Physical coastal environment of Otago Harbour and offshore: assessment of effects of proposed dredging by Port Otago Ltd

Prepared for

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Executive Summary

This report synthesises the findings of a number of reports investigating the physical coastal environment in the vicinity of Otago Harbour in relation to deepening of the lower Otago Harbour shipping channel proposed by Port Otago Ltd.

The physical coastal environment of the harbour and of the wider Blueskin Bay area are described in detail.

Otago Harbour is a robust, dynamic environment subject to variable wave energy and sediment supply, and to a history of human modification to the shores, the main channel and the entrance configuration. The area of Blueskin Bay between Taiaroa Head and Karitane Peninsula is subject to high-energy waves, strong tidal and oceanic currents, and a large but variable volume of sediment transfer on the continental shelf and nearshore seabed.

Feasibility studies were carried out on the proposal to deepen the shipping channel through the lower Otago Harbour, and to identify the most suitable method of sediment disposal and the offshore disposal site with the least adverse effect.

The main considerations for the effects on the physical coastal processes were:

- Potential changes to the hydrodynamics of the harbour and the entrance channel,
- Potential changes to the wave environment of the harbour, the entrance channel and the disposal site,
- Changes to patterns of sedimentation within the harbour, the entrance channel and the wider Blueskin Bay area, and
- The dispersal of fine sediments due to the dredging operation.

Studies carried out to investigate these effects have shown that they are mostly negligible, and of magnitudes within the variability of the natural environment. Table 6.1 sets out the issues and potential adverse effects of the project. Rankings of the severity of the possible consequences, the duration of the effect and the probability of occurrence are given for each effect.

Apart from the physical change to the seabed topography in and along the margins of the channel, and at the disposal site, the effects of the dredging operation on the physical coastal environment are considered to be minor.

1. Introduction

1.1 Background

This report is part of a collection of reports addressing progressing Port Otago Limited (POL) operations to expand the capacity to service large container ships of 6000 to 8000 TEU (twenty-foot equivalent units). These ships have 50% more capacity and are longer and wider than existing ships that come to the harbour. Port Otago proposes dredging the approaches to Port Chalmers and the berth area, deepening the channel to a minimum of 15.0 metres below chart datum. This will involve dredging and disposal of up to 7.2M m^3 of material.

This report addresses the effects of the proposed dredging activity and the resulting deeper channel on the physical coastal environment. This includes the effects on hydrodynamics, sediment transport and shore processes in Otago Harbour and in the wider Blueskin Bay area. Assessment of the effects has used an approach consistent with international practice (for example PIANC EnviCom Working Group reports on *Environmental risk assessment of dredging and disposal operations*, *Dredging management practices for the environment* and *Dredged material as a resource*), the requirements of the RMA (1991) and NZCPS (1994 and 2008 proposed).

A review of literature on coastal and continental shelf processes of Otago Harbour and Blueskin Bay (Benn and Single 2007) was undertaken in order to summarise the main understandings of coastal and shelf processes in the study area, and to identify any significant gaps in the current knowledge base. A further report by Single and Benn (2007) considered the feasibility of the proposed dredging activity and resulting deeper channel. The main effects on the physical coastal environment identified in the feasibility study concerned possible changes to the hydrodynamics of the harbour, and the transport of sediment in the harbour and from a possible dredged-sediment disposal site in Blueskin Bay. The report also identified gaps in the information required to fully assess the effects of the dredging activity, and identified additional studies required to address the gaps in information.

Subsequently, a number of studies have been carried out to augment the knowledge base and to investigate specific aspects of coastal processes in the area as well as specific effects associated with dredging, disposal, a deeper harbour channel and vessel effects. These studies include :-

- Hydrodynamic factors within Otago Harbour

  Modelling of the tidal propagation was carried out by NIWA to assess the effects of a deeper channel on tide height, currents and timing of the tide into and out of the harbour. The results are reported in Bell *et al.* (2009).

  Met Ocean Solutions Ltd assessed the wave environment of the harbour with regard to the deeper channel. The results are reported in Bell *et al.* (2009).

- Hydrodynamic factors outside the harbour between Taiaroa Head and Karitane Point

  Measurements of currents outside the harbour were carried out to determine the magnitude and directions of currents with regard to possible dredged material placement sites. The results are reported in Bell and Hart (2008).

  Modelling of the currents and wave processes was carried out by NIWA and Met Ocean Solutions Ltd to assess the wider coastal environment for receiving dredged material. The results are reported in Bell *et al.* (2009).

  Met Ocean Solutions Ltd assessed the wave environment in the vicinity of the outer channel to identify changes to the wave propagation across the deeper channel and into the nearshore and beaches. The results are reported in Bell *et al.* (2009).

- Sediment characteristics of material to be dredged from the main harbour channel.

  Opus International Consultants Ltd carried out an investigation of the geotechnical aspects of the harbour seabed to identify the types and quantities of different sediments that would be dredged in deepening the channel. The results are reported in Opus International Consultants Ltd (2008). Opus also undertook an interpretative evaluation of the data to determine the types and locations of the materials, as well as the validity of interpreted data supplied by Port Otago. These results are reported in Opus International Consultants Ltd (2009).

- Sedimentological factors of potential dredge spoil receiving sites, including sediment characteristics of the seabed and potential dispersal of placed dredge sediments.

  NIWA carried out seabed surveys and modelling of sediment transport in the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point in order to identify sediment characteristics and sediment transport paths from potential dredged sediment placement sites. The results are presented in Willis *et al.* (2008) and Bell *et al.* (2009).

- Vessel wake from existing and larger ships using the dredged channel, and the effects on the shores of the harbour.

  Port Otago staff carried out observations of vessel wakes and assessed the potential changes of wake characteristics based on theoretical analysis of ship waves and the effects of the deeper channel, and from measurements carried out near Te Rauone Beach by ORC (Goring 2007). This work is presented in Single and Pullar (2009).

The work on the physical coastal environment was carried out in conjunction with work on ecological matters (see James *et al.* 2007, James *et al.* 2009 and Willis *et al.* 2008).

1.2 1.2 Project Next Generation

1.2.1 Description of the proposed activity

A full description of the proposed dredging activity is presented by Port Otago Ltd in the main Application and Assessment of Effects document. The depth of the main channel will be increased to 15m from the present maintained channel depth of 13.0 m. Figure 1.1 shows the areas requiring dredging. The entrance channel will be deepened to 15m at Harington Bend and sloping to a depth of 17.5m in the outer approach channel (in the vicinity of the Fairway Beacon). Figure 1.2 shows the changed bathymetry of the harbour due to deepening the shipping channel and modification of the channel margins to widen the main bends (Harington Bend and Taylor's Bend) and the swinging basin at Port Chalmers.

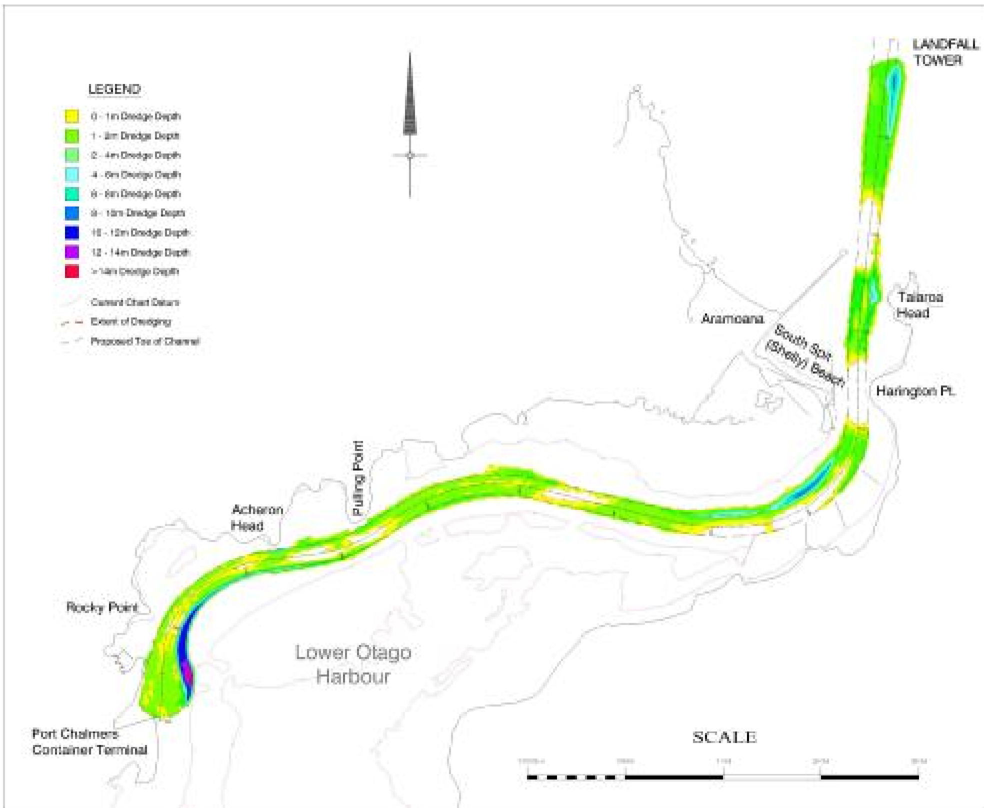

Figure 1.1 Extent of dredging required in the main shipping channel of Otago Harbour.

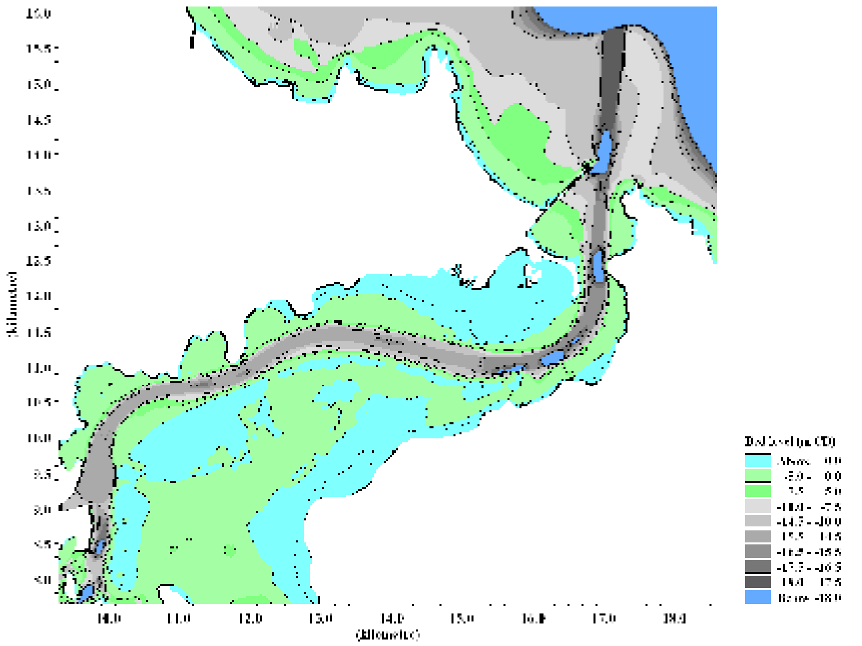

Figure 1.2 Proposed bathymetry of the Lower Harbour and entrance region. (Source: Figure 3.8, Bell *et al.* 2009).

It is estimated that up to 7.2M m^3 of sediment will be removed by dredging. The material is comprised of approximately 62% fine sand and 37% clayey silt and silty clay. However there will be small fractions of rock (mainly from the areas near Rocky Point and Acheron Head). Samples of sediment from the proposed dredging areas were tested for contaminants (heavy metals and metalloids, organic and inorganic compounds) and were all found to fall within the

Australian and New Zealand Guidelines for Fresh and Marine water Quality guidelines (Opus International Consultants 2008).

Use of the dredged material as a resource has been considered and is discussed in detail by Pullar and Hughes (2009). Some of the sand volume dredged as part of the maintenance dredging consent is likely to be made available for nourishment of beaches in the Dunedin area. However, it is likely that all of the dredged material for the capital dredging proposal will be placed offshore. James *et al.* (2007) and Single and Benn (2007) discuss the initial assessment of possible receiving sites. The preferred site was determined after field measurements and modelling investigations. The receiving ground is required to accommodate up to 7.2M m^3 of sediment and covers an area of approximately 2km in diameter with a mound height of up to an estimated initial height of 1.6m above the seabed. The centre of the preferred site is located approximately as shown in Figure 1.3, and is situated on the distal end of a submarine depositional feature known as the "Peninsula Spit" (Bell *et al.* 2009).

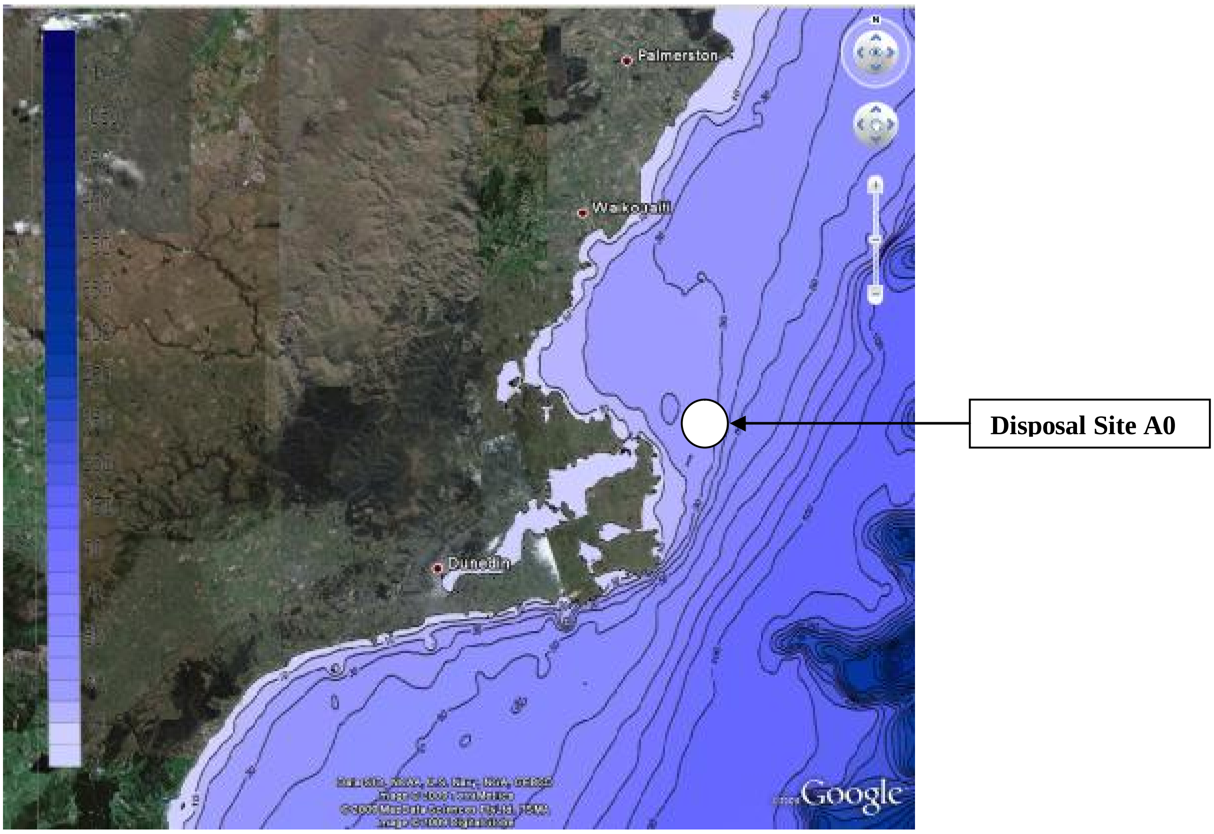

Figure 1.3 Approximate location of the preferred disposal site (known as AO in the technical documents) (Background image source: Google Earth, 2009).

It is proposed that a trailing suction hopper dredge (TSHD) will be used for the majority of the dredging operation, with a backhoe dredge (BHD) for the rocky areas. Rock to be removed from near Rocky Point and Acheron Head will either be broken up with a backhoe or blasted depending on the strength of the rock. Pullar and Hughes (2009) discusses the details of the dredging methodology and how the work is likely to be undertaken.

1.2.2 Initial consideration of possible effects of the activity on the physical coastal environment

In considering the feasibility of the project, it was important to assess the sustainability of the 15m channel and the dredging processes required to attain that outcome. Single and Benn (2007) cover the assessment on the physical coastal processes in detail through consideration of the effects of a finished deeper channel from Taiaroa Head to Port Chalmers on the physical coastal process environment of Otago Harbour and the nearshore area around the inlet, the effects of the dredging activity, and the effects of placement of the dredged sediment at sea.

Seven types of effects on physical coastal processes were identified. These were:

- Changes to hydrodynamics of the channel north of Harington Point (the entrance channel),
- Changes to hydrodynamics within the harbour,
- Changes to sediment transport dynamics within the channel,
- Changes to sediment transport dynamics on the tidal flats and channel margins,
- Changes to future maintenance dredging demands, and
- Changes to the effects of shipping activities.
- The effects of the placed sediment on the hydrodynamics and sediment transport in Blueskin Bay and on the coastal margin.

Initial modelling showed that the effects of a deeper channel on the hydrodynamics of the harbour are not likely to be significant. There is likely to be a change in the speed of propagation of the tidal wave along the harbour by a few minutes, and a small change to the tidal elevations. Changes to the velocities of the tidal currents are unlikely to be significant within the channel and across the intertidal sand flats.

The initial modelling allayed concerns that the deeper channel could result in raising the level of high tide within the harbour to such an extent that flooding of the harbour margins could result. Work by Wilson (1989) indicated that past channel dredging has suppressed the effects of eustatic sea level rise over the last century. Deepening the channel further could delay or suppress the effects of projected future sea level rise. Detailed hydrodynamic modelling has been undertaken to identify changes resulting from the deeper channel.

The effect of wave propagation across the channel, north of Taiaroa Head may result in effects on ship handling, pitch and roll. This aspect of the effects of the proposed channel deepening has been assessed using detailed wave modelling.

Ship wake has been identified as one of many contributing agents in causing change at Te Rauone Beach. This issue is examined by Single and Pullar (2009).

The dredging activity will result in direct disturbance and removal of the sediments from the channel and the channel margins as well as approximately 8,000m^2 of lower intertidal zone (tidal flats) beside the existing swinging basin at Port Chalmers. Placement of the dredged sediment at the receiving ground will result in the creation of a sediment mound comprised of sand, clayey silt, silty clay and rock. The surficial sediments of the mound are likely to be winnowed by wave induced currents and will move away from the site along with the natural movement of native sands along the seabed. The placed dredged sediment may also result in slight modification of the local wave environment and wave induced currents. This aspect of the effects of the receiving grounds has been assessed using detailed hydrodynamic and wave modelling in conjunction with seabed sediment transport investigations.

The dredging method will result in turbidity to the waters of the harbour, along the sailing line between the dredging site and the receiving grounds, directly over the receiving grounds during placement, and in the vicinity of the receiving grounds during placement or due to winnowing of fine sediment from the mound. This aspect of the effects of the proposed channel deepening has been assessed by plume modelling using hydrodynamic data and models.

1.3 Scope of this report

The scope of this report is to provide an overview of the physical coastal processes, and an assessment of the potential effects of the proposed dredging and disposal activities on the physical coastal environment of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Peninsula – the wider Blueskin Bay. The specific objectives of the report are to:

- Describe the existing hydrodynamic processes of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point, and to describe the sediment transport patterns for the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point.
- Summarise the changes to the hydrodynamic processes of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point as a result of the proposed dredging and disposal and deeper channel.
- Summarise the changes to the wave environment in the Lower Otago Harbour and the area in the vicinity of the entrance channel as a result of the proposed deeper channel.
- Summarise the potential effects of changes to the wave environment on the physical coastal environment of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point as a result of the proposed dredging and disposal.
- Assess the effects of the proposed dredging operation and placement of dredged sediment on the sedimentation processes of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point. These effects include turbidity in the harbour, at the dredged sediment placement site and areas in-between, changes to wave refraction and sediment movement on the seabed as a result of placement of dredged sediment, and changes to maintenance dredging operations as a result of the deeper channel.

In particular, this report presents a synthesis of the findings of the studies described in Section 1.1, namely:

- *Benthic offshore surveys of proposed dredge spoil disposal sites off Otago Peninsula.* Willis TJ, Bradley A, Handley SJ, Paavo B, Page MJ, James M (2008)
- *Port Otago project next generation summary of existing physical coastal environment information and scoping for further studies*. Single MB, Benn J (2007)
- *Te Rauone Beach coastal resource management.* Single MB (2007)
- *Factual report of geotechnical investigations: Port Otago–Project Next Generation.* Greene S, OPUS International Consultants (2008)
- *Port of Otago dredging project. NIWA: Preliminary hydrodynamic modelling and scoping further work.* Oldman, J.W.; Bell, R.G.; Stephens, S.A. (2008)
- *Offshore ADCP deployments (Otago Peninsula) for Port of Otago dredging project.* Bell RG, Hart C (2008)
- *Port of Otago dredging project: Harbour and offshore modelling.* Bell RG, Oldman JW, Beamsley B, Green MO, Pritchard M, Johnson D, McComb P, Hancock N, Grant D, Zyngfogel R (2009)
- *Geotechnical Advice "Next Generation" Project – Interpretation of Geotechnical Data and Quantity Survey.* Hanz M, OPUS International Consultants (2009)

2. The Physical Coastal Environment of Otago Harbour and Blueskin Bay

2.1 General geography of the area

Otago Harbour is the focal point of the Dunedin City area and provides the contemporary and historical link to trade and migration into Otago. Dunedin City (population about 115,000) is located at the south-western end of the harbour. Port Otago is located at Port Chalmers (population about 1,300), on the northern side of the harbour.

