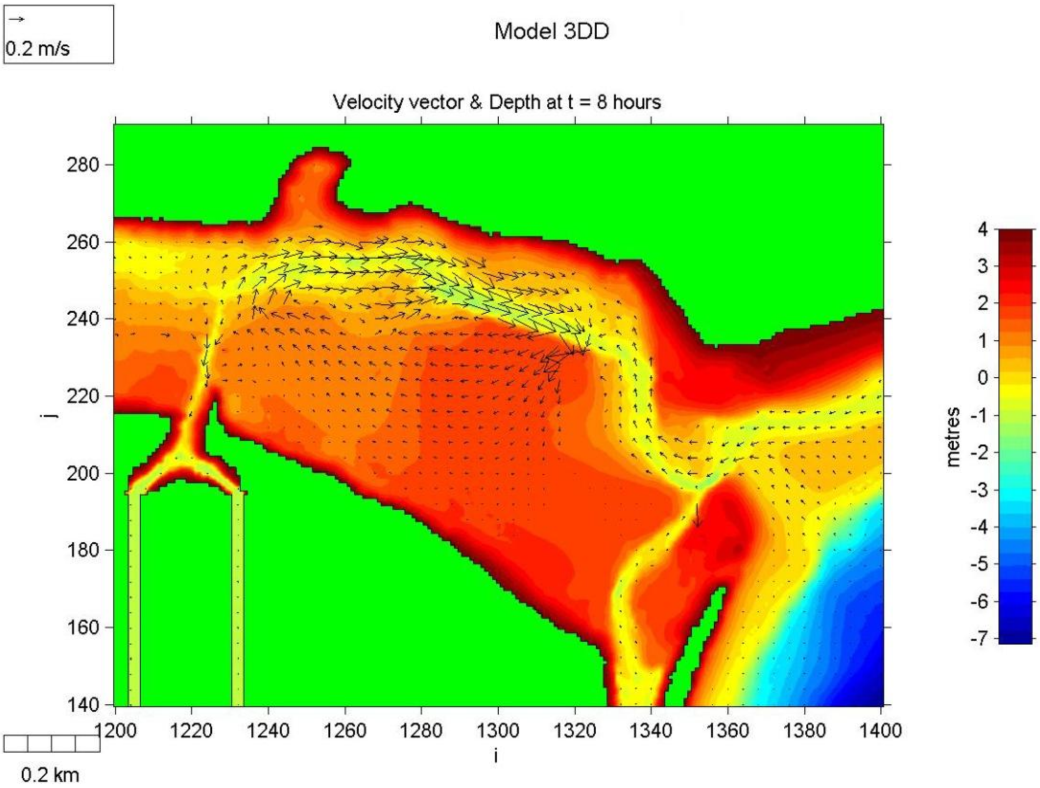


Figure 8.18 Difference in current velocity over 600+UECv1 and control bathymetry during peak ebb tide flows (top) and peak flood tidal flows (bottom).



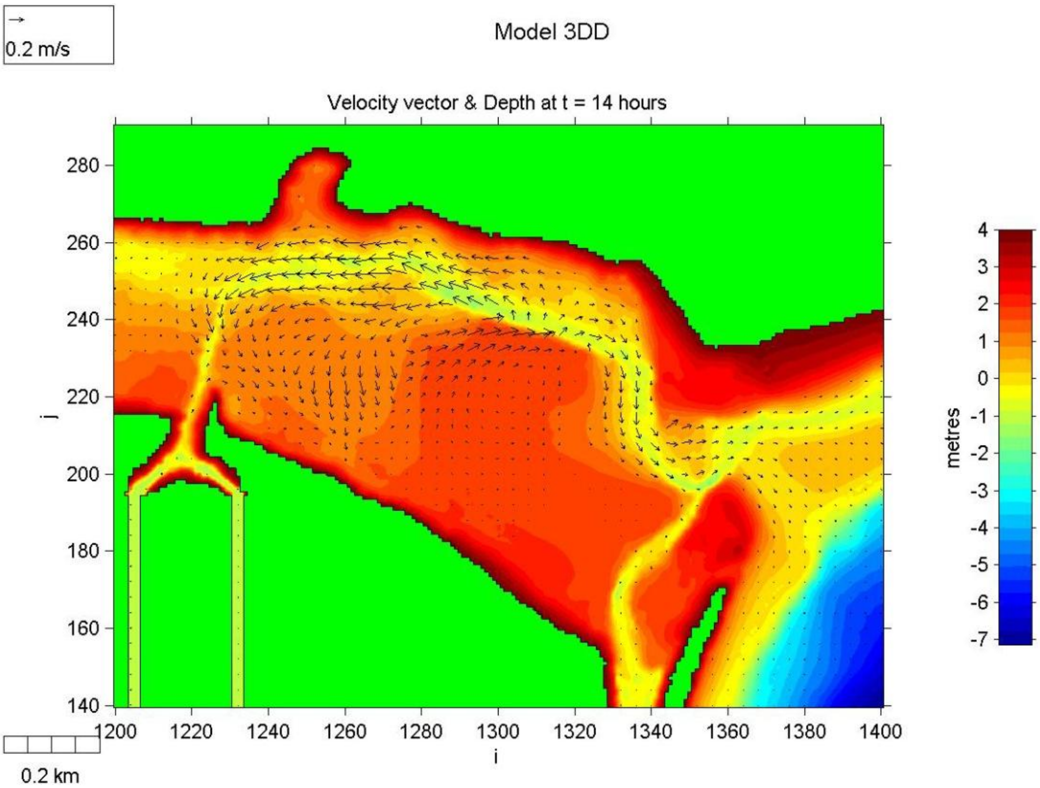


Figure 8.19 Difference in current velocity over 600+UECv2 and control bathymetry during peak ebb tide flows (top) and peak flood tidal flows (bottom).

Analysis of velocity difference plots between the modelled control and 5 different bathymetric scenarios presented above indicates that the main impact on current velocities due to dredging is mainly restricted to the dredging area. In bathymetry 600+UECv1 the excavation was extended to incorporate the upper entrance to the canals and the confluence was dredged to a depth of 1m below chart datum. Results indicate a reduction in current speeds at the upper canal entrance channel under these conditions (Figure 8.18). This resulted in a reduction in velocities in the entrance channel. 600+UECv2 (Figure 8.19), where the dredged area was extended to include the channel to the upper entrance but the confluence area was left at present depth, produced similar changes to the current speeds as were experienced over the 600 version.

8.4 Discussion and Conclusions

Several reasons make the extensive sandbanks found in the lower reaches of the Kromme Estuary a preferred sand source for beach nourishment. Firstly the flood dominant nature of the Kromme Estuary has led to significant accumulation of marine sediment in the lower reaches, a situation common to many estuaries worldwide (Bryant, 1980) and most estuaries of the southern and eastern Cape coast of South Africa (Reddering and Esterhuysen, 1987). River impoundment due to two large storage dams on the Kromme River with a combined capacity greater than the MAR for the Kromme River catchment area has completely eliminated the ability of large flood events to scour marine sediment accumulated in the lower reaches, as would have previously occurred.

Results of 1-D numerical modelling of the Kromme Estuary presented in Bickerton and Pierce (1988) suggest that a 1:50 year flood with a maximum design flow of 2100 $m^3.s^{-1}$ would scour +/- 150 000 m^3 of sand from the lower Kromme Estuary. Although no record of previous volumes of sand scoured from the Kromme Estuary exist, good record was made of flood scour experienced in the Nahoon Estaury in East London, some 300 km to the north east. Reddering and Esterhuysen (1987) compared cross measurements and sediment data from before and after the flood event of 1 and 2 November 1985, during which peak flow of 1400 $m^3.s^{-1}$ were recorded for the Nahoon River. By comparing cross sections, this study calculated that a total of 4.08 X 10^5 m^3 of sand was scoured from the estuary, with 3.18 X 10^5 m^3 scoured from the lower 1.2 km. The Nahoon Estuary is 5km long, therefore 78%of sediment was scoured from the lower 24% of the estuary. 2.44 X 10^4 m^3 (6% of the total) was removed from intertidal areas, increasing the post flood tidal prism by only 3.5%. While the majority 94% was removed from subtidal areas. The differential scour was attributed to different cohesion properties, with loose sand accumulated in the flood tidal deltas of the lower estuary more easily erodable than sand further up the estuary where a higher mud content.