Figures 2.1 and 2.2 locate places referred to in the text, and show the general location of Otago Harbour and the adjacent coastal area. The two coastal areas at the focus of this report are the harbour and the offshore area from Taiaroa Head to Karitane Peninsula. This area of open coast is often referred to as Blueskin Bay, a name also used for the estuary southwest of Warrington. In this report, the estuary will always be referred to as Blueskin Bay Estuary, while the general open coast area will be referred to as Blueskin Bay.

Figure 2.1 Location map of the Otago Harbour area (from NZMS 260 Series via TopoMap).

Figure 2.2 The lower harbour (from NZMS 260 Series via TopoMap).

Otago Harbour is approximately 20km long and averages 2.5km in width. The harbour is bounded to the south and east by Otago Peninsula, and to the north and west by the hills of Mt Cargill. The harbour is effectively divided into upper and lower sections by Quarantine Island located between Port Chalmers and Point Quarantine. The harbour has extensive areas of intertidal sand flats, located mainly on the southern side of the harbour, but also extending south from Aramoana (Figure 2.2).

The long narrow shape of the harbour, and the large intertidal areas, require the port areas of both Port Chalmers and Dunedin to be serviced by an artificially maintained shipping channel. Sediment dredged from the channel is deposited at receiving grounds outside the harbour at Heyward Point, off Aramoana Beach (Spit Beach site) and at Shelly Beach.

Apart from Port Chalmers, the other main communities located around the lower harbour are Careys Bay and Deborah Bay, just north of Port Chalmers, Aramoana, which lies at the northern side of the entrance to the harbour, the settlements of Otakou and Te Rauone Beach, on the shore of the eastern side of the harbour south of Harington Point, and Harwood, to the southwest of Te Rauone Beach (Figure 2).

Communities of interest in Blueskin Bay and coastal areas that may be affected by the placement of dredged sediment offshore include the settlements of Purakanui, Waitati, Warrington and Karitane, and the shores of Kaikai Beach, Whareakeake (Murdering Beach), Long Beach, Purakanui Bay, Warrington Spit, the rocky shore from Warrington to Puketeraki and Karitane.

2.2 Regional Geology and Quaternary history

2.2.1 Regional setting

The rocks that outcrop along the Otago coast, including those around Dunedin represent four major stages of geological history. They are:

1) The Basement rock - comprised of Tertiary schist;

2) Two Tertiary sedimentary sequences;

3) Three late Tertiary eruption phases of the Dunedin Volcano; and

4) Glacial and inter-glacial deposits laid down approximately 15,000 to 10,000 years BP.

Figure 2.3 presents a generalised regional map of the geological make-up of the study area and the wider hinterland, and shows the spatial extent of these four evolutional stages of geological history. From Figure 2.3 it can be seen that Otago Peninsula and the shoreline to the north to Blueskin Bay estuary is dominated by the Dunedin volcanic complex and modern alluvial deposits. The coastline north of the estuary to Karitane is characterised by Tertiary Sediments and remnants of the volcanic flows that now form the sea cliffs along this section of shore (from Nicholson, 1979: 29).

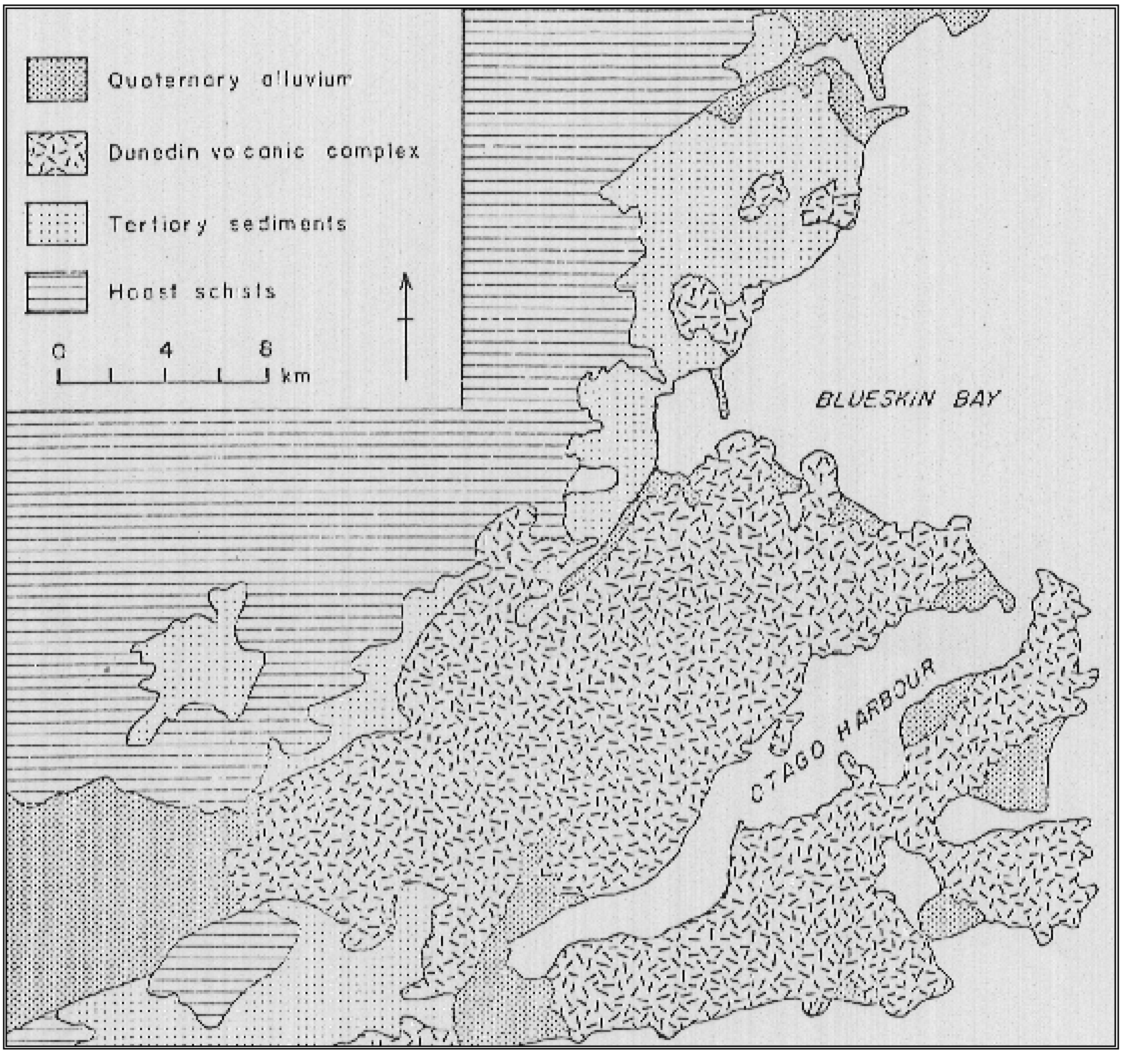

Figure 2.3 A generalised map of regional geology of Blueskin Bay and surrounding hinterland (Source: Nicholson, 1979).

Otago Peninsula, Dunedin and Otago Harbour are located on what is thought to be the centre of the Dunedin Volcano. The volcano took several million years to develop, with successive lava flows progressively overlapping in the westward direction upon a surface of low relief that was created by the two Tertiary sedimentary sequences. Alluvium was laid down over the volcanic rocks during the Quaternary (last 1.8 million years). Loess deposits are also present and are thought to have been sourced from what is now the seabed, during glacial periods when sea level was at a significantly lower elevation than today.

The glacial and interglacial periods that featured during the Late Quaternary through to the Holocene were the main controlling factors of the morphology of the Otago Shelf. The area has been subject to prolonged periods of sediment supply from offshore, and progradation of the shores. Areas of the margins of Otago Harbour now covered with dune sands were probably covered by seawater less than 6,000 years ago.

2.2.2 Seabed sediments

The quartz sands of the nearshore zone off Otago are derived from Otago Schists, with their ultimate source being the Clutha River and to a lesser extent the Taieri River. The mineral suite of these nearshore sediments is made up of quartz, sodic plagioclase, chlorite, epidote, zoisite, garnet, wollastonite, and biotite, many of which are signature minerals of the Haast Schist that the Clutha River transports to the littoral zone south of Otago Peninsula (Bardsley 1977, Andrews 1973 and 1976, Williams 1979).

Carter (1986) produced a sediment budget for the coast south of Otago Peninsula to Nugget Point. From this budget, he showed that the dominant source for the modern sediment (younger than 6,500 years) is the Clutha River, which delivers in the order of 3.14 million tonnes of sediment to this coastal system each year. In comparison, the much smaller Taieri River provides a mere 0.6 million tonnes per year, with the nearshore and biogenic productivity providing 0.4 and 0.25 million tonnes of sediment per year respectively. Carter also noted from his study that although suspended mud size particles make up over half of the modern sand input, little is retained on the Otago nearshore shelf. Carter proposed that of all the sand and gravel sized material delivered to the Otago coast by the Clutha River; approximately half is stored within the large nearshore sand-wedge, with approximately 1.1 million tonnes per year transported north under the influence of wave processes and nearshore currents.

Figure 2.4 illustrates the general shelf sediment facets off Otago. It can be seen that sediments are distributed as an inner shelf belt of modern terrigenous sand; a middle shelf belt of relict terrigenous sand and gravel; and an outer shelf zone of biogenic sand and gravel (Andrews, 1973). Beyond the shelf, relict sandy muds line the submarine canyons and slope bottom (Nicholson, 1979). The distribution of modern sands and muds that lie close to the shore reflect the location of river mouths.

A submarine feature in the form of a submerged spit is situated off Otago Peninsula (referred to as 'Peninsula Spit' by Carter and Carter, 1986). It is a product of the inner continental shelf sand-wedge. The submerged spit can be seen in Figure 2.5. It is approximately 25 kilometres long, tapering from 3 to 4 kilometres width where it abuts the northern shore face of Cape Saunders and fades out northwards on the mid shelf off Karitane. Separate to this submarine feature, is the ebb-tide delta of Otago Harbour. The shipping channel truncates the ebb-tide delta. There is also a prominent accumulation of sediment immediately to the east of the shipping channel. This feature takes the form of a bar, trending north from Taiaroa Head for approximately 2km.

A nearshore sand-wedge blankets the inner-mid Otago continental shelf, where the deposition of up to 34 metres of Holocene sediment has accumulated. The wedge appears to have evolved in two main stages. The first stage occurred during a period of relatively stable sea level between 9,600 and 8,800 years BP, when mean sea level was approximately 24 to 27 metres below where it is today. Accumulation lessened with the re-commencement of the Holocene regression and when the sea level stabilised to its present position (about 6,500 years BP), the second stage of the evolution of this sand-wedge commenced with a deposition of modern sands over the lower wedge (Carter and Carter, 1986).

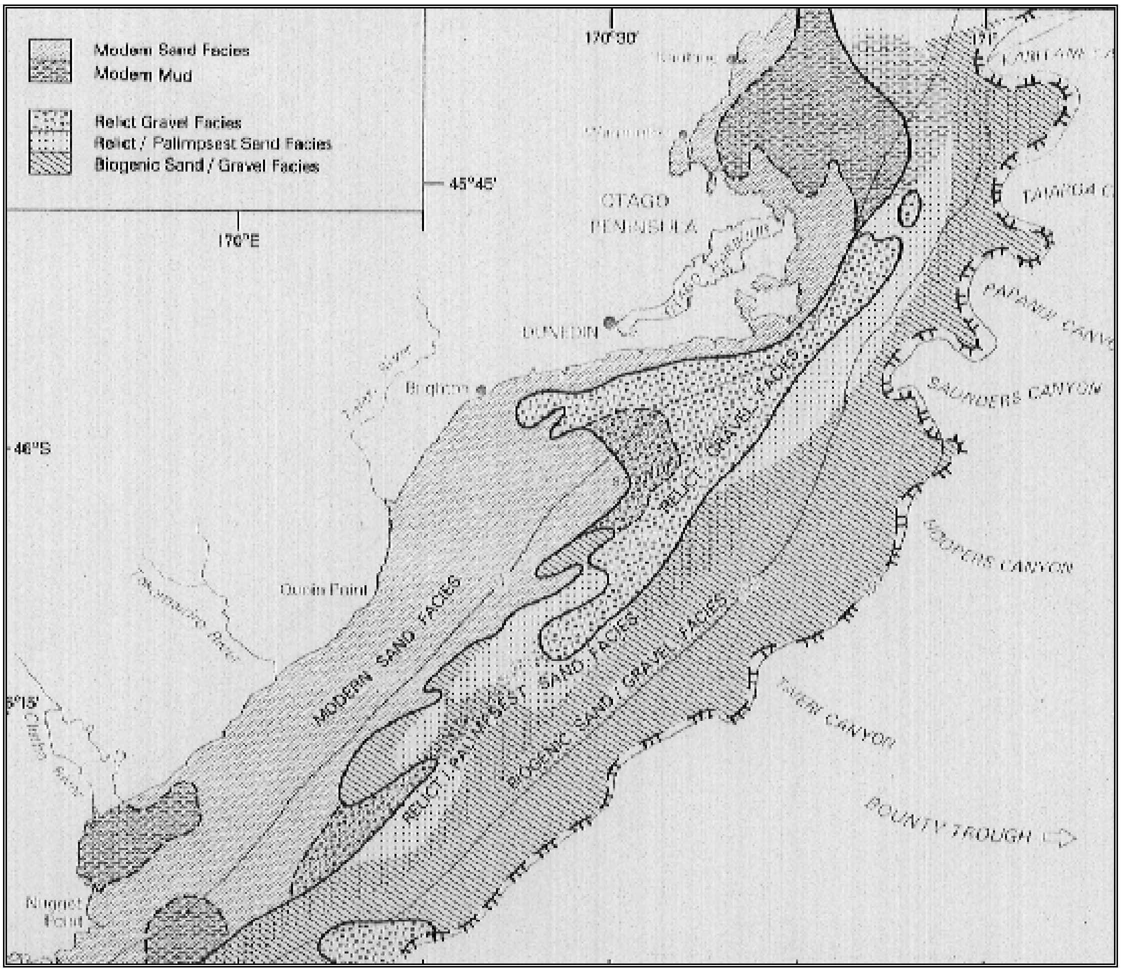

Figure 2.4 Spatial distribution of five main sediment facets deposited on the South Otago shelf (Source: Andrews 1973).

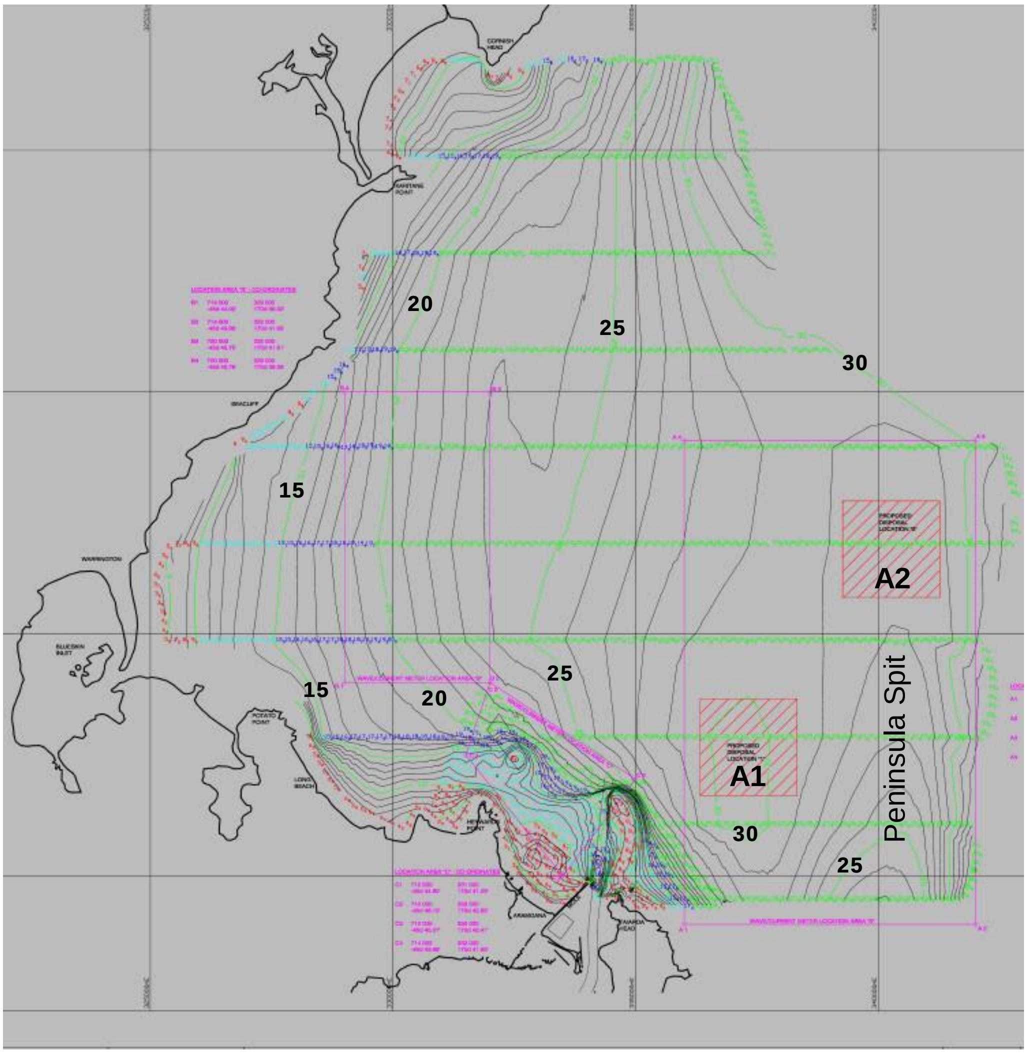

Figure 2.5 POL seabed sounding lines (2 km spacing offshore) and contours at 1 m increments and annotated every 5 m increments (m; Chart Datum), illustrating the bathymetry coverage within Blueskin Bay and the inner shelf. The hatched squares (A1, A2) indicate initial site options considered for placement of dredged sediment (Source: Figure 3.1 Bell *et al.* 2009).

2.3 Otago Roads

2.3.1 Wave Environment

Waves provide energy to do work in generating sediment transport on the seabed. The direction of the wave approach is important in governing the direction of sediment transport. However waves work in conjunction with other ocean currents in determining the nature and direction of coastal and inner shelf sediment movement. In water deeper than about 15 to 16 m, wave energy and the motion of water particles under the wave can act to disturb sediment particles on the seabed, initiating movement that results in entrainment of the particle by a combination of wave, tidal and oceanic currents. In shallower water, incident waves play a very important role in short and long-term beach stability, beach form and evolution, and have a direct effect on nearshore processes that include sediment transport. In the nearshore, where depth are less than about 10 m, waves start to shoal and transform, changing shape and direction of travel. The energy of shoaling and breaking waves govern patterns of sediment transport to a considerably greater degree than tides and oceanic currents.

The depth of effect of wave-induced currents is a function of the wave length, determined by the wave period, such that longer period waves will ‘feel’ the seabed at greater depths than shorter period waves. In Blueskin Bay, this results in waves from the southerly quarter having an effect at greater depths than those from the northerly quarter, as wave periods are greater for waves from the south.

Wave environment for Blueskin Bay and Offshore

The most frequent wind directions for the area offshore of Otago Peninsula and Blueskin Bay are from the north / northeast and south / southwest. As a result of the local geography, the direction of wave propagation into the bay is modified such that waves approach predominantly from the northeast and southeast.

Very few studies before the work for Next Generation had directly measured the wave climate of the offshore or nearshore environment of this area. Instead data from local studies of directions of deepwater wave approach obtained from ship records, and hindcast modelling of the wave environment have been used to determine the wave climate of the Otago nearshore area. Many studies, including research by Pattle (1974), and Hewson (1977) have shown that the East Coast of the South Island is dominated by oceanic southerly swell waves, with local waves playing a secondary role. Nicholson (1979) presented a review of data obtained from ship observations, a drilling rig off the North Otago Coast, and those observations made onshore by Hodgson (1966), where he noted that the southerly swell component is generally a longer period wave when compared to other waves that are generated locally. From this data Nicholson calculated that, north-easterly swell occurred 29.2% of the time, with swell arriving from the east (probably either refracted southerly or easterly deepwater waves) occurring 44.7% of the time. The predominate offshore wave height as obtained by Nicholson (1979) was 1.5 - 2 metres (making up 47.3% of all occurrences) with waves of heights between 3 - 6 metres occurring 26.3% of the time. As longer period waves generally have greater energy for a given height, Nicholson concluded that the southerly swell plays the most important role in sediment movement along the inner shelf east Otago Peninsula.

Sanford South Island Ltd (2001) assessed sea state conditions at Taiaroa Head recorded over a 40-year period (1961 - 2001). The data showed that swell waves predominantly propagate from the northeast, and these waves are generally low in height. Southerly swell waves are the second most dominant wave, and are larger than those propagating from the northeast. The data also showed a seasonal trend with occasional large wave energy events with wave heights greater than five metres typically experienced during the autumn and winter months. Such waves propagate from the south and southeast and refract around Taiaroa Head into Blueskin Bay.

Recent work by NIWA for Project Next Generation (Oldman, Bell and Stephens 2008) has used a 20-year WAM wave hindcast for an area 3 nautical miles due east of Taiaroa Head at approximately 170.778°E, –45.774°S to represent the wave environment. Based on the hindcast data, the mean significant wave height H_s (average of the highest 1/3rd of waves) was 1.1 m, mean wave approach direction D (coming from) was 125° (i.e. from south-east) and the mean wave period T_m was 6.4 seconds. The distribution of significant wave height (H_s) and mean wave period (T_m) are shown in Figures 2.6 and 2.7 respectively. The directional distribution of the waves at this site is shown in Figure 2.8.

Figures 2.9 and 2.10 show diagrammatic representations of the wave environment from modelling work by MetOcean Solutions Limited (Bell *et al.* 2009). Figure 2.9 shows a summary of the wave heights from the southeast sector, while Figure 2.10 shows the contrasting wave height patterns for waves approaching from the southeast and northeast.

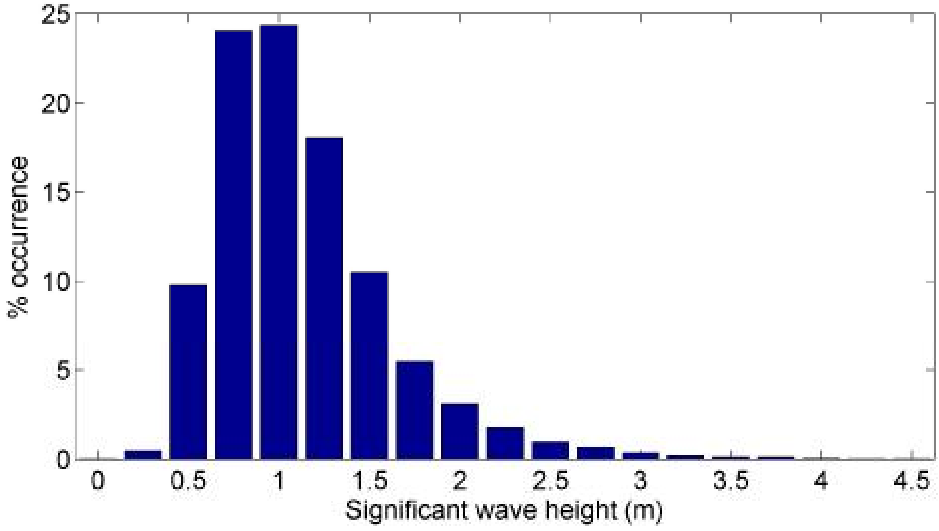

Figure 2.6 Distribution of significant wave height from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head (Source: Figure 20, Oldman, Bell and Stephens 2008).

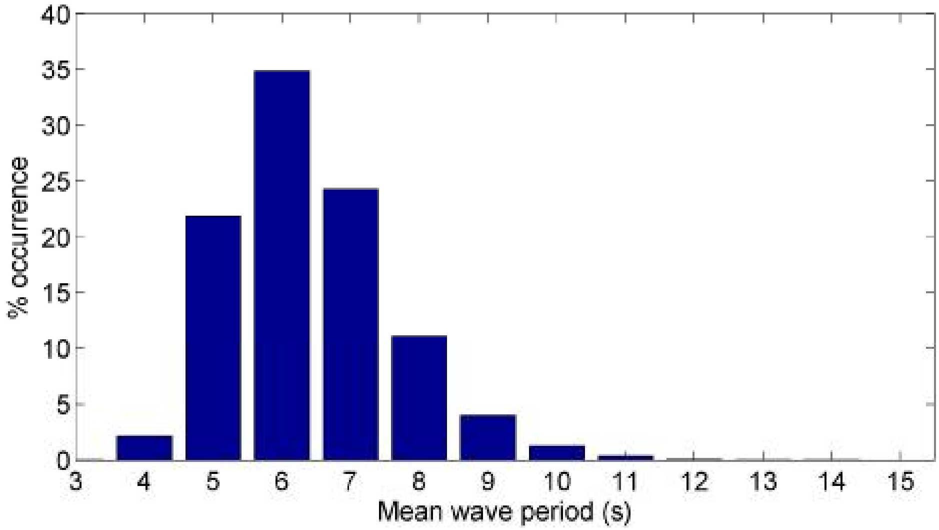

Figure 2.7 Distribution of mean wave period from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head (Source: Figure 21, Oldman, Bell and Stephens 2008).

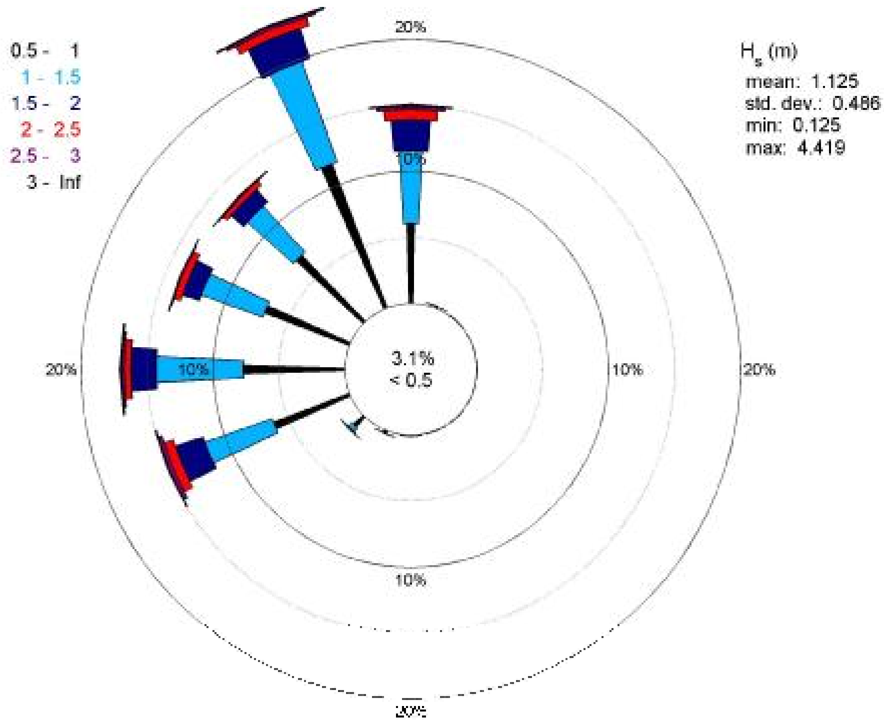

Figure 2.8 Wave rose from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head. Directions are shown in the direction to where the waves are travelling (Source: Figure 22, Oldman, Bell and Stephens 2008).

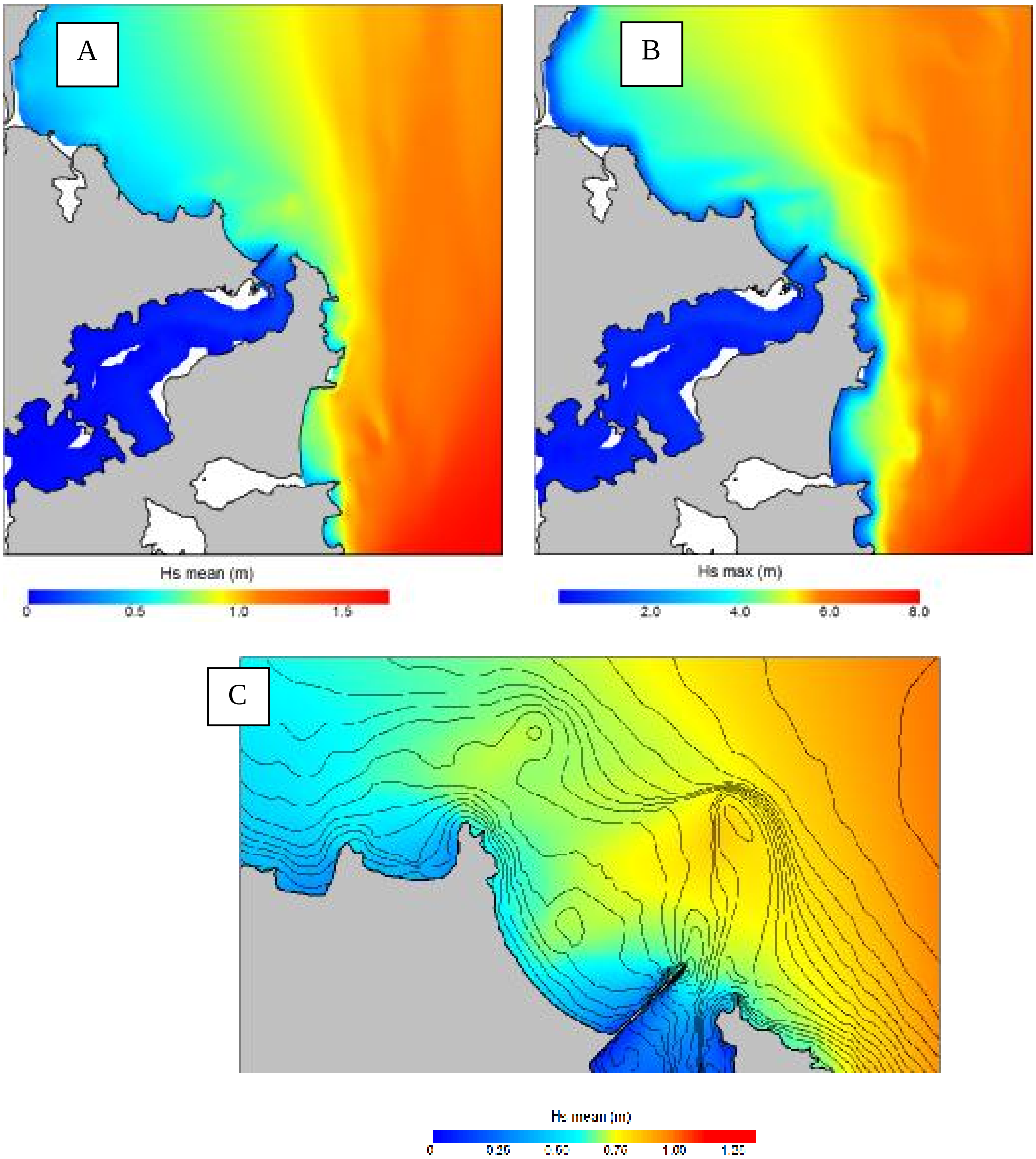

Figure 2.9 Mean (A) and maximum (B) significant wave heights over a 5-year period (2003–2007). A close-up of the mean wave heights near the entrance is provided on panel C (Source: Figure 8.5, Bell *et al.* 2009).

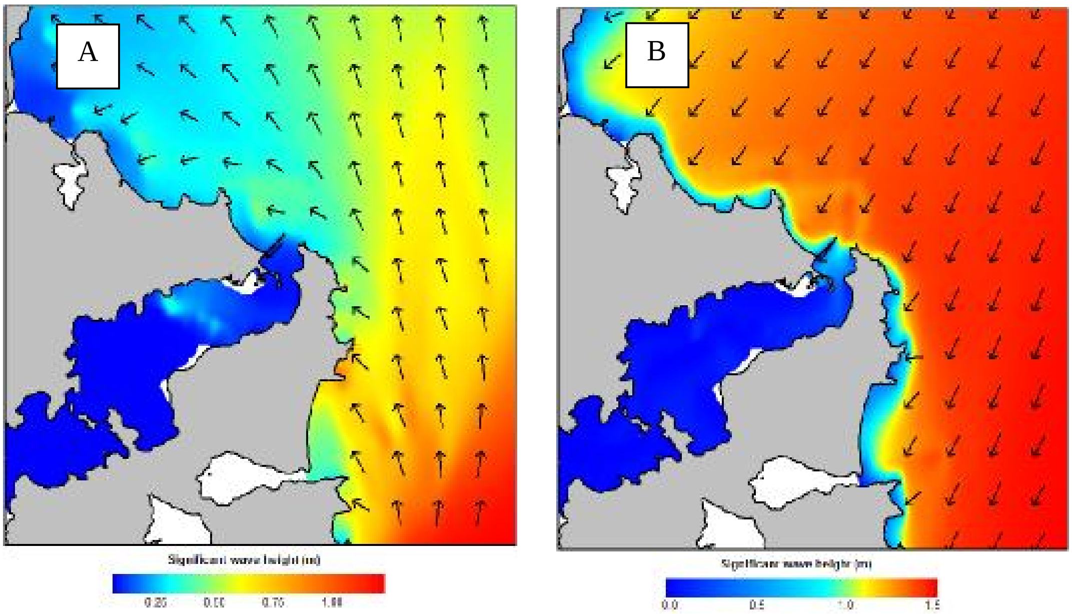

Figure 2.10 Typical wave height patterns for waves from the southeast (A) and the northeast (B) (Source: Figure 8.6, Bell *et al.* 2009).

Wave climate within Blueskin Bay

With the beaches of Blueskin Bay being situated on the leeward side of Otago Peninsula this section of coastline is also leeward from the dominant southerly swell. Although the southerly swell is still a dominant wave within Blueskin Bay, Hodgson (1966) noted that its intensity and effectiveness is considerably reduced by the effect of wave refraction, and that within this leeward area local winds play a more important role in wave propagation.

The movement of nearshore sediment is determined by both the angle at which the waves approach the shore and the amount of energy reserved in the waves from the open sea. The direction of wave approach to the shoreline is dependent upon the direction of the generating winds, and also the configuration of the near-shore environment. The near-shore influences the approaching waves through refraction.

The amount of refraction experienced by longer waves is always much greater than for short waves as they 'feel' the influence of the seabed sooner. As a result swell waves are often seen breaking parallel to the shore.

Refraction is important when considering the amount of energy delivered to the coastline by a given wave train, and is also an important factor with regard to wave energy received by the beaches of Blueskin Bay. The change of wave direction of two or more parts of a wave crest results in convergence or divergence of wave energy. Within Blueskin Bay the submarine contours follow closely that of the shoreline. Concentration of energy (greater wave heights) is experienced on headlands, and dispersion of energy (smaller wave heights) occurs within bays.

The gradual shelf slope that characterizes Blueskin Bay means that shorter period waves undergo little refraction until close to the shore. Consequently there is little loss of deepwater wave energy as the northeasterly waves move across the shelf. This results in most of the wave energy from this source being expended at the shore. Under these conditions, waves approach obliquely to the shore from Purakanui northwards. South of Purakanui to the Harbour Entrance, wave approach is shore-parallel.

In contrast, the longer period southern swell waves begin shoaling 6 to 7 kilometres offshore. Such waves first 'feel' the bottom at a water depth of over 100 metres, thereafter beginning to refract. Although a longer period wave and therefore of higher energy for a given height than the northeasterly wave, the southerly undergoes intense refraction to arrive parallel to the Blueskin Bay beaches. Consequently wave energy levels generally tend to decrease from north to south along the coastline towards Otago Peninsula. North of Warrington Spit and Seacliff, waves need to undergo less refraction to arrive parallel to the coast and as a result wave energy spent on these beaches is greater than those located further south. This means that an energy gradient is produced thus promoting a northerly transport of sediment under southerly swell conditions increasing in a northeastwards direction.

The wave climate of Blueskin Bay can be summarised as being 'quieter' than the outer Otago shelf and those beaches south of Otago Peninsula, with the bimodality in local wind conditions being reflected also in the wave environment in Blueskin Bay. Of the waves that do enter the bay, strongly refracted southerly swell dominates but refraction lessens its intensity. The northeasterly locally generated waves are unimpeded within the bay, although they are generally less powerful than the southerlies affecting the outer-shelf. Overall the regime within Blueskin Bay can be described as a low energy coastal environment that experiences periodic high-energy storm waves propagating from the south.

2.3.2 Ocean and Tidal Currents

Many reports have described the southern current that moves northwards up the East Coast of the South Island at a regional scale. Also well recognised is the disruption that Otago Peninsula has on this northward current, by forcing an anti-clockwise 'eddy' or gyre to form in its lee (Andrews, 1973; Carter, 1986; Carter and Heath, 1975; Nicholson, 1979; and Murdoch ***et al.***, 1990). This gyre, when considered together with the wind and wave processes has a direct effect on nearshore processes within the lee of Otago Peninsula in Blueskin Bay, as well as the coast south of Taiaroa Head to Cape Saunders.

Recent measurements of currents in Blueskin Bay by Bell and Hart (2008) show variations in the direction and strength of the tidal currents depending on the state of the tide, wind direction and strength, and the strength of the Blueskin Bay gyre. Currents within the bay were driven by alternate northeast and southwest winds, but can also be driven by southwest winds, resulting in a net drift to the north. They also found that the prevailing current near Heyward Point is generally eastwards but during southerly storm conditions can be driven to the northwest.

At a local scale McLintock (1951) noted the wave currents together with those of the tide combine to transport sediment inshore and eastward along Aramoana and Shelly Beaches. Royds Garden (1990) present results of modelled tidal currents at the harbour entrance and they too recognised these effects of tide and wave generated currents. Bell and Hart (2008) found that combinations of wind, tide and the Southland Current result in the formation of an eddy current northeast of Taiaroa Head as shown in Figure 2.11. This situation is likely to affect sediment transport in the vicinity of the harbour entrance and the ebb tide delta at local spatial and temporal scales, and may result in bifurcation of sand transport offshore from Wickliffe Bay (Figure 2.11) such that sediment moves separately in a north-westerly direction near the coast and across the harbour entrance and in a north-easterly direction offshore and along the Peninsula Spit.

Recent studies have examined the tidal currents through the harbour entrance (Old 1998, 1999; Old and Vennell 2001). There is a strong asymmetry between the ebb and flood flow structures. While the ebb flow extends beyond 2km from the entrance, the flood flow is limited to within 500 m of the coast. These tidal currents also have an important effect on the general current flows past the harbour entrance, and any resulting sediment transport. The asymmetry of the tidal flow and the flood dominance within the harbour entrance determine the sediment transport pathways across and within the harbour entrance, resulting in the need for maintenance dredging in this area (the Entrance and Howletts claims in particular).

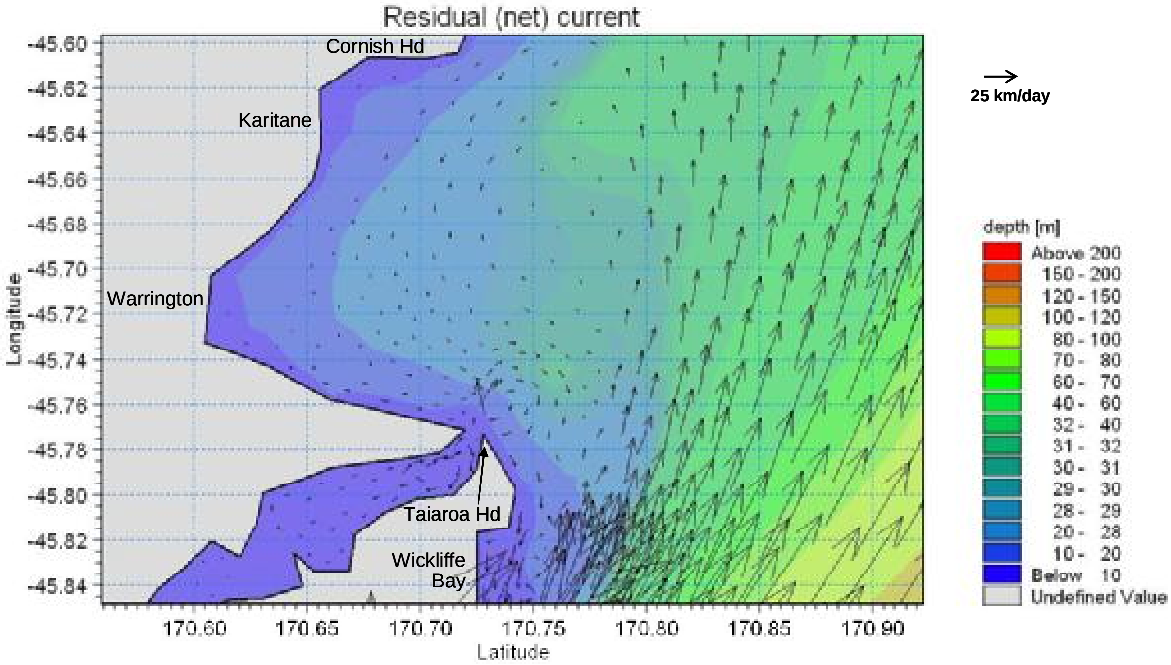

Figure 2.11 Residual depth-averaged current pattern over the initial two field deployments at A1 from the calibrated Run10 of the offshore hydrodynamic model. [Note: residual currents inside Otago Harbour should be ignored] (Source: Bell *et al.* 2009, Figure 10.4a).

2.3.3 Bathymetry

Figures 2.5 and 2.12 show the bathymetry of the area offshore from Otago Harbour.

The width of the continental shelf out from Taiaroa Head is approximately 30km. The seabed slopes gently to depths of 100-250m at the edge of the shelf. A series of drowned Quaternary shorelines have been identified across the shelf. The seabed of Blueskin Bay slopes to a depth of 30m at a distance of about 17km from Warrington Spit. The contour at 30m forms a near straight line from south to north starting from about 5.5km offshore of Taiaroa Head. The 'Peninsula Spit' is located landward of the 30m contour (shown clearly on the right side of Figure 2.5). The crest of the 'spit' slopes from a depth of about 20m at the southern end to a depth of 30m at the distal end. The depth inshore of the 'spit' is about 30m in an area northeast of the dredged channel.

The dredged sediment disposal grounds at Heyward Point and Aramoana form small sand-hills on the general seabed topography. Leon (2005b) investigated the changes in bathymetry of the maintenance dredge spoil disposal grounds. In 2004, the crest of the Heyward Disposal site was about 9m below MSL, sloping north to the general seabed level of about 11m depths. The change in seabed topography since 1974 is equivalent to about 43% of the total placed dredged sediment (since 1974). The crest of the mound at the Spit Disposal site in 2004 was 5.7m below MSL, sloping gently to the general seabed level of 9m below MSL. There has been slow accumulation at the Spit site since 1983, equivalent to about 44% of the total dredged sediment placed at the site. The accumulation of sediment at these sites includes placed sediment and sediment passing through the area naturally due to nearshore sediment transport processes.