As discussed in section 2.8.2 it is estimated that sediment influx into the lower Kromme Estuary is in the order of 20 000 - 40000 $m^3.yr^{-1}$, both from the Sand River and Kromme Estuary mouth. The 13 000 – 27 000 $m^3.yr^{-1}$ is in the order of the 21 200 $m^3.yr^{-1}$ calculated for the Nahoon Estuary by Reddering and Esterhuysen (1987).

Results of hydrodynamic modelling indicate that the excavation and removal of up to 600 000 m^3 of sediment from the large flood tidal delta on the southern bank inside the mouth of the estuary will have highly localised impacts on flows and sediment transport in the lower reaches of the Kromme estuary. In addition this reduction in current velocities in the excavated area and adjacent channel will most likely lead to increased rates of sediment deposition in this area.

At present the Marina glades canal system is connected to the main estuary at two locations, the ski canal behind the artificial sand spit and the upper entrance 1km from the mouth. According to Schumann and De Meillon (1993) tidal flow through the canal system is of sufficient magnitude to provide adequate circulation and flushing required to maintain good water quality within the canals. Aerial photographic evidence suggests that the ski canal entrance channel has been closed at times. The canal system was extended in 2004, although no flow or water quality data is available since the extension, site visits by the author indicate flows of sufficient magnitude through most of the canal system to maintain good flushing. In fact erosion of certain areas has been experienced due to strong currents at canal intersections (Author pers observation).

Schumann and De Meillon (1993) noted that the configuration of sand banks in the mouth area have a large influence on the flows within the canal system. Thus particular attention was paid to identifying impacts of sand extraction on hydrodynamics within the canals. Collection of current direction and velocity data at both entrance channels allowed for calibrated hydrodynamic modelling.

Modelling results indicate that none of the dredging scenarios lead to any substantial changes in current velocities at the mouth, therefore concerns expressed by Entech (2002b), can be considered unsubstantiated. Four out of the five dredging scenarios appear to have no effect on currents in the canal entrances or upstream of the excavation, with the exception of 600+UECv1 where current speeds in the upper entrance are reduced due to excavation of this area.

Dredging activities should be restricted to the target area within the large FTD and preferably follow bathymetric scenario 600+UECv2, where confluence to upper entrance of canals is not dredged, as modelling simulations indicate that this will maintain present velocities in this area. This will avoid undesirable sediment accumulation in the upper canal entrance which may occur due to decreased velocities produced by dredging this confluence area. Dredging operations should start at western/landward side of sand bank near the upper entrance to the canals and work eastwards/seawards. In addition any shoaling areas in the main channel should be dredged to further improve navigability. Such practice is widely used in beach nourishment projects worldwide, such as Narrowneck on the Gold Coast of Australia where a large volume 1.3 X 10^6 m^3 of sediment has been dredged from the sand banks and boating channels of Broadwater Estuary (ICM, 2000).

Once capital nourishment is complete dredging for ongoing maintenance nourishment should be limited to the estimated rate of input 20-40 000m^3 (CSIR, 1992) in order to make sand extraction sustainable in the longer term. Once extraction begins, regular bathymetric surveys of the estuary area will also provide valuable information on the effects of these dredging operations on the sediment distribution, accumulation and transport within this dynamic estuarine and associated canal system.

As priority regular bathymetric or cross section depth surveys should be carried out in the lower Kromme Estuary in order to assess the changes in sedimentation. In order to increase confidence in the estimated rates of infilling of dredged areas, sediment transport modelling could be conducted. This modelling could be verified by comparison with actual measured infilling once dredging commences to provide even more accurate estimation of long term rates of infilling and effects of dredging on the sedimentation and hydrodynamics of the lower Kromme Estuary providing useful information for long term management purposes and giving insight into the sustainability of this sand source for beach nourishment.