Port Otago propose to locate the dredged sediment placement site for the capital dredging project at a location around the distal end of the 'Peninsula Spit', centred at or about Latitude 45.735S, Longitude 170.80E, about 6.3km northeast of Taiaroa Head. This site is referred to as site A0.

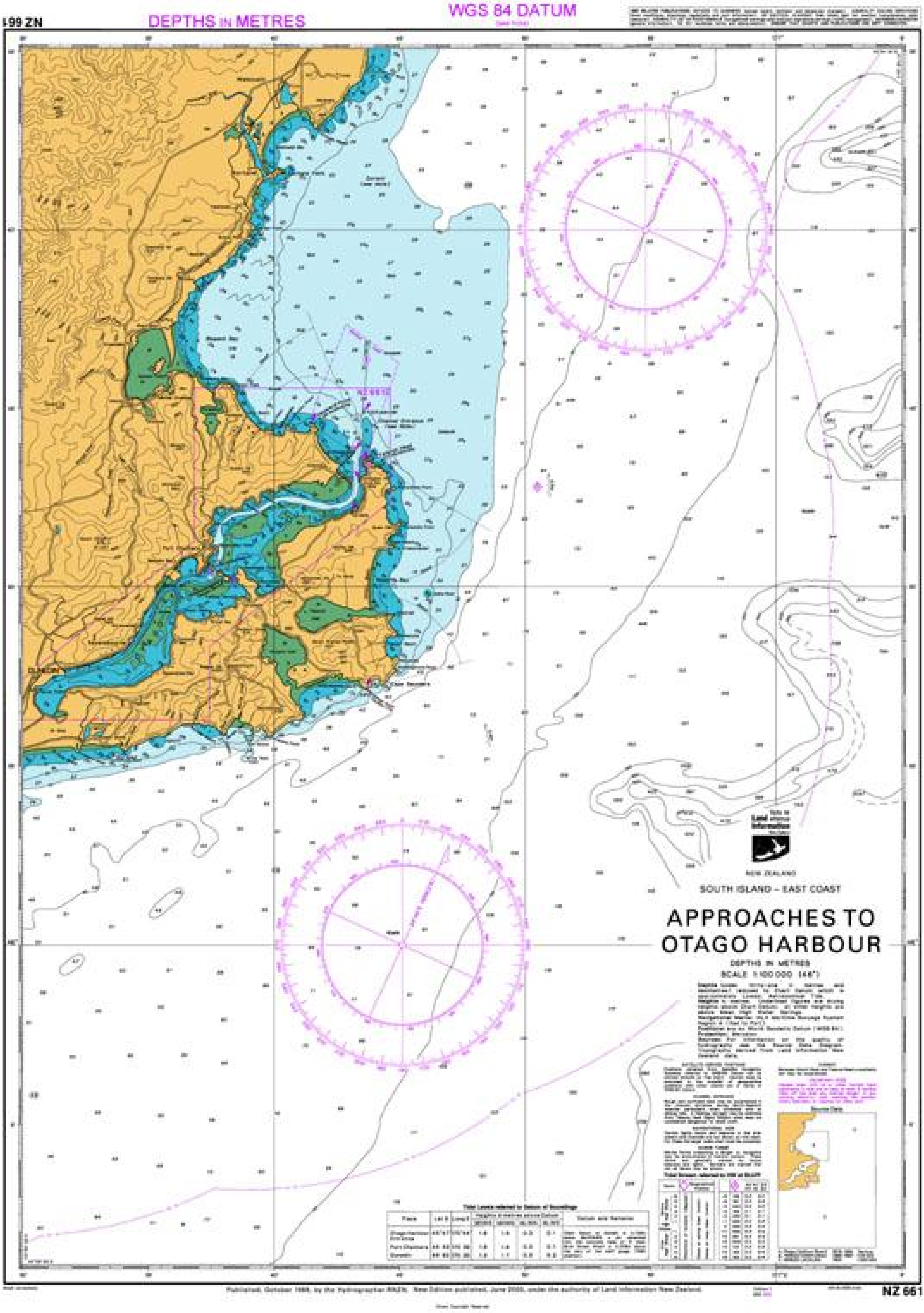

Figure 2.12 New Zealand Hydrographic Chart NZ661 Approaches to Otago Harbour (Thumbnail download www.LINZ.co.nz).

2.3.4 Sediment Characteristics

The textural characteristics of the nearshore sediments (size, shape and arrangements) can be described as medium to fine sand, with a mean diameter between 3Ø-2Ø (0.125mm – 0.14mm), well to very well sorted, and strongly positively (finely) skewed. Carter *et al.* (1985) summarised the textural nature of the nearshore as being homogeneous in that

> *"Close inshore the sediment has no discernible textural trend"* p13

The only exception to this textural trend is that of the ebb tide delta situated at the harbour entrance. This local area as being very coarsely skewed. The relatively homogenous nature is consistent with a single dominant source for the material.

The sediments present on the inner shelf have important implications with regard to the type of material found at the beaches of Blueskin Bay, as the source of the beach sediments is almost entirely from offshore. Willis *et al.* (2008) found that the sediments of Blueskin Bay were generally well consolidated. As shown in Figures 2.13 and 2.14, although fine sands dominate the area, very fine sands and silts dominate the central region of the bay, with slightly coarser fine sand dominating sediments in shallower parts of the bay.

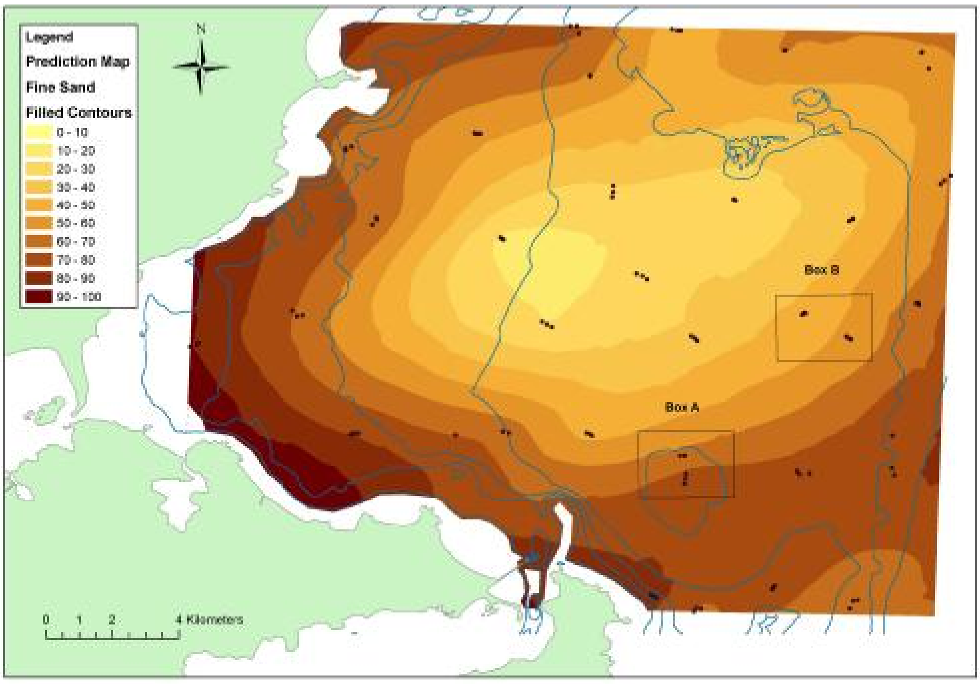

Figure 2.13 Distribution of fine sand (grain size 125-250 µm) content (%) in the sediments of Blueskin Bay. Note that Box A and Box B in this diagram are referred to as Site A1 and A2 respectively in this and the biological resources report (Source: Willis *et al*. 2008).

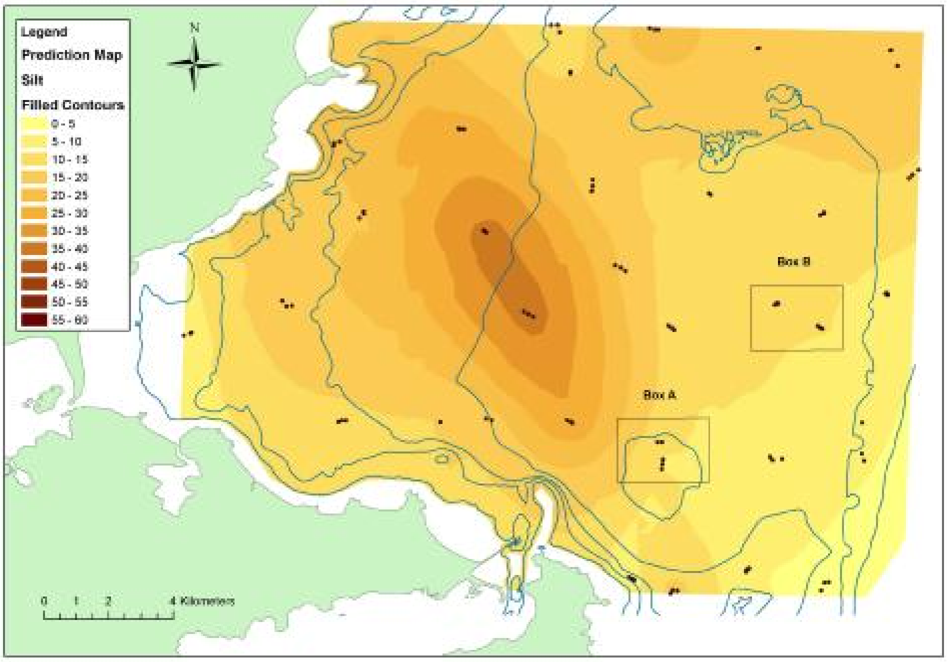

Figure 2.14 Distribution of silt (grain size < 63 µm) content (%) in the sediments of Blueskin Bay. Depth contours are at 5 m intervals from 10 m to 30m. Note that Box A and Box B in this diagram are referred to as Site A1 and A2 respectively in this and the biological resources report (Source: Willis *et al*. 2008).

The sediment of the nearshore is predominantly very well sorted, although sorting values range from 0.05Ø (very well sorted) to 0.74Ø (moderately sorted). The spread of values is indicative of varying degrees of energies acting upon the shoreline between Karitane and Taiaroa Head, with anomalies away from the general trend of very well sorted sediment confined to localised areas.

Bunting *et al*. (2003a) found that the sediments of the beaches and nearshore between Taiaroa Head and Karitane range from 2.75Ø (0.15mm) to 1.61 Ø (0.33mm), corresponding to descriptive classifications of fine sand to medium sand respectively. A large proportion (85% of all samples) of the sediments are fine sand size, that is 2.55Ø to 2.08Ø (0.17mm to 0.24mm).

The textural characteristics of the sediments compare well between studies that span 44 years. It can therefore be concluded that the physical nature of the sediments of the coastal system between Taiaroa Head and Heyward Point have not changed significantly over the period since the study by Elliott (1958). The findings of Bunting *et al.* (2003a) also show that the disposal of the sediment dredged from the shipping channel of Otago Harbour offshore at the Shelly, Aramoana, and Heyward Point has not changed the textural nature of the beach and nearshore sediments. These areas do not appear to stand out as anomalies from the surrounding seabed.

The above description of the textural characteristics of the beaches and seabed within Blueskin Bay provides a useful mechanism to aid in the understanding of the processes responsible for the deposition and transportation of the sediments. This section of the Otago coastline possesses a relatively homogeneous size range of fine sand. This is likely to be a direct effect of two dominant factors. The first is that the main contemporary source of sediment to the coastal system is from one dominant source, the Clutha River. The second is that a relatively consistent and narrow range of energy is received in the nearshore and at the shore. Moreover, the finely skewed samples obtained between Heyward Point and Karitane indicate that small streams and the Blueskin Bay Estuary are responsible for the supply of fines to this section of shore. These are additional to the main dominant sediment source. This is also reflected in the slightly less well-sorted nature of the sediments north of Heyward Point.

2.3.5 Sediment Transport Paths

Work for previous maintenance dredged sediment disposal consents by Kirk (1980), Single and Kirk (1994) and Bunting *et al.* (2003a, 2003b) determined sources, sinks and transport routes of the nearshore and beach sediments from Taiaroa Head to Heyward Point using a concept of "rollability". This method considers the sediment from the whole environment in a relative manner. Sources and sinks of sediment can be identified. These indicate where sediment is travelling from and to, respectively. The results of the rollability analysis for sediments sampled in 2002 are shown in Figure 2.16. This method can be used to infer transport pathways but not rates or volumes of sediment movement. The inferred transport pathways of sediment are from 'sources' to 'sinks'.

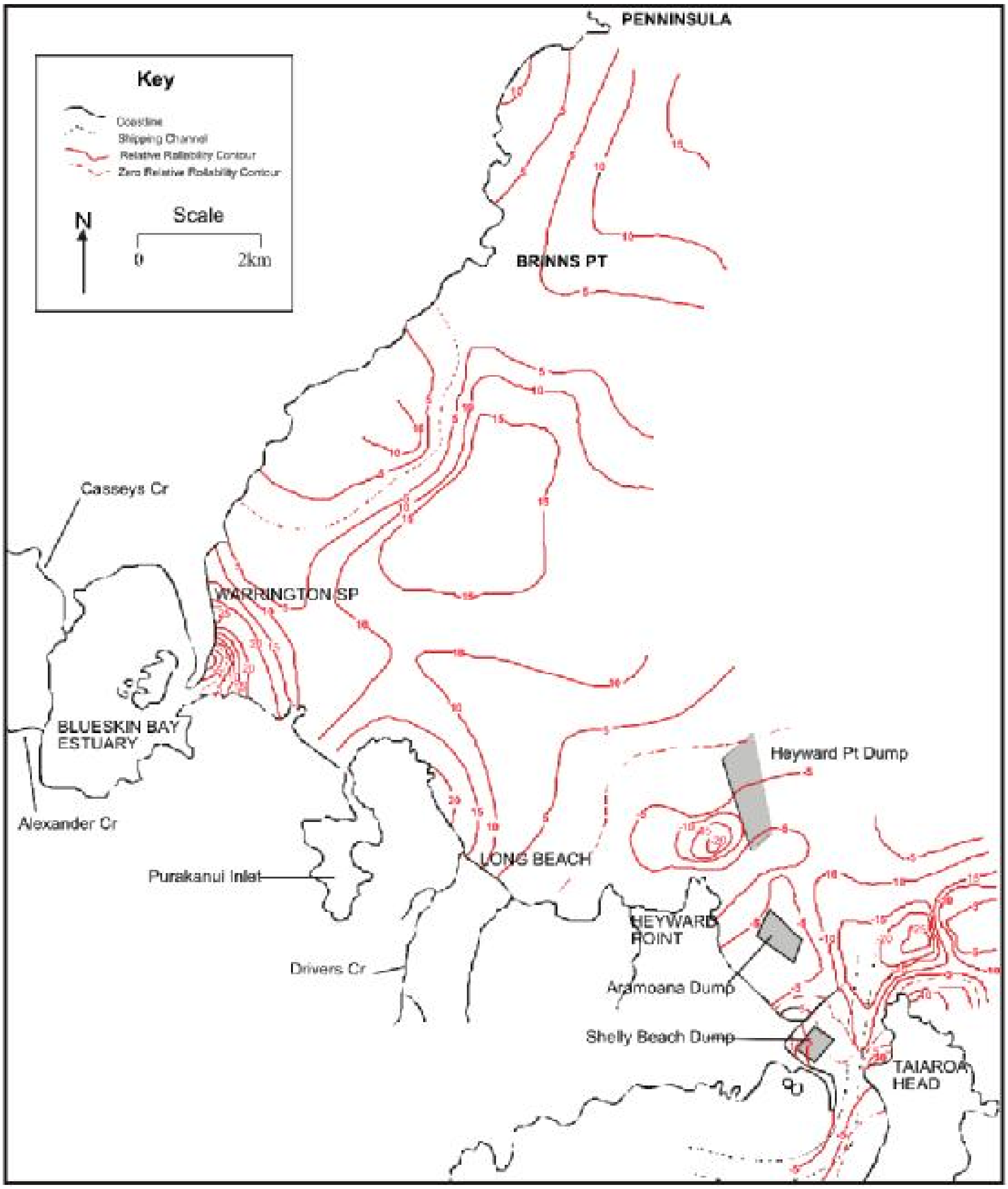

Figure 2.15 Average relative rollability (%) distribution for sediment samples collected in 2002. Negative values indicate a 'sink' or depositional area, while positive values indicate a 'source' area for sediment transport (Source: Bunting *et al.* 2003a).

Sediments collected by NIWA (Willis *et al.* 2008) were also analysed in the Geography Department, University of Canterbury, using the same rollability method as used by Kirk, Single and Bunting. The inferred transport pathways are shown in Figure 2.16.

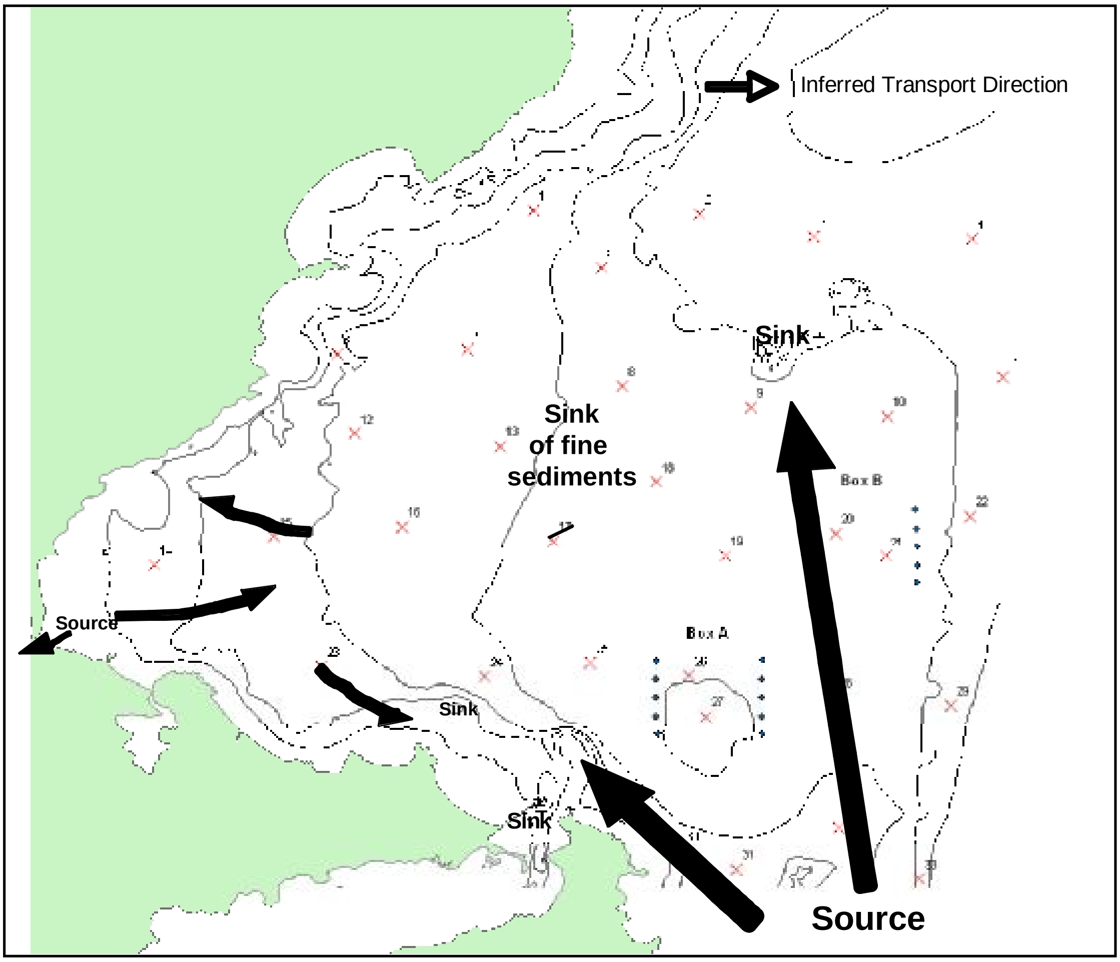

Figure 2.16 Sediment transport paths inferred from rollability analysis of samples (red crosses) collected by NIWA for Willis *et al.* (2008).

The results of the studies from 1980 through to 2008 are relatively consistent in that the main sources and sinks of sediment and major pathways show the same pattern for all studies. The main sediment source areas identified are the shelf south of Taiaroa Head, and areas around Mapoutahi Point (between Purakanui Bay and Blueskin Bay Estuary), Warrington Spit and Potato Point (north end of Long Beach). There are two secondary source areas of sediment. These are the area offshore and the beach at Karitane and the offshore area between Warrington Spit and Brinns Point. The main sink areas are the entrance channel and nearshore area off Aramoana Beach, and the distal end of the Peninsula Spit.

Rollability analysis of nearshore and beach samples showed two separate nearshore coastal compartments. Sediment sources dominate the nearshore between Heyward Point and Karitane Peninsula (the northern compartment). The implied sediment transport direction for the area is movement onshore and alongshore from Karitane to Warrington Spit and also south toward Heyward Point. Where Warrington Spit abuts the hinterland a source area is present. From here a strong gradient exists along the length of the spit to a dominant sink at the inlet channel.

Sediment sinks dominate the coastal area south of Heyward Point to Taiaroa Head, including the entrance to Otago Harbour. Two strong sink areas exist, one being located between Heyward Point and the Heyward Point dredge placement site, and the other north of Taiaroa Head, east of the harbour channel. This latter sink is likely to be the product of sediment being deposited as part of the general northward transport of sediment and the deposition of sediment that has been flushed out from Otago Harbour by the ebb tide. The rollability analysis also indicates that longshore transport of sediment is dominant over onshore or offshore transport.

The relative role of the northern compartment acting as a source of sediment for the southern compartment between Taiaroa Head and Heyward Point is also indicated from other descriptive sediment characteristics. An increase in sorting, and gradual increase in positive skewness values in a southerly direction was found in the sediment samples.

Overall, both rollability and the sediment textural characteristics show that the northern coastal compartment acts as a source of sediment to the southern compartment together with the southern current that delivers sediment up the east coast. The three dredged sediment receiving areas (Heyward Point, Aramoana and Shelly Beach) do not appear to supply sediment north into Blueskin Bay Estuary, nor do they appear to supply sediment back into the entrance channel.

The rollability assessment is consistent with the findings from analysis of current and wave measurements and modelling.

2.3.6 Shores

The volcanic rock that abuts the shoreline north of Otago Harbour forms a contemporary back-beach cliff at Aramoana, Kaikai, Murdering, and Long beaches. The presence of well water-weathered, rounded basalt cobble ridges at the foot of these cliffs suggests that the initial source of beach sediment to the coastal system was direct wave attack upon these high basalt cliffs. The beaches between Taiaroa Head and Karitane are modern (in geologic time) depositional features made up of quartz sands sourced and deposited onshore directly from the Otago shelf. This is confirmed by analysis of Maori artefacts from excavations at the foot of the fossil seacliffs (Skinner 1953, 1959 and Lockerbie 1959).

There are three types of shoreline in Blueskin Bay. These are:

1) Bay-Head Beaches;
2) Spit Complexes; and
3) Sea Cliffs.

Kaikai Beach, Murdering Beach, Long Beach, and Karitane Beach are all bay-head beaches. The morphology of all four of these beaches is very similar. At the southern locations, a sand beach fronts a now fossil, sea-cut cliff. Karitane has a bay-head beach formed in alluvial deposits flanking Karitane Peninsula. Warrington Spit, Purakanui Beach, Aramoana and Shelly Beach at the entrance of Otago Harbour are all sand-spit complexes. Sea cliffs, the third shore type make up the Headlands of Taiaroa Head, the shore from Warrington to Green Point, and Karitane Peninsula.

The nearshore processes of Blueskin Bay are predominantly low energy with respect to the outer Otago shelf. As a result the bay is a depositional environment, acting as a re-entry trap to catch the northeast sediment drift along the Otago shelf.

Once within the coastal system of Blueskin Bay, the sands are reworked by a variety of local processes and transported into the smaller bays and onto the beaches. Within the beaches immediately north of Otago Peninsula, longshore drift occurs in both directions along the shore (northward during southerlies and southward in north-easterlies). Although the net direction of drift is not large, it is in a northward direction.

Nicholson (1979) and Kirk (1980) have described the coastline north of Otago Peninsula as displaying active and rapid progradation. Superimposed on this long-term trend are short-term periods of erosion and deposition, a feature that is typical of sand beaches. With the aid of shoreline surveys and aerial photographs, Nicholson calculated rates of shoreline change for the period between 1863 and 1979 and found considerable rates of progradation at Long

Beach and Purakanui Spit. Between 1975 and 1997 progradation was nearly zero and these beaches appear to now be in a state of relative stability.

Table 2.1 shows the long-term net change to the shoreline position. Long Beach has advanced seaward by about 206 metres since 1863, at a long-term rate of 1.83 metres per year. The seaward face of Purakanui Spit has moved seaward by about 360 metres, at a rate of about 2.7 metres per year. It can also be seen from Table 2.1 that there appears to be a decline in this rate of shoreline advance in a southeastward direction towards the harbour entrance where Kaikai Beach presents a long-term near-stable beach state, and Murdering Beach is moderately erosional, retreating approximately 173 metres since 1863. These measured rates of change indicate that differential supply of sediment to adjacent beaches is occurring and also different wave energies are spent on the beaches.

Warrington Spit advanced approximately 97 metres between 1967 and 1997 at a rate of about 3.23 metres per year. However this shoreline eroded 28 metres between 1975 and 1997. Some sections of the shore between Warrington and Karitane are known to be erosional, with past erosion at Karitane presenting hazard to a roadway and Karitane School.

Table 2.1 Summary of net rates of shoreline change at Warrington Spit, Purakanui, Long, Murdering, and Kaikai Beaches, 1863 to 1997 (adapted from Nicholson 1979 and Bunting *et al.* 2003a).

LOCATION	NET SHORELINE CHANGE (m)	RATE OF CHANGE (m/yr)
Warrington Spit (1967-97)	+97.03	+3.23
Purakanui	+358.8	+2.68
Long Beach	+206.3	+1.54
Murdering Beach	-173.5	-1.29
Kaikai Beach	-18.6	-0.13

NB: + denotes shoreline advance, - denotes shoreline retreat.

Bunting *et al.* (2003a) present an analysis of beach profile surveys carried out at Aramoana, Murdering Beach, Long Beach, Purakanui, Warrington Spit and Karitane between 1990 and 2003. Storm incidence and onshore winds result in short-term changes to the beach profiles in the form of erosion and accretion. Over that time period dune and upper foreshore growth had occurred on all of the beaches except Karitane.

2.3.7 Human Activities

Human activities have modified the offshore physical coastal environment and approaches to Otago Harbour in three main ways:

1. By modification of the harbour inlet form and stability through construction of the Mole and Long Mac, and by dredging of the harbour channel,
2. Disposal of dredged sediment at the Heyward and Spit sites,
3. Disposal of dredged sediment at Shelly Beach.

Between 1846 and 1994, shoreline position and sediment transport at Aramoana was significantly altered by coastal engineering structures. Progradation of Aramoana Beach after the Mole construction (from 1884) indicates sediment has accumulated on the updrift side. The beach area between the mole and Harington Point (Shelly, or Spit Beach) retreated rapidly after the construction of the Mole, indicating the beach is on the downdrift side of the Mole and starved of sediment. The position of the channel has remained effectively fixed because of the training works.

Maintenance and development dredging of the shipping channel in Otago Harbour has been carried out since 1865. Approximately 33.7 million m^3 of sediment has been dredged from the harbour (Davis 2008). Prior to 1930, approximately 7.4 million m^3 of dredged sediment was used in reclamations around the harbour, and some (possibly up to 1.5 million "hopper yards") was placed in the vicinity of Te Rauone Beach. Sediment dredged from the channel and port areas has been deposited offshore at the Heyward site since 1930 (Lusseau 1999), the Aramoana (Spit) site since 1983, and the Shelly Beach site since 1987.

Leon (2005b) presents an analysis of the volumes of sediment placed at each site, and the changes to the seabed topography for the period 1974 to 2004. The total dredged sediment placed at the Heyward site over that period is 3,170,000 m^3, the total dredged sediment placed at the Aramoana (Spit) site between 1983 and 2004 is 2,650,000 m^3, and the total dredged sediment placed at the Shelly Beach site between 1987 and 2004 is 362,000 m^3.

In addition to sediment disposal from the maintenance dredging, about 3.2 million m^3 of sediment was disposed of in the vicinity of Heyward Point as a result of capital dredging of the lower harbour in 1976 (Lusseau 1999).

Changes to wave refraction over the disposal sites is unknown. There is no documented evidence of localised erosion or changes to the wave environment in the vicinity of the Heyward site or at Aramoana Beach. However anecdotal evidence from fisherman, and from surfers at Aramoana indicate the possibility of some changes to the pattern of breaking waves due to the presence of these existing disposal sites during larger wave events.

Sediment placed at the Heyward site disperses quickly from the main location of placement (usually in the southeast corner of the site), and there is no direct relationship between the volume of sediment placed at the site and changes to the volume of sediment at the site over time. Sediment accumulation at the Aramoana (Spit) site initially moved shoreward, but then areas of accumulation changed to be near the seaward limit of the site. It is likely that the position of accumulation in any year is related to the position of placement, as dispersal from the placement area is relatively slow. Analysis of historical data shows that Aramoana Beach has been accreting since the construction of the mole. Accumulation of sediment on the disposal site has also occurred during years when no dredged sediment has been placed there. It is likely that a combination of natural and human sediment inputs are occurring at Aramoana.

At Shelly Beach, sediment placement has been carried out to provide sand as nourishment to the eroding beach. A significant erosion hazard was identified for this beach in the early 1990s (Johnstone 1997, Single and Stephenson 1998). Retention of placed dredged sediment on Shelly Beach and in the nearshore south of the Mole has assisted in mitigating the erosion hazard to the beach (Leon 2005a).

2.4 Otago Harbour

2.4.1 Geology

Otago Harbour was formed by volcanism during the late Miocene (over 5 millions years BP) and crustal folding of a syncline during this period. During the Holocene and since the end of the last glaciation (about 15,000 years BP), the harbour basin has flooded with seawater and infilled with sediment. Rising sea level between 9,600 and 6,500 years BP swept sand into the harbour from a large spit formed north of Otago Peninsula. South of Otago Peninsula, a tombolo built out from St Clair to join what was an island to the mainland. Lauder (1991) puts the age of the harbour as about 6,000 years, and since its formation has been subject to infilling from sand swept in from the continental shelf and from sediments eroded from the catchment hills.

Scott and Landis (1975) and Cournane (1992) identified the Aramoana tidal flats as a relict feature from 6,000 to 3,000 years BP. From seismic tests, Cournane found that the Tertiary rocks on both sides of the harbour were not continuous under recent harbour sediments, and suggested that the thickness of the sediment layer at Aramoana over the basement rocks was about 85m. Borehole data also indicated significant sub-surface silt layers up to 8m thick in the lower harbour that may become exposed in the shipping channel at depths greater than 12 to 15m.

Opus International Consultants (2008, Opus) carried out detailed investigations of the sediment composition of the Lower Harbour to determine the nature of the materials to be dredged as part of the present Port Otago Ltd proposal. This work yielded similar results to past studies. Sand was found to be the dominant fraction of sediment in the Entrance section of the Lower Harbour and towards Taylors Bend, with silts and some clay being present at depths greater than 12 m up-harbour towards Port Chalmers.

2.4.2 Sediments in the Lower Harbour

Sediments in Otago Harbour range from silt to coarse sand containing shell fragments. Finer grained sediments including mud and silts can be found with the fine sand in the Upper Harbour, while coarser sand sizes are found with the fine sand in the Lower Harbour.

Opus International Consultants were engaged to provide geotechnical information about the sediments of the lower harbour, with particular emphasis on sediments characteristics of the areas to be dredged in deepening the shipping channel and widening the swinging basin (Opus 2008). The two main objectives of the geotechnical investigation were to characterise in detail the sediments to be dredged and to determine whether or not the dredged sediment would be contaminated.

Subsurface samples were taken In order to achieve these objectives. Figure 2.17 shows the location of the sites. The sites are within the area proposed for dredging. Two different methods were used to extract the sediments for description and testing for contaminants. They were:

- Vibrocoring - This is used for investigations for dredging works and involves vibrating a tube into soft sediments to obtain a fully cored sample. The maximum core length was limited to 3m, so the use of this method was restricted to locations within the existing channel. A total of 37 vibrocore holes were completed to an average depth of 2.7m below the seabed, with minimum and maximum depths of 0.65 and 3.16m, respectively.
- Rotary Borehole Drilling – This was used in locations where materials of interest had a thickness greater than ~ 3m, such as on the margins of the existing channel, where the channel would be widened, or where rock was expected. A total of 6 rotary-drilled boreholes were completed to an average depth of 8.6m below the seabed, with minimum and maximum depths of 2.5 and 12.1m, respectively.

Figure 2.18 shows a description of the sub-seabed sediments in relation to the location of the cores along the channel. The starboard and port notations are relative to inbound travel along the channel, so the Starboard Side refers to locations nearest Rocky Point, the Aramoana tidal flats and the Spit, while the Port Side refers to sites adjacent to the mid-harbour inter-tidal flats. Section names for the channel are also denoted on Figure 2.18. Blue lines for different sections of the channel show the proposed dredged depth.

Sand is most commonly encountered in the channel sections near the entrance to the harbour and beyond, namely from the Harington Bend to the Entrance sections. The laboratory analysis found that sand was generally loosely packed in cores and had a water content between ~ 20 – 30%.

Clayey silt is most prominent from the Swinging Basin to the Cross Channel sections. The behaviour of this material is dominated by the high silt content. These sediments were generally soft to very soft and non-plastic. Water content was between ~ 30 – 40% and had a measured shear strength between 14 – 24kPa.

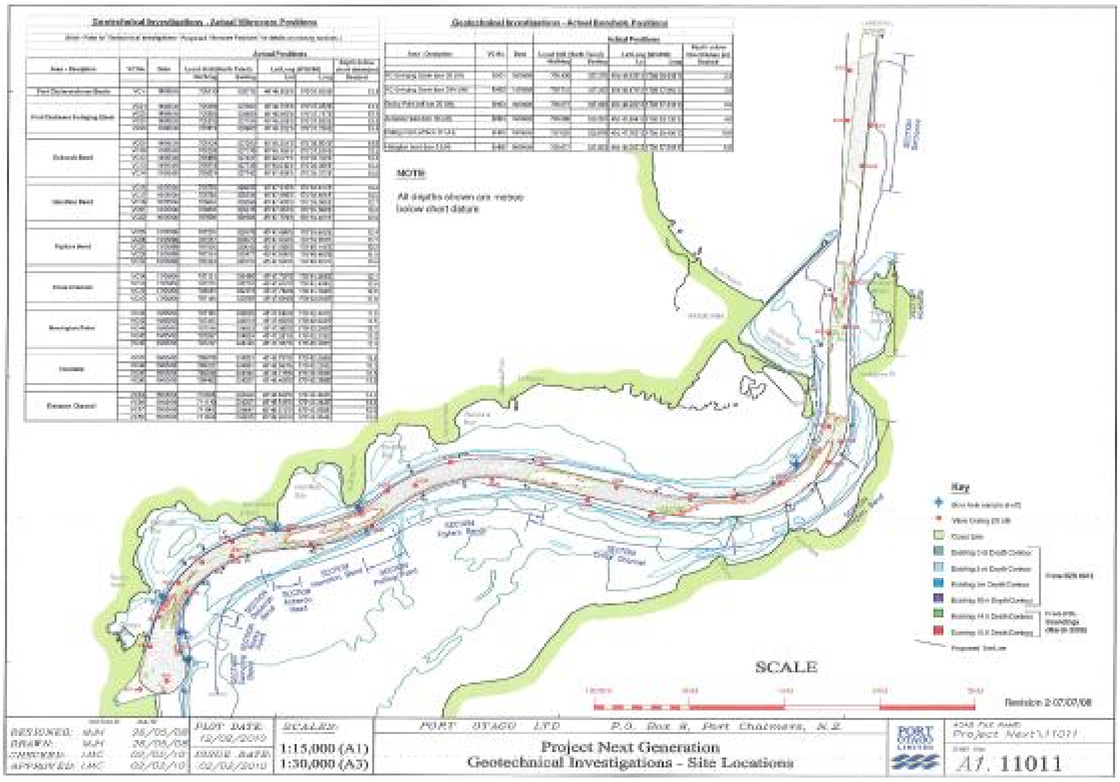

Figure 2.17 Location of sediment sampling sites (Port Otago Drawing 11011).

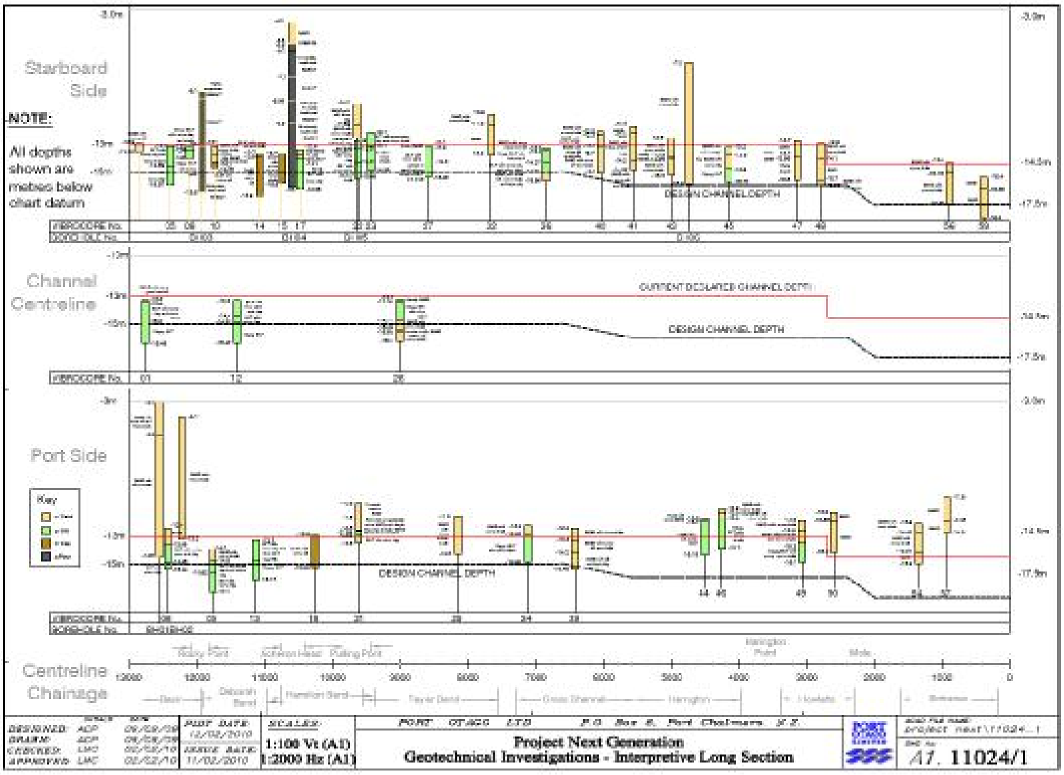

Figure 2.18 Description of sediments taken from bores relative to channel position (Port Otago Drawing 11024).

Silty clay was the least common sediment type encountered and is most prominent in the area around Acheron Head. The silty clay had a relatively high clay content and sediments were generally soft to very soft, had a high plasticity and water content ~ 60%. The shear strength of these materials was measured to be between 12 – 22kPa.

Rock was only encountered at Rocky Point and Acheron Head, and consisted of completely weathered basalt (cobbles and boulders) near the seabed and moderately weathered basalt at depth. At borehole (B5) off Pulling Point, basalt cobbles were found but the borehole had to be terminated due to bad weather. Rock strength ranged from extremely weak to weak within the upper 2 to 4m and became moderately strong to very strong below this. Laboratory testing returned uni-axial rock strength values of 101 and 62MPa for sites B3 and B4, respectively.

Pullar and Hughes (2009) presents a summary of the proportions of different sediment types to be dredged. This information is presented in Table 2.2. The information has been derived from the work in Opus (2008).

It can be seen that the sediment to be dredged is predominantly fine sand, with the secondary volume being clayey silt. From Figure 2.18 and Tables 2.2 and 2.3, it can be seen that there are areas and depths at which the sediment types are relatively uniform and other areas where there are a mix of sediments. Pullar and Hughes (2009) discusses the implications of this for dredging methodology and for the effects of the dredging activity in detail.

Table 2.2 Approximate dredged quantities of materials for the different channel sections (Source: Pullar Hughes 2009). Note that the quantities shown are in-situ and hence will have a bulking factor of about 20% when dredged.

No.	Claim	Rock (m^3)	Sand (m^3)	Silt (m^3)	Clay (m^3)	Total (m^3)
1	Entrance	0	1,366,330	0	0	1,366,330
2	Howletts Point	0	588,637	37,573	0	626,210
3	Harington Bend	0	724,139	340,771	0	1,064,910
4	Cross Channel	0	502,613	270,638	0	773,251
5	Taylors Bend	0	137,961	613,158	15,329	766,448
6	Pulling Point	0	7,476	19,224	0	26,700
7	Hamilton Bay	0	26,284	123,908	225,288	375,480
8	Acheron Head	19,593	21,871	3,190	911	45,565
9	Deborah	0	180,979	370,787	67,259	619,025
10	Rocky Point	5,571	4,178	7,312	348	17,409
11	Basin	0	880,664	574,884	0	1,455,548
	Sub-total	**25,164**	**4,441,132**	**2,361,445**	**293,806**	**7,121,547**
	%age of Total	*1%*	*62%*	*33%*	*4%*	*100%*

The geological descriptions based on logging of cores received from all 43 locations are presented in Table 2.3. Results are summarised according to the channel sections where each hole was located (as shown in Figure 2.17).

Table 2.3 Overview of geological description of materials found in borehole grouped by channel section (Source : Opus 2008).