In conclusion both the estuary and beach systems prove to benefit from this approach. Removing sand from the lower reaches of the Kromme Estuary will improve navigability with modelling results indicating localized reduction in current velocities over the dredged areas and minor changes to overall currents at the mouth, upstream or at the canal entrances. The creation of a wide sandy beach will vastly improve the amenity value of the beach while providing protection to beach front properties.

9 CONCLUSIONS

Previous studies conclude that erosion of St Francis Bay beach is indisputably the result of the interruption of sediment supply as a result of the stabilisation of the Santareme dunefield from 1975 to 1985 (Bickerton and Pierce, 1988; CSIR, 1992; WPR, 1993; McLachlan et al., 1994; La Cock and Burkinshaw., 1996; Illenberger and Burkinshaw, 1997; Entech, 2002a). Secondary factors identified include: river impoundment Bickerton and Pierce, 1988; CSIR, 1992; WPR, 1993; McLachlan et al., 1994; La Cock and Burkinshaw., 1996; Illenberger and Burkinshaw, 1997)., cyclic alongshore sediment supply past Cape St Francis (WPR, 1993), significant shift in wind direction since 1982/1983 identified by Schumann (1992).

The greatest retreat of 40-60m (a rate of 2 $m.yr^{-1}$) was measured along the southern half of the beach between 1978 and 1993 (Illenberger and Burkinshaw, 1997). Thereafter beach profiling between 1991 and 2006 indicates continued retreat at a reduced rate of 0.5 $m.yr^{-1}$.

Comprehensive fieldwork conducted by the author led to a better understanding of the physical processes and dynamics of St Francis Bay and provided reliable input data for numerical modelling. Comparison between bathymetric data collected in 2005 and 2006 by the author with bathymetric data collected by SANHO in 1952, indicate that a large quantity of sediment, in the order of $8.8 X10^6 m^3$ has been lost from St Francis Bay over this period. Great losses were measured in the deeper areas, between 10-15 m water depths. The relative stability of the shallower areas, +/- 5 m water depth, can be attributed to the presence of solid rocky substrate throughout much of the bay in this depth range, confirmed during aerial, dive and sediment surveys. Comparison of beach survey data, offshore wave data and tidal data for the erosion event experienced between the 19 and 21 March 2007 confirmed the significant cross shore erosion caused by occasional large, long period South to South East swell events especially in conjunction with equinox tides, as previously reported (WPR, 1993; Entech, 2002a). Collection of wave and current data in 6.5 m water depth about 400 m offshore of St Francis Bay beach provided the first measured data for the inshore area of St Francis Bay. This data confirmed and quantified the importance of the orientation of St Francis Bay, significantly the relative protection offered by Cape St Francis from the predominant waves from a south westerly direction. Waves from this direction have to undergo significant refraction and experience a great reduction in wave height, while waves from the south east to easterly direction are allowed a direct approach and experience minor loss of wave height from offshore to inshore St Francis Bay.

Numerical modelling investigations provided further information regarding the existing processes and dynamics. Basic sediment transport calculations conducted by Mead *et al.*, (2006) agreed with previous calculations presented by Bickerton and Pierce (1988) and WPR (1993) with net southerly transport calculated south of Umzuwethu and minor net northerly transport north of Umzuwethu. Modelling of wind driven currents provides a further possible mechanism for transport of sediment suspended by wave action, identified as an important sediment transport mechanism in water depth > 8m along the coast of India (Black *et al.* 2008). Modelling results suggest that predominant winds from the south west would drive currents and sand to the north out of the bay.

Further hydrodynamic modelling with 2DBEACH concluded that longshore currents are strong and unidirectional along the headland and weak and variable along the beach. Erosion is considered to result from cross-shore transport under large waves from a southerly to easterly direction and factors such as the predominant alongshore wind-driven currents transporting sand to the north east and out of the bay.

Furthermore bathymetric features of varied scale influence the waves and currents shaping the beach. The greatest elements include the non erodable headland and the large reef feature known as Umzuwethu, which acts as a discontinuity to longshore transport creating a large salient which gives St Francis Bay beach its ‘dog-leg’ plan form.