Section Name	Geological Description of Materials	Boreholes & Vibrocores in Section
Swinging Basin	Grey, sandy SILT and fine SAND. Silt is soft to very soft and non-plastic. Sand is loosely packed	B1, B2, VC1, VC1c, VC5, VC6, VC8
Deborah Bend with Rocky Point	SILT in the southern part close to Carey's Bay and silty CLAY closer to Acheron Head. Sediments soft to very soft and plastic where clay present. Completely to moderately weathered basalt in borehole 3 along the north side of the existing channel.	B3, VC9, VC10, VC12 - 14
Hamilton Bend with Acheron Head and Pulling Point	Clayey SILT with some sand, soft to very soft, non-plastic to slightly plastic. Silty CLAY, soft to very soft and plastic close to Acheron Head. Completely to moderately weathered basalt in boreholes 4 at Acheron Head. Basalt cobbles at Pulling Point	B4, B5, VC15, VC17, VC18, VC21, VC22
Taylors Bend	Clayey SILT at Dowling Bay end of section and sandy SILT at Waipuna Bay, soft to very Soft, plastic where clay content high.	VC23, VC26, VC27, VC29, VC32
Cross Channel	Clayey SILT, soft to very soft, slightly plastic sand content increasing toward eastern end of section.	VC34, VC36, VC39
Harington Bend	Fine SAND near Otakou changing to clayey SILT near Harrington Point and the Spit.	B6, VC41, VC42, VC44 - 46
Howletts	Fine SAND with some Silt near the eastern side around Pilot Beach.	VC47 - 50
Entrance	Fine SAND	VC54, VC56, VC57, VC59

Table 2.4 Summary of chemical testing for Port Otago's "Next Generation" dredging project (Source: Opus 2008).

Parameter	Detection limit (mg/kg)	Guidelines (mg/kg) ANZECC[1]	Sample Concentrations (mg/kg)				
			VC5	VC12	VC21	VC34	VC47
Metals							
Arsenic	2	20	7.1	7.9	<2.0	<2.0	3.3
Cadmium	0.1	1.5	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium (Total)	2	80	17	16	2.5	2.6	8.9
Copper	2	65	6.7	6	<2.0	<2.0	4.4
Lead	2	50	7.1	6.7	0.79	0.81	4.3
Nickel	0.4	21	11	10	2.2	2.1	7.2
Zinc	4	200	44	42	8.1	6.8	27
Organic Compounds							
PCB (Total)	0.02	0.023	<0.001	<0.001	<0.001	<0.001	<0.001
TPH (Total C7 - C36)	60	--	<60	<60	<60	<60	<60
PAH							
Anthracene	0.0020	0.085	0.002	<0.0020	<0.0020	<0.0020	<0.0020
Fluroanthene	0.0020	0.6	0.0021	<0.0020	<0.0020	0.002	<0.0020
Phenanthrene	0.0020	0.24	<0.0020	0.0025	<0.0020	<0.0020	0.0049
Inorganic Compounds							
Cyanide (Total)	0.1	--	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrogen (Total)	0.051	--	<0.051	<0.051	<0.051	<0.051	0.082

Notes:

- all concentrations are in mg/kg (ppm) unless otherwise stated
- nv indicates that a guideline value does not exist for the quoted reference
- only those PCB, TPH, and PAH compounds above detection limit are listed, otherwise only the total will be listed.

[1] Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ, 2000), low trigger value

Laboratory testing was completed to determine the mechanical and chemical properties of the sediments. Mechanical testing involved particle size analysis, atterberg limits, and water content, shear strength (cohesive), solid density, and unconfined compressive strength (rock). Chemical testing included a screen level analysis for heavy metals, inorganic compounds PCB, PAH and TPH as well as the inorganic compounds cyanide and total nitrogen. The findings were compared to guideline values from the "Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ, 2000)". Table 2.4 lists a summary of the results with the guideline values included for comparison.

With regard to chemical testing, none of the parameters analysed exceeded the guideline values used. Based on these results, Opus (2008) concluded that the materials to be dredged are not contaminated.

2.4.3 Hydrodynamics

The tidal compartment of the harbour (the amount of water flowing in during a tidal cycle) is between 6.9 x $10^7 m^3$ and 7.5 x $10^7 m^3$ (Quinn 1979, Royds Garden 1990). The spring tidal range is 1.98m at Port Chalmers and 2.08m at Dunedin, while the neap tidal range is 1.25m at Port Chalmers and 1.35m at Dunedin (HydroLinz website).

High tide at Port Chalmers occurs around 10-15 minutes after high tide at the Spit, and there is a tendency for the time difference to be slightly smaller during spring tides and slightly larger during neap tides. The time difference for spring low tides between the two sites is up to 50-60 minutes, and for neap low tides the difference is 35 minutes. The tidal time differences are explained by the tide wave travelling up the harbour faster with increased water depth. Therefore it travels faster during neap low tides than during spring low tides.

Old (1999) found for the ebb tide, that slack water (with a weak eddy) occurs around the time of high water at Port Chalmers. Consistent ebb flow forms 30 minutes after high water but is confined to within 500 m of the mole tip. An ebb tide jet begins to form around 1 hr after high water, narrowing and strengthening to peak around 3 hrs after high water. On the ebb tide, peak flow velocity of 1.36 $m.s^{-1}$ occurs on the eastern side of the channel near the centre of Harington Bend.

During flood tide, peak flows of 1.59 $m.s^{-1}$ occur at the southern end of the spit on the western side of the channel due to constriction between Harington Point and the Long Mac and shallow water.

A deep scour hole prevents maximum velocities occurring at the narrow entrance of Harington Point, where it would otherwise be expected. At the harbour entrance, ebb tide maximum velocity is 1.03 $m.s^{-1}$. On the western side of the channel the flow is sinusoidal over a tidal cycle but the ebb flow has a pulse-like, high velocity nature upon leaving the harbour and the flow across the entrance bar has a strong ebb-dominated asymmetry. Tidal flow has a flood-dominated asymmetry on the eastern side of the entrance near Taiaroa Head (peak velocity = 1.15 $m.s^{-1}$) caused by constrictions of the entrance and ebb flow jet that produces a westward sediment entrainment flow from the eastern side.

The flood tide period is shorter and its flow is stronger than the ebb tide, therefore the harbour is flood dominated and sediment will naturally move into the harbour and infill it. Tidal flows and sediment analysis show that a large volume of sediment can move into the harbour as bedload. Some of this sediment is deposited at Harington Bend during the flood tide and removed on the ebb, thus there is some balance between sedimentation and scour in this part of the channel. However sand-sized sediment moves further into the harbour within the channel, along the channel flanks and on the shallow margins of the entrance.

2.4.4 Human modifications

The harbour has been substantially modified by human activity through reclamation, causeway and groyne construction, dredging and channel stabilisation, catchment modification and lining the harbour shoreline with seawalls. Reclamation has resulted in reduction of the harbour tidal compartment. However Wilson (1989) found that MSL at Dunedin had decreased 40mm since 1888 due solely to channel deepening. He suggested that if the channel had not been deepened, MSL rise over the last century would probably be about 1.4 mm.y^{-1} rather than 1.0 mm.y^{-1} as was previously accepted.

Inflows from modified urban and rural catchments have resulted in changes to the sediment supply and chemistry in parts of the harbour. Baird (1997), Purdie and Smith (1994) and Stevenson (1998) have investigated sediment contaminants and sedimentation within the upper harbour. They found that sediment texture was influential on infaunal organisms and absorption of pollutants. They also found that the amount of heavy metals was low and well within typical levels for other New Zealand inlets. Most trace metal pollutants were sourced to stormwater runoff from the Leith River (Baird 1997).

Sediment samples from along the Lower Harbour shipping channel were tested for contaminants including Heavy Metals and Metalloids, Organic and Inorganic Compounds (Opus International Consultants 2008). Concentrations for all contaminants were found to be well below Australian and New Zealand guidelines for fresh and marine water quality. Generally, the level of trace metals reduced with distance from Port Chalmers to Harington Bend. However the level of contaminants was greater in the channel near the distal end of the Long Mac than along the cross-channel area between Taylor's Bend and Harington Bend. Further contamination testing as part of the work by Opus (2008) yielded similar results with many samples showing undetectable levels of contaminants, and all samples within (and well below) ANZEC guidelines.

Most of the shoreline of the Upper Harbour has been modified, and is comprised of placed rock. Training walls and groynes also play an important role in determining the hydrodynamic flow of the harbour, stability of the position of the navigation channel and sediment movement on the shores and harbour bed. Davis (2008) presents a detailed discussion of these structures.

The following sections highlight the issues at Te Rauone Beach and Shelly Beach. These beaches are the most dynamic shores in the immediate vicinity of the harbour entrance channel.

2.4.5 Te Rauone Beach

Episodes of erosion have affected Te Rauone Beach since 1890. Otago Regional Council commissioned a study of the erosion in the mid 1990s (Tonkin and Taylor 1998) as the erosion was adversely affecting residential sites and along the backshore. The shoreline changes in this area are a result of changes to sediment supply due to the modification of the harbour entrance, the addition of ad-hoc human modifications to the shoreline in front of private property, the natural wave environment and vessel wash at the shore. Otago Regional Council (Tonkin and Taylor 1998, Ramsay 2006, Goring 2007, Bell 2007), Dunedin City Council (Johnstone and Henderson 1993, Todd 2002) and Port Otago Ltd (POL 2004) have investigated erosion and shoreline change at Te Rauone Beach. In addition, Port Otago staff mapped the shore from aerial photographs taken at seven dates between 1950 and 2004.

Single (2007) presents a description of the coastal process environment, shoreline changes at Te Rauone Beach and a summary of the findings of previous studies. He also identifies options for coastal management for the area. These options include engineering works and artificial beach nourishment. The design and implementation program for beach management has not been finalised, but the parameters for the design include consideration of the effects of wake and surge conditions that result from shipping movements in the harbour channel as well as the natural wave environment and sediment loss and supply. Work for Project Next Generation (Single and Pullar 2009) has been included in the assessment of the management options and design considerations. The recommended option employs a combination of beach nourishment with structures to encourage sand retention.

2.4.6 Shelly Beach

Shelly Beach was formed as a result of constraint of movement of the harbour entrance with the construction of the Mole and the Long Mac groyne. The beach is at the head of the embayment between the two structures. Erosion of this beach has been an issue for many years, and has been the subject of studies to determine the processes at work and potential solutions to the erosion through coastal management (Single and Kirk 1994, Single and Stephenson 1998, Bunting *et al.* 2003b, Leon 2005a).

The present solution to the erosion is the placement of maintenance dredging sand onto the nearshore seabed within the Shelly Beach embayment. This solution has been very successful (Leon 2005b). However dune management is required in order to maintain a healthy dune system between Shelly Beach and the harbour. These dunes provide protection of the Aramoana saltmarsh area. A Coast Care group such has been formed for other New Zealand coastal areas (for example in communities in the Bay of Plenty) would facilitate management of the dunes. Port Otago Ltd is at present investigating the establishment of such a group for Shelly Beach.

The distal end of the spit, including the shoreline south of the Long Mac groyne, and adjacent to the Spit Wharf is also subject to erosion processes. The mitigation of this erosion is an area of study being undertaken by Port Otago Ltd as part of the management of ongoing effects of the harbour entrance works.

3. Changes to the existing process environment

3.1 Introduction

Results from modelling and field studies have given information to accurately assess the changes to the hydrodynamic and sedimentation processes in Otago Harbour, as well the area offshore from Taiaroa Head north to Karitane Peninsula (Oldman *et al.* 2008, Bell and Hart 2008, Bell *et al.* 2009). The findings drawn from reports on that work are presented in the following sections.

3.2 Hydrodynamic modelling

A hydrodynamic model of the harbour was generated to simulate <u>relative</u> hydrodynamic changes before and after dredging and to provide supporting current flow fields for plume dispersion modelling. The model was calibrated using tides and currents from a previous field investigation carried out for the Otago Harbour Board in 1988 (Barnett *et al.*, 1988), and tuned to match the field data. The match with tide heights was satisfactory (with differences between measurements and the model predictions of up to 0.1 m). A reasonably good match was obtained between modelled and measured currents in the main channels, particularly in the central core of the channel flow.

The Harbour model was also validated on two different sets of data: a) S4 current-meter measurements during the 2008 field programme from the eastern side of the Harbour; b) vessel-mounted ADCP survey currents measured by the University of Otago in the period 1998–2000. There was a reasonable fit to the overall pattern of flows and balance between of ebb and flood currents, particularly in the Eastern Channel (south-west of Grassy Point). At two sites there were some differences between the model results and the field measurements, especially for the flood tide. These can mostly be explained by localised effects on currents, including wind or rapid changes in seabed bathymetry that are picked by a current meter at a "point", whereas the current velocities in the model are depth-averaged and spatially averaged over a 30 m × 30 m model cell. Validation of the model using the boat-mounted ADCP currents from the main channel shows a good visual match between the modelled and measured boat-mounted ADCP current vectors - both in the magnitude and direction of the vectors and also the overall pattern of flows within the channels.

Overall, the Harbour hydrodynamic model performed well in predicting the tide height and more-importantly, tidal currents. The good calibration also leads to a dependable modelling platform whereby the assessment of suspended-sediment plume transport can be achieved with reasonable confidence.

3.2.1 Findings

The comparison of the calibrated hydrodynamic model runs for the existing situation and the 15-m dredged channel option provided an estimate of the relative changes in tide heights and current speeds from the dredging. The main focus in the comparison between before and after dredging was on spatial differences for a mean (average) tide.

Tidal range—Deepening of the shipping channel leads to a slightly larger tidal range within the Harbour as a deeper channel means the tide wave travels with less dampening from seabed friction. However these tidal range differences due to the 15-m dredged channel are relatively small (i.e., less than 1% of the average 1.6-m tide range). Along the deepened part of the channel, the increase in mean tide range (twice the half-range) is almost negligible in the Harbour Entrance (up to 0.004 m) and between 0.004 and 0.006 m increase over the existing situation from Harington Bend to Tayler Point. The highest increases in tide range of 0.006 to 0.008 m would occur around Port Chalmers, Portobello Bay and Harwood areas of the Lower Harbour and in the Upper Harbour, with the highest change at Dunedin. These changes amount to a difference of no more than 0.6% of the existing average 1.6 m tidal range.

High-water phase—High and low water will arrive slightly earlier due to the channel deepening. In the Upper Harbour, Deborah Bay, Port Chalmers and Portobello Bay, the advance would be up to 3 to 4 minutes. Between the Harbour Entrance and the commencement of Harington Bend the difference in the timing of the tide would be less than 1 minute, with a negligible change in the Mole area of the Entrance and beyond. This would occur as the tide wave travels faster in deeper water, and then levels off as it propagates up the Victoria Channel of the Upper Harbour, which will not be subject to the capital-dredging programme. Similar, but slightly smaller advances in the timing of low water would also occur.

Tidal currents—Overall there are likely to be only small changes of less than ±0.01 m/s (±0.02 knot) in the speeds of tidal currents following dredging. This change is not perceptible to human users of the harbour. The dredging results mainly in <u>reductions</u> rather than increases in speed, and largely within the Lower Harbour. There would be localised <u>increases</u> in the average major (peak) current of up to 0.02-0.05 m/s (0.04-0.1 knot) off the groyne at Beacon No. 10 on south side of Harington Bend and <u>decreases</u> in peak current (negative) of up to 0.10 m/s off Carey's Bay, just north of Port Chalmers as a result of the tidal flow being channelled into the wider Turning Basin. Much of the main shipping channel will experience reduced peak velocities. Smaller changes would occur in peak velocities in the side channel north of Quarantine Island (an increase of 0.01–0.02 m/s), with decreases of 0.02 to 0.04 m/s generally over the eastern side of the Lower Harbour between Harwood and Ohinetu Point. Most of the significant changes in current speeds (e.g., magnitudes >0.06 m/s) would only occur in localised patches, mainly on channel bends (Harington Bend, Port Chalmers Turning Basin) or around the groyne at Harington Bend (Beacon No. 10). It is in these areas, where dredging the intertidal or shallow flanks of the existing channel (to accommodate a wider and deeper channel) would have the most effect on currents compared to the existing situation. The change in phasing (timing) of the peak mean-tide current would be 2 and 4 minutes earlier in the Lower Harbour with the deepened channel. These differences are in the same range as the advances to the high and low tide timing.

Mostly the inclination (or direction) of the peak-tide currents would be similar to the existing situation (within ±2°). The main change in inclination would be in outer Portobello Bay, and the connecting shallow subsidiary channel through the intertidal bank to the main shipping channel. This arises from dredging required to widen and deepen the Port Chalmers Turning Basin and lead-in transition on the eastern side of the shipping channel. The changes in peak-current inclination would be up ± 7–8^{o} in magnitude, arising from changes in eddies that form later in the flooding tide in northern Portobello Bay as a result of deepening and shortening of the entrance to the subsidiary channel.

Hydrodynamic changes before and after dredging were also considered for 20-knot southwest and northeast wind scenarios in an earlier feasibility report (Oldman et al. 2008). Similar high-water phase changes and differences in velocities and tide ranges to the tide-only situation (with no winds) were obtained, indicating the tide dominates the Harbour hydrodynamics. Consequently, no further analysis was undertaken on extending the analysis of changes for different wind and tide combinations.

3.3 Hydrodynamics (currents) outside the harbour

The 3-dimensional DHI MIKE-3 Flexible Mesh (FM) model was used to simulate current flows on the Otago shelf (Figure 3.1). The model was calibrated against field data measurements at a number of sites (shown in Figure 3.2).

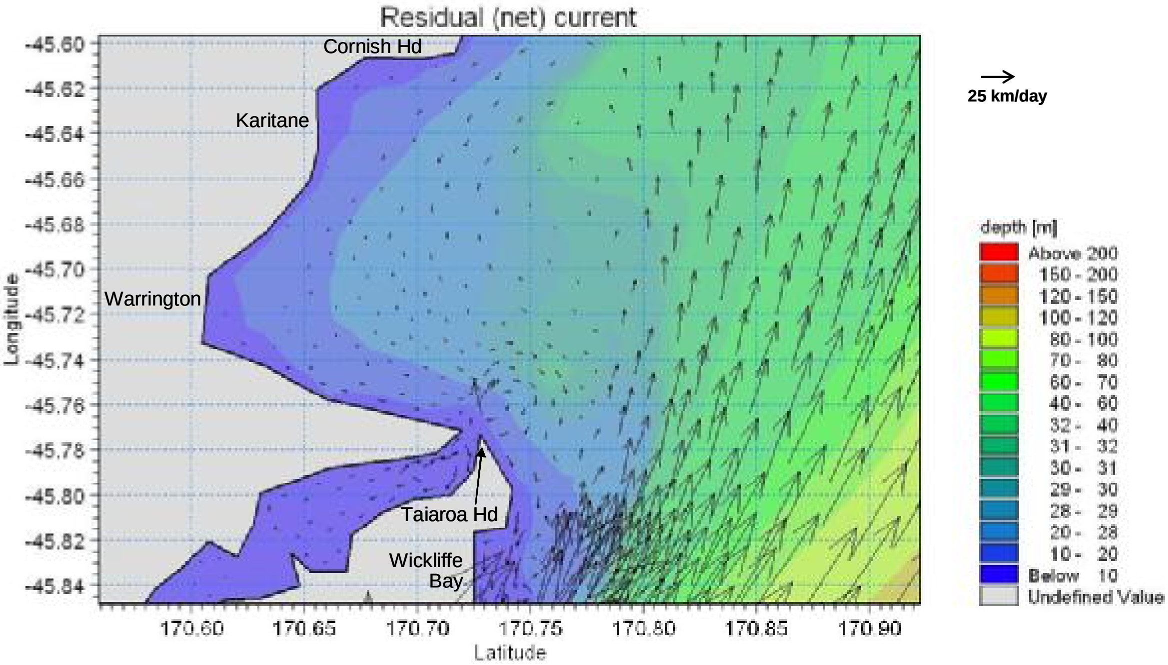

Figure 3.1 Residual depth-averaged current pattern over the initial two field deployments at A1 from the calibrated Run10 of the offshore hydrodynamic model. [Note: residual currents inside Otago Harbour should be ignored] (Source: Figure 10.4a Bell *et al.* 2009).

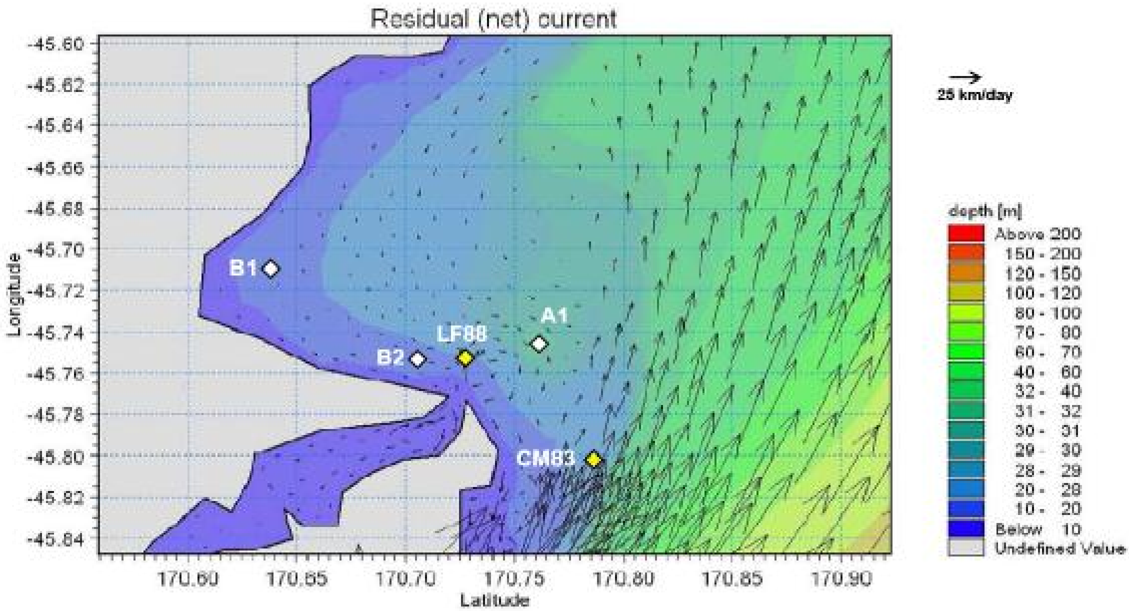

Figure 3.2 Current-meter mooring sites plotted on the backdrop of the residual depth-averaged current pattern over the initial two field deployments at A1 from the calibrated Run10 of the offshore hydrodynamic model. White diamonds are from the 2008 field programme, and yellow diamonds from previous moorings in the 1980s (Source: Figure 10.4b Bell *et al.* 2009).

The model shows that the inshore component (Subtropical Waters) of the Southland Current is strong and persistent, peeling off from Cape Saunders to the NE, with the net residual current gradually reducing in velocity as it moves more northwards over the submergent Peninsula Spit in outer Blueskin Bay.

On the inner shelf, there is an anticlockwise eddy in Blueskin Bay (Figure 3.1a) as deduced by Murdoch et al. (1990), but it is relatively weak and it sweeps down through the outer part of Blueskin Bay in depths of greater than 20 m, rather than moving along the coastline.

The main feature on the inner shelf, hitherto not documented, is a relatively small clockwise eddy of about 5 km in diameter off Taiaroa Head, juxtaposed between the ebb-tide jet from the Harbour entrance and the Southland Current flow to the NE offshore. The current-meter mooring site at A1 (Figure 3.2) was located towards the outer edge of the Taiaroa Head eddy, giving rise to a persistent residual current to the SE (Bell *et al.* 2008).

In the nearshore zone south of Taiaroa Head, including Wickcliffe Bay, the depth-averaged current residual is to the south (Figure 3.1), which is driven by the return flow of the separation eddy off Cape Saunders. This residual current only includes the influences of winds, tides and the Southland Current. Waves and swell also generate current drift in the nearshore region, with stronger swells arriving from the SE (compared with local seas from the NE) likely to generate a nearshore wave drift to the north in the opposite direction to the current residual.

A reasonable calibration of the 3-layer offshore hydrodynamic model was achieved focusing on obtaining a good match with net or residual currents. Residual current patterns and behaviour are more important for longer- and larger-scale plume and sediment transport processes offshore, than tides and responses to winds over short time scales. Critical to the success in achieving a realistic match of the modelled residual current to that measured at the offshore site A1 (30 m depth) was the ability to derive a realistic southern boundary condition to drive the model by quantifying the spatial variation along a shore-normal transect of the mean flow of the Southland Current from NIWA's ocean circulation models.

While the chosen field mooring location (A1) proved eventually to be unsuitable as dredged sediment receiving ground option, it proved to be an excellent location to test and verify the offshore model because of the complexities that exist there in the circulation pattern. In this locality, a small-scale clockwise eddy off Taiaroa Heads interacts with the ebb-tide jet from the Harbour Entrance, local offshore winds and the Southland Current further offshore. At A1, the SSE residual or drift current was reasonably well predicted after tuning the hydrodynamic model, the boundary conditions and its associated irregular bathymetry grid. If the mooring site had been located further offshore within the Southland Current, the subtleties within the inshore flows may not have been well resolved, particularly the Taiaroa Head eddy, which preferentially transports material towards the coastline of Otago Heads. Not having a mooring further offshore within the main Southland Current flow was not critical in this project. Sensitivity tests of the offshore model using realistic variations in the spatial distribution and strength of the Southland Current boundary condition showed the results on the shelf were relatively insensitive compared to the situation of using the mean or average flow of the Southland Current. Local winds play a role in modifying the underlying residual currents offshore that are generated or influenced by the Southland Current, which the model was also able to mimic.

Overall, the MIKE-3 FM offshore hydrodynamic model is performing well in predicting residual or net currents that specifically include the Southland Current, tides and local offshore winds. Therefore simulating transport of suspended sediment and long-term sand transport from the preferred dredge disposal site can be achieved with reasonable confidence.

3.4 Waves in the Lower Harbour

Harbour wind-wave modelling was undertaken for the purposes of characterising the wave climate within the Lower Harbour, and identifying the influence of various wind directions and speeds on wave generation. SWAN (Simulating Waves Nearshore) was used for all the wave modelling. The modelling was only undertaken on the existing channel bathymetry grid, as changes in significant wave heights would be small (less than a few cm) for a deeper channel. The reasoning is that short-period wind waves are not limited or influenced much by the larger depths (e.g., >12 m as in the existing channel or dredged channel option) for the relatively short wind fetches that occur in the Lower Harbour.

The resulting wave information for different wind velocities was used to assess ship handling by Port Otago Ltd. However the model results also provide insights into the influence the Harbour orientation, channel alignment and varying depths have on the spatial distribution of waves within the Lower Harbour.

Example wave model results for significant wave height for the 99th percentile northerly wind conditions are presented in Figure 3.3, and the westerly condition in Figure 3.4. These results clearly show the fetch-limitations to wave growth and the attenuation that occurs over the shallow intertidal areas. The highest waves in the Lower Harbour originate from westerly winds (highest waves) and south westerlies (next highest). These are also the directions associated with the strongest winds. These predominant winds, combined with the geographical alignment of the Lower Harbour and shipping channel and the associated wind fetches over open-water pathways, result in the largest wind-generated waves occurring in the channel reach from Cross Channel through to and around Harington Bend. The largest significant wave height reaches approximately 1.2 m in the Harington Bend area for a 99-percentile wind (25 m/s or 49 knots) from due west (as can be seen in Figure 3.4).

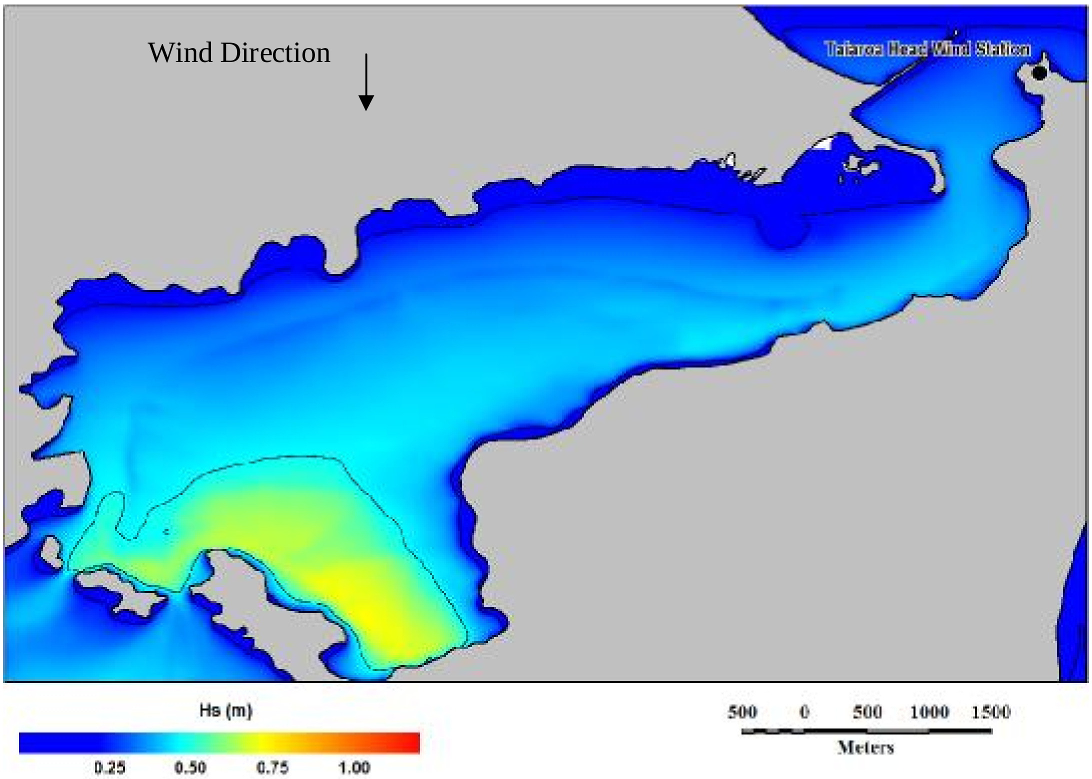

Figure 3.3 Wind-generated significant wave heights from the 99th percentile northerly winds (Source: Figure 9.3 Bell *et al.* 2009).

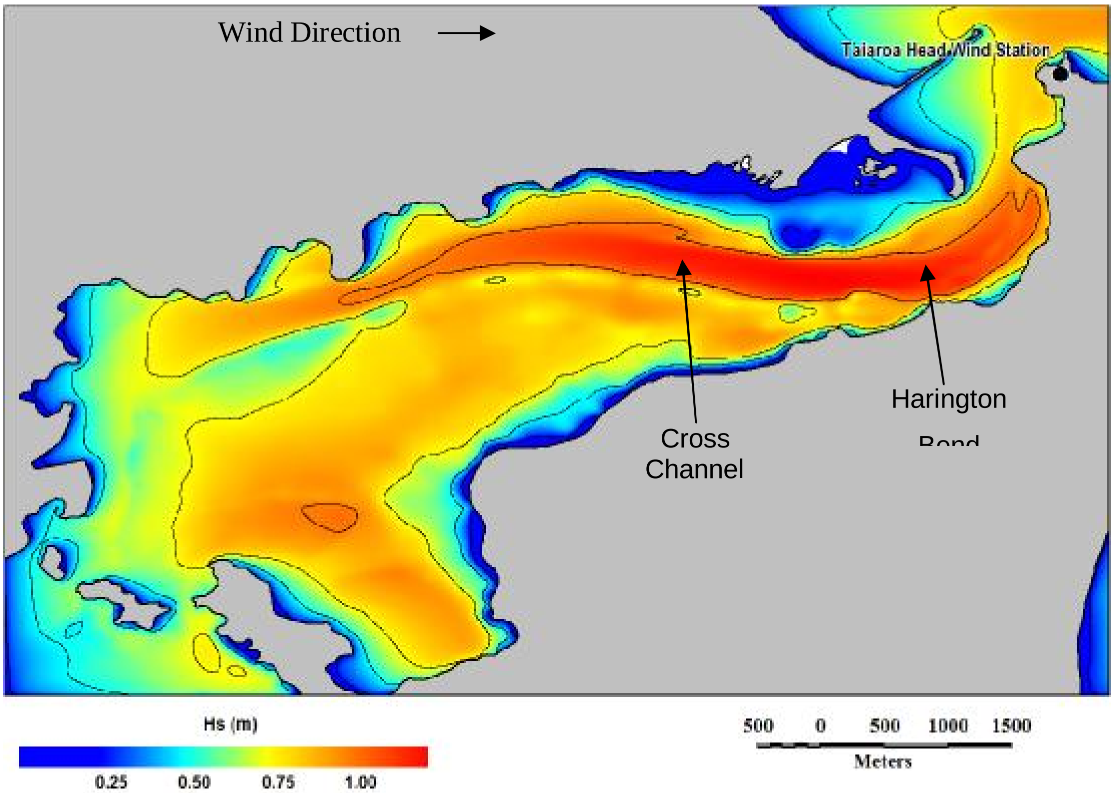

Figure 3.4 Wind-generated significant wave heights from the 99th percentile westerly winds (Source: Figure 9.4 Bell *et al.* 2009).

Increases in significant wave height for a 15-m channel option would be small (less than a few cm) in the main channel with negligible changes outside the footprint of the proposed widened channel. In particular, the waves would not be significantly different at the shore around the Lower Harbour. Wave heights (relative to existing conditions) would change most in two specific areas where the channel bends (east side of Turning Basin and north side of Harington Bend) would be substantially dredged from approximately intertidal depths presently to the new channel base depth or lesser depth if on the batter side-slope. In this case, these localised areas would begin to experience similar wave characteristics to the existing channel (because they would be deeper and amalgamated with the main channel), rather than the intertidal depth-limited waves experienced presently.

3.5 Entrance Channel

The Entrance Channel crosses an ebb-tidal bar formation located between Taiaroa Head and the Landfall Tower, as shown on Figure 3.5. The current flows over the ebb-tide bar are complex and are affected by the oceanic currents (the Southland Current) and by tidal currents. There is a westerly flood flow through Transect 2 (right to left in Figure 3.5), while the ebb flow is biased towards the north. Residual flows are slightly biased towards the north due to the dominant ebb-tide jet and weak flood-tide currents. These flows in combination with wave processes have fashioned the geomorphic shape and orientation of the ebb-tide sandbar.

The computer generated models determined that the tidal currents were not strong enough to transport sand sized sediments alone, but that the initial entrainment of the sediments was likely due to wave currents.

It is the shape of the ebb tidal bar in relation to the predominant alongshore sediment transport system that results in a long interception distance for sediment moving north and west along the seabed. The cross-sectional shape and location of the channel margins in this location is therefore influenced by sediment spilling into the channel from the south and east. In cross-section the channel is asymmetrical with a steeper side on the east and a flatter bank to the west. As a result, the dredging demand for this area of the channel is quite high in comparison to other sections of the channel, and the eastern channel margin requires 'shaving' to maintain the channel position. In summary, the hydrodynamic processes of the tide are working at right angles to the sedimentation processes relating to oceanic and wave-induced currents, resulting in sediment being transported across from east to west, and along the channel towards and out of the harbour.

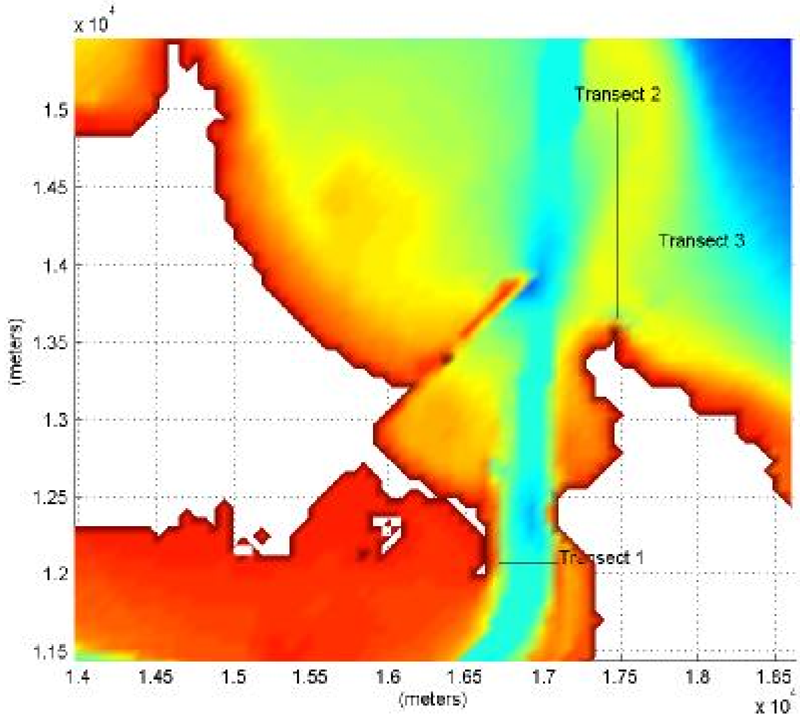

Figure 3.5 Depth shading of the Entrance Channel area, showing locations of transects modelled for currents before and after dredging (Source: Bell *et al.* 2009, Figure 5.9).

3.6 Waves offshore

A detailed analysis of the wave climate was undertaken for two representative locations between Taiaroa Head and Karitane Peninsula; an offshore site in the vicinity of the A1 receiving ground option, and a location near the fairway beacon on Landfall Tower. The numerical wave hindcast model was used to generate information about the long-term wave climate in the area. Annual, seasonal and monthly significant wave height statistics for each site were calculated. The Landfall Tower receives more sheltering of waves than the offshore A1 location; the mean annual significant wave height (Hs) at A1 is 1.06 m while at the Landfall Tower it is 0.85 m. The largest waves tend to have peak periods in the range 10–13 seconds, and the height–period distribution is similar for both locations. The winter and autumn months are more energetic, while November is the least energetic month. At location A1, two directional modes are evident from the NE and the SE. Wave directions are constrained near the entrance region.

3.6.1 Effects of disposal mound on the offshore wave climate

Waves refract, shoal and dissipate as they approach the shore, and the nearshore wave climate will respond to changes to the offshore bathymetry. The dredging proposal will result in a deeper entrance channel and the creation of a mound in the dredged sediment receiving ground. These changes have the potential to influence the adjacent wave climate. The numerical wave hindcast model was used to simulate waves over a 5-year period (2003–2007) using the modified bathymetry, so that the model outputs could be compared directly with the existing bathymetry simulation. Figure 3.6 illustrates the difference in the bathymetries used (positive depth change for two options for a dredged-material receiving site and negative depth change for dredged areas associated with a 15-m deep Harbour channel option). Note: the two disposal area options were modelled simultaneously in the wave hindcast model, as the distance between the offshore mounds in the model is sufficient for the effects to be independent.

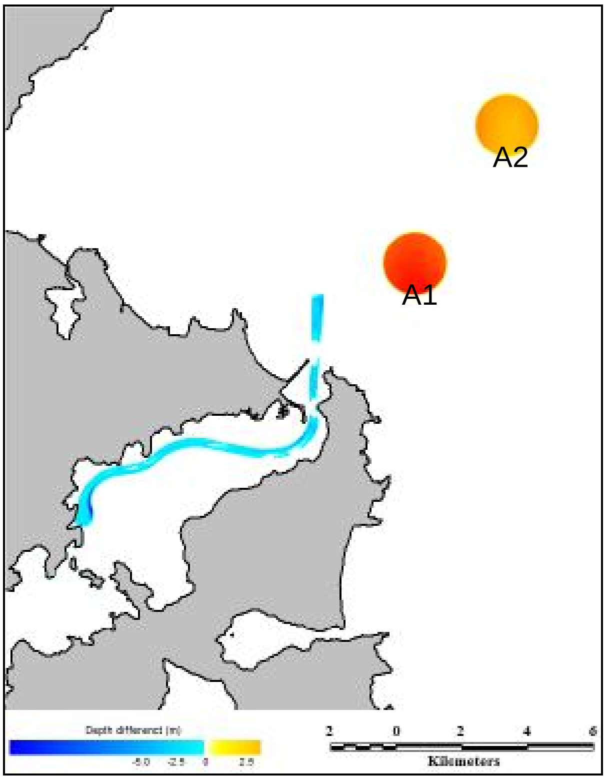

Figure 3.6 Bathymetry difference between the existing bathymetry and proposed modifications (dredged 15-m option and two disposal area options, A1 and A2) (Source: Bell *et al*. 2009, Figure 8.8).

The comparisons between the mean and maximum significant wave heights over the 5-year hindcast are shown on Figures 3.7 and 3.8, respectively. The furthest offshore receiving ground option (A2) would have little discernable impact on the wave patterns, especially mean wave height (Figure 4.6), while the option closer to Taiaroa Head (A1) has a minor focussing effect in the lee of the mound (to the NW). The dredging programme for maximum significant wave heights would result in a maximum of 3-5% change to the wave heights for the existing situation. The model results show no evidence of change to the wave environment at the shoreline, and there is no evidence that the changes would be detrimental to surfing conditions or give rise to adverse coastal change.

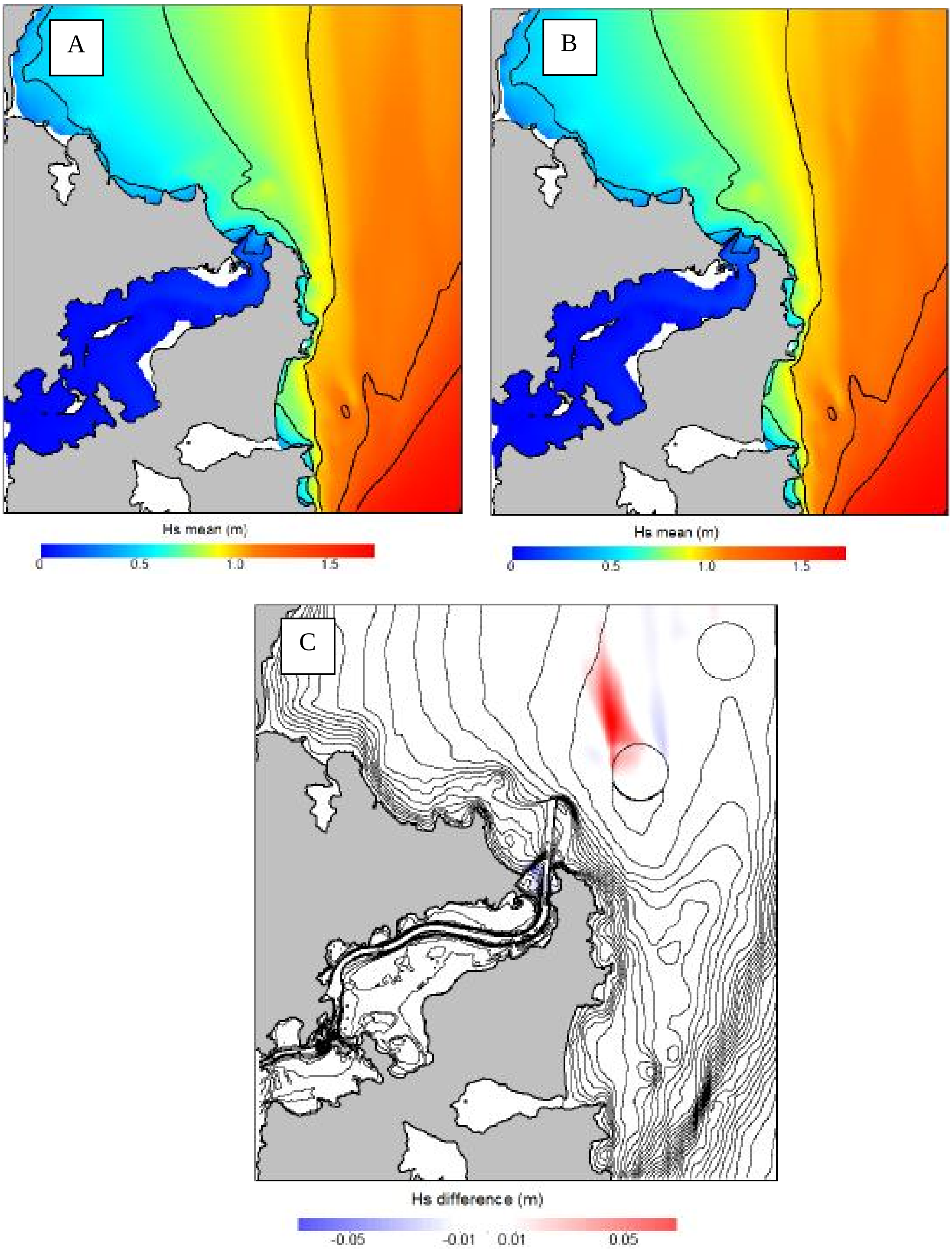

Figure 3.7 Mean significant wave height (m) over 2003–2007 for the existing (A) and modified (B) bathymetries, plus the predicted differences in mean wave height (C) (Source: Bell *et al*. 2009, Figure 8.9).