Reef design included empirical calculations and numerical modelling. Empirical calculations suggest that a reef of 100m longshore length situated 225 m offshore of MSL will provide sufficient sheltering and accretion in the form of a salient. Numerical modelling results confirm the effectiveness of MPR’s to protect St Francis Bay beach through wave dissipation, wave rotation and changes in nearshore circulation. Good wave dissipation was achieved using the numerical model WBEND for storm waves up to 1: 10 years (4.5m) from the south east and maximum tidal levels (2.4m); substantial wave rotation was measured using 3DD Boussinesq modelling, showing good indication of the effectiveness of this mechanism to change wave approach and longshore currents. Empirical calculations predict a salient with a maximum width of 85m and an alongshore length of 617 m. 2DBEACH numerical modelling conducted by Mead *et al.* (2006) on planar bathymetry predicts a maximum salient width of 74 m and alongshore length of 535 m. Detailed analysis of the hydrodynamics using the numerical model 2DBEACH indicates that the desired four cell circulation identified as critical to salient formation (Ranasinghe *et al.*, 2006) is achieved for a significant portion of the wave climate.

It is important to point out that the formation of a salient in the lee of a submerged reef provides coastal protection by both modifying the wave climate in the reefs lee (by dissipation and rotation) and providing a wide beach that acts as a buffer zone during storm events. However, the salient is mobile and dynamic, responding to the changing metocean conditions, it is not a solid 'pavement' and does erode during storm events, providing the important sand in the nearshore system to form natural sand bars to protect the coast (e.g. Turner, 2005). The experience of the Gold Coast multi-purpose reef and more recently the Mount Manganui Reef in New Zealand (Black *et al*. 2007)) have shown the effectiveness of submerged reefs in providing beach control points. Even so during extreme events acute erosion may still occur. Thus, while the revetments on St Francis Bay Beach may be lowered, it is recommended that they are not removed, but rather remain (buried if possible) to provide a last line of defence (Mead *et al*., 2006).

Physical model testing was conducted to improve and assess reef design from a surfing and construction perspective. Minor alterations included the sharpening of the nose of the reef and bringing the second half of the right hand section out by 5°. Measurement of peel angles led to the identification of 3 different sections on the right hander and one short intense section on the left hander. According to surfing skill classification system derived by Hutt (2001) both sections of the reef will be suitable for surfers of intermediate to advanced skill levels. However calculation of breaking intensity using measured orthogonal gradients indicate 'very high' to 'extreme' breaking intensities on the reef, suggesting that in general waves on the reef will be more suitable for surfers of advanced skill levels. Capacitance wave gauges located before and after the reef measured good wave height reduction through wave breaking during all tides, importantly dissipation increased with wave height.

Hydrodynamic modelling was conducted in order to investigate potential impacts of sand extraction from the large sand banks within the mouth of the Kromme Estuary for use as beach nourishment. The hydrodynamics over different dredging scenarios representing extraction of up to 600 000 m^3 were compared with the control. Results indicate that changes in currents would be highly localised, restricted to the areas of extraction and adjacent channel where significant reduction in currents would most likely lead to deposition and infilling. Considering estimated rates sediment influx into the estuary, it is proposed that dredging in the order of 20 000– 40 000 m^3 of sediment per year for maintenance nourishment could be sustainable in the long term. This is roughly half of the 50 000 to 100 000 m^3 which is estimated to be transported out of the bay per year, therefore it is critical that significant nourishment be maintained on the beach through the protection offered by the construction of multi-purpose reefs offshore and the trapping of wind-blown sand through dune rehabilitation with appropriate native dune plant species.

This hybrid approach to beach management at St Francis Bay is an example of how a range of coastal management options can be used together to develop a sustainable management plan which provides multiple environmental and socio economic benefits. In future, extension of the sand pumping system to discharge beyond the surfing break Bruce's Beauties will transform this break back its previous breaking quality that originally gave this clean, mean, green jewel of South Africa the title of the "perfect wave" and will lead to further improvement in the amenity of the area.

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