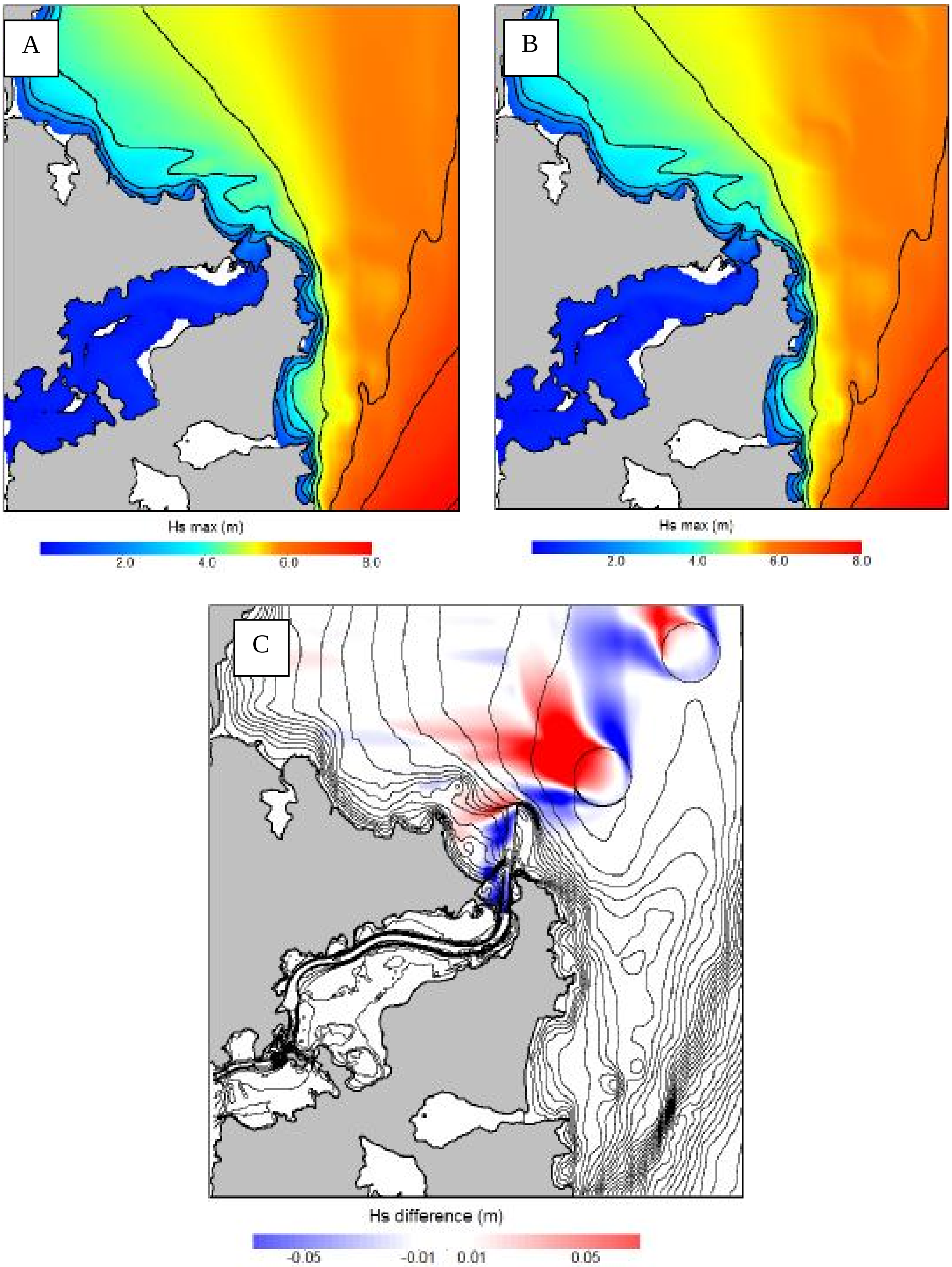

Figure 3.8 Maximum significant wave height (m) for 2003–2007 for the existing (A) and modified (B) bathymetries, plus the differences in maximum wave height (C) (Source: Bell *et al*. 2009, Figure 8.10).

Detailed analysis of the time-series of wave hindcast data (existing versus modified) at discrete locations along the coast further quantified the changes that would result from the disposal mound and deeper channel. Annual, seasonal and monthly significant wave height statistics were assessed. It was found that there would be a very slight reduction in wave heights at some locations near the harbour entrance. For example, in the middle of Aramoana Beach the reduction in height would be around 0.01 m, while at Shelly Beach the wave height reduction would be around 0.02–0.04 m. These effects are due to changes to the shoaling of waves crossing the proposed dredged approach channel and wave refraction over the A1 receiving ground option.

Although the preferred receiving ground option (A0) was not modelled, changes to the wave environment would be of a similar to lesser magnitude and type as those found for sites A1 and A2. The wave environment at the shore would be less modified than under the A1 option.

3.7 Sedimentation

3.7.1 Harbour plume dispersion and deposition

With the proposed dredging programme, it can be expected that there will be changes to patterns and processes of sedimentation in Otago Harbour and the offshore area from Taiaroa Head to Karitane Peninsula. These changes will result from:

- Additional fine sediment put into the active sedimentation environment in the harbour during the dredging activity (excavation in the channel and deposition at the receiving ground),
- Changes to the channel form as the sides and margins of the deepened channel "relax" into an equilibrium condition, and
- The addition of the dredged sediment onto the offshore seabed.

The hydrodynamic and wave modelling was used to identify patterns of plume dispersion through application of Harbour and offshore plume dispersion models. The MIKE-21 Particle tracking model was applied inside the harbour. The DHI Particle Tracking (PT) module for the Flexible Mesh (FM) version of MIKE-3 was used to simulate the transport and fate of suspended material outside the harbour. This model is commonly used worldwide for modelling or monitoring of dredging works. The models were tested for sensitivity and found to be relatively insensitive to the effects of winds, the choice of dispersion coefficients and the use of different quartile silt distributions examined for a sand-dredging claim within the Port Chalmers Turning Basin. This means that for discharged sediments, dispersion and mixing processes (excluding settling of silts versus sands) and wind-driven effects on currents play a relatively minor role in determining the fate of sediment discharges from the trailing suction dredging operation. Discharge sources well below the water surface i.e., near the bed (nominally 1 m) and 5 m below the surface for the overflow, also contribute to constraining the settling sediments within the channel systems, rather than leading to substantial spreading out across the adjoining intertidal flats, with the only opportunities for wider spreading occurring around high tide. Insensitivity to the effects of winds and wind modifications to the tidal currents emphasizes that the to and fro tidal advection in the channel is a dominant factor in determining the transport of suspended-sediment plumes.

In addition, due to the plume model characteristics, the resulting suspended-sediment concentrations (SSC) are presented in terms of saturated-weight of sediment rather than dry-weight per volume. This means that the actual SSC would be about 70-80% lower than predicted. (Bell *et al.* 2009).

Key results from the MIKE-21 modelling of suspended-sediment concentration simulations show:

- The dredger discharges in the Turning Basin would have the most influence on elevating average SSC above background levels in the Upper Harbour, in contrast to dredging at Harington Bend and beyond, which would have little influence on SSC in the Upper Harbour beyond Goat and Quarantine Islands.
- The highest depth-average SSC values (e.g., over 100 mg/L with some patches up around 1000 mg/L) would occur in the main shipping channel, subsidiary side channels e.g., channel north of Quarantine Island through to Portobello Peninsula,

and on the intertidal banks adjacent to these channels e.g., the mid-harbour intertidal banks from discharges at Harington Bend.

- Discharges from predominantly-silt claims generally show a wider spread of affected areas onto intertidal flats and side channels than discharges of silt-sized material from predominantly sand areas. This difference is related directly to the magnitude of the discharge or flux of silt-sized material, which was set to 1000 kg/s for “silt” claims compared to 60 kg/s for “sand” claims, even though the latter discharge would run for much longer. However, there wouldn’t be widespread dispersion of these finer silt-sized sediments over large tracts of the Harbour, as the channel tidal streams dominate the transport of suspended sediments rather than dispersion/spreading processes. Also there would be only limited opportunities around the more quiescent period either side of high tide when diluted plumes from the overflow sources - that discharge most of the time at 5 m below the surface (except at Turning Basin - east) - can spread out further over adjacent intertidal or shallow sub-tidal areas.
- While there is only a short distance separating the two Turning Basin source locations (east and west sides), there would be a substantial divergence in areas affected by suspended-sediment plumes due to the strong flow divergence at Quarantine Island. From the “west” source location, discharge plumes would be transported up the Victoria Channel partway into the Upper Harbour while plumes from the “east” source location would be preferentially transported and dispersed to areas around the Portobello Peninsula and into the Latham Bay area of the Upper Harbour.
- Most of the eastern side of the Lower Harbour from Te Rauone Beach to Harwood would be largely unaffected by discharge sources (from the dredge while in operation or during transit to the receiving ground) other than the Harington Bend discharge location, and then only in patches.
- The eastern side of the Upper Harbour from Grassy Point to Dunedin would be also largely unaffected by sediment discharge sources.
- Average SSC will be low in the plume that emanates from the Mole to Taiaroa Head channel section for dredging claims in the Turning Basin, but will gradually increase up to a depth-average SSC of 100–200 mg/L for discharge sources at Harington Bend. These average SSC levels offshore from the Mole would reduce somewhat as the dredger works the Howlett claim (between Harington Point and the Mole) and further reduce in the Outer Channel claim as the silt content of the sandy seabed sediments reduces considerably to virtually nil.

A period of 100 days was selected as the most likely length of time required to carry out the dredging (not counting down time). Due to the differing capacities of dredging vessels, the contracted operator could take longer or shorter than the 100 days to complete the dredging. However, the volumes of the dredging claims predominantly govern the values of total deposition. For example, this means the total deposition thicknesses wouldn’t change much for a 120-day period of dredging. However, daily rates of deposition could change somewhat depending on the capacity of the dredger that is contracted.

Key results for predicted sediment deposition accumulated over an entire 100-day dredging season (assuming no subsequent resuspension of settled silts) show:

- A marked difference in silt deposition between the predicted deposition in the main shipping channel and all other Harbour sub-areas, with deposition values much higher within the main channel. However these high predicted deposition values exclude subsequent resuspension by tidal currents and/or wind waves, so are mostly unrealistic. They occur in the model when sediments settle out eventually in more quiescent periods of the ebb or flood tide periods, and remain fixed to the bed in the simulations. In practice, these sediments will be re-mobilised frequently, until eventually a proportion is flushed through the main channel system, while some material re-settles in areas of the channel and consolidates into the fabric of sands on the channel floor;

- Other Harbour sub-areas which would exhibit accumulated deposition of over 10 mm in the 100-day dredging period, in the 1% of model cells with the highest deposition for that sub-area, would be in: a) the reach of Victoria Channel to Kilgours Point (99% of cells would have less than 14 mm deposition over the dredging programme); b) the side channel off Quarantine Point at the tip of Portobello Peninsula (995 of cells would have below 10 mm deposition); c) the southern side of the central intertidal bank and adjacent shallows that separate the shipping channel from the side channel through Ohinetu Point, which would arise primarily from discharge sources in the Harington Bend and The Spit areas (99% of cells would have less than 24 mm deposition); d) the sequence of central intertidal banks adjacent to the shipping channel, with the highest likely to occur in the sandbank opposite Port Chalmers (99% cells would have below 82 mm of deposition), arising mostly from dredging of the eastern side of the Turning Basin; e) the subsidiary channel from Quarantine Island through to Latham Bay, again from dredging the eastern side of the Turning Basin (99% of cells would have less than 13 mm deposition over the dredging period);
- Outside the main shipping channel, the highest <u>median</u> deposition in any sub-area of the Harbour would occur on the intertidal sandbank opposite Port Chalmers, with half the model cells in this sub-area showing deposition of nearly 4 mm or more. In most other sub-areas outside the main channels, the median deposition is small at less than 1 mm over the dredging programme.

The long-term fate of silts within the Harbour is difficult to address with suspended–sediment modelling, as it would involve very long computer simulations with a combination of wave, tide and silt-transport models. However, some general tendencies can be inferred from the plume modelling results and our understanding of silt transport in harbours. Firstly, the plume modelling shows that only the main channel and the side channel between Quarantine Island and Portobello Peninsula would be subject to the highest initial deposition thicknesses. These channel silts would be reworked regularly by tidal currents, especially on spring tides, and spread throughout the entire shipping channel, preferentially settling in more quiescent sections of the channel system and also with a sizeable proportion being exported out the Entrance. In the shallower sub-tidal areas, and intertidal banks, some of the initially settled silts are likely to be remobilized by wind waves rather than by currents, and will then be transported elsewhere in suspension by the current until settling again. For a typical 3-second wave, and a upper-range significant wave height of 0.6 m, the threshold for mobilizing non-cohesive medium silts (0.01 mm) would be exceeded in depths less than about 7 m, which includes most of the Harbour outside the main shipping channels, except a small part of the basin in Portobello Bay. Consequently, during moderate to high waves, silts available for reworking will be winnowed from the seabed surface, especially off exposed shallow areas and intertidal flats where wave orbital velocities can be high.

Silts in the long-term would be dispersed further and more thinly throughout the Harbour, eventually finding their way into the main channel system to be exported to the ocean or preferentially settle "permanently" in quiescent areas where wave activity and currents are low or sporadic such as Dunedin Basin, inlets in the Upper Harbour behind the railway embankments, sheltered sub-tidal embayments (e.g., Careys Bay and the inner Port Chalmers berths), the deep basin in Portobello Bay, and in the lee of groynes or half-tide training walls.

3.7.2 Offshore plume dispersion and deposition

During the disposal operation, when the dredge hopper is emptied at the offshore disposal site, the following processes would occur (as shown in Figure 3.9):

- A major portion of the released sediment load descends rapidly en masse to the seabed and deposits itself there;
- A minor portion of the sediment load goes directly into suspension (especially finer size fractions), increasing the concentration of suspended material in the water column and drifts off with the current, dispersing and gradually settling with time;
- Finer material (e.g., silts) within the mass that falls directly to the seabed will spread out radially along the seabed away from the impact zone;
- Deposited material can be subsequently re-suspended when wave conditions are sufficient strength to mobilise the seabed surface sediments and transported by currents before settling again when conditions allow.

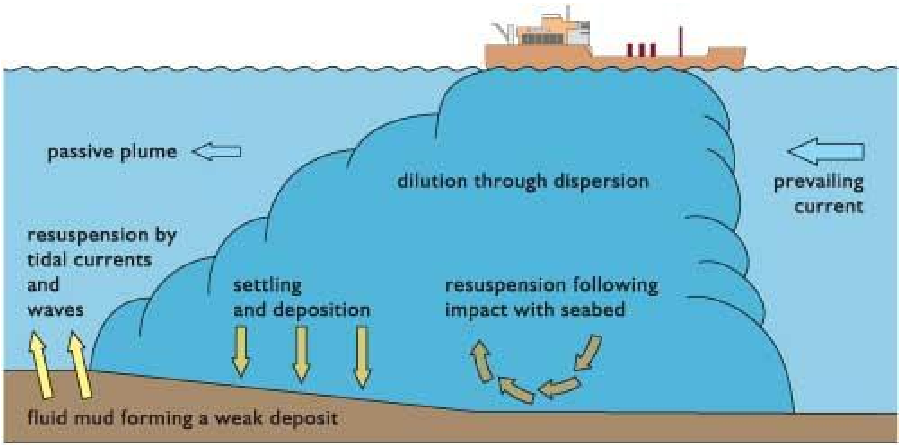

Figure 3.9 Schematic of a dynamic sediment plume discharged from a dredge hopper. [*Source: CIRIA (2000)*].

The model simulation of dredged sediment placement over the A0 receiving ground was based on a discharge of the contents of a hopper on a typical medium-sized dredging vessel taking approximately 10 minutes, with a turnaround time of 2 hours applied to the plume simulations before the next hopper load. The two key aspects of the plume dispersion and deposition of sediment are the: 1) magnitude (mean and maximum) of suspended-sediment concentrations and the spatial extent of the plume; and, 2) an estimate of the total seabed deposition and extent of deposition over the dredging season. Investigation of these aspects required a different approach to the set-up of the plume simulations.

The model parameters result in SSC being presented in terms of saturated-weight per volume. Therefore the SSC results are conservative (over-estimates) compared to dry-weight SSC values, which may realistically be 50-90%, lower than predicted by the model, depending on the equivalent dry bulk density of the sediments in the hopper. The model results will be less different for silt sizes than for fine sands.

3.7.3 Plume concentrations and spatial extent

Suspended-sediment concentrations were analysed from single simulations of each of six 48-hour wind scenarios from either NNE or from WSW, applied for each of five selected placement sub-sites within the 2 km disposal area at A0. Each hopper load was assumed to contain an average mix of dredgings from “silt” and “sand” sources in proportion to their respective total volumes from all dredging claims. Mean and maximum composite plots for each sediment-size component and depth-layer of the plume simulation were generated for the 48-hour wind sequence.

Key results for the A0 receiving ground for an average hopper mixture were:

- Suspended-sediment concentrations (SSC) would be highest in the bottom near-bed layer (bottom 20% of the water depth) due to the settling of sediment towards the bed and having commenced discharge from the hopper at 5 m below the water surface;
- Medium silts cause the higher local elevations in SSC in the bottom layer within a few kilometres of the receiving ground, but the fine silts are more dispersive spreading over a wider area (due to their lower settling rate);
- In the vicinity of the receiving ground, considering both fine and medium silts, moderate WSW winds are the most adverse wind conditions for the maximum bottom layer SSC, which would be up to 160 to 220 mg/L (excluding coarse silts and sands). The highest maximum surface-layer concentrations reached in the vicinity of the disposal site would be in the range 30–60 mg/L for each of the size classes and across all six wind scenarios, with the higher surface-layer values occurring during light NNE winds when combining all size classes, the maximum total surface-layer SSC would be around 185 mg/L;
- Average SSC would be substantially lower than the maximum values, because the 2-hour gap between discharge from the dredging vessel would allow the concentrations to reduce from settling and dispersion;
- The dilute edge of the near-bed plume could occasionally reach coastal areas between Taiaroa Head and Wickcliffe Bay but not under stronger winds from the WSW or NNE. SSC would be elevated above background surface SSC by up to only 0.7–1.5 mg/L, for fine and medium silts (with a total SSC increase of only 2.2 mg/L) under light NNE winds. In the bottom layer, maximum total SSC increase would be somewhat higher at around 2.8 mg/L above background concentrations for the same wind conditions;
- The dilute edge of the plume could reach areas of the coast north of Karitane and beyond but would elevate the total surface SSC by only about 0.02 mg/L in the Karitane area, and up to only 0.9 mg/L further north towards Stony Creek and Shag Rock under light NNE winds. In the bottom layer, maximum increase in total SSC north of Cornish Head would only reach 0.41 mg/L above background concentrations under strong WSW winds;
- In the bottom layer, the highest excess concentrations occur at the receiving ground where the fine sand (class 4) concentrations would reach around 1600–1700 mg/L for light wind conditions, and less for stronger wind events. Of the silt-size classes, medium and coarse silts would contribute similar maximum excess concentrations in the bottom layer of up 200–230 mg/L "downstream" in the vicinity of the receiving ground, with the higher values occurring during a moderate WSW wind. For this moderate WSW wind scenario, the total maximum SSC in the bottom layer combining all size classes would be around 2100 mg/L in the vicinity of the receiving ground;
- For coastal areas likely to be reached occasionally by the dilute plume, excess surface SSC would be highest for light NNE winds, which are conducive to wider spreading (dispersion) of the plume and less vertical shear in the water column (which occurs in stronger winds). In terms of the bottom layer, light NNE winds would cause the highest SSC off Otago Heads, but strong WSW winds would cause the highest SSC off the northern coast. In all coastal cases, the maximum SSC would remain quite small and occur periodically depending on the winds;
- In the vicinity of the receiving ground, the highest excess concentrations in the surface water would most likely occur on light NNE winds, with the highest

concentrations in the bottom layer for sands also likely to occur during light winds (any direction), while for silts, it would be reached during moderate WSW winds;

- Overall, winds don't appear to substantially affect the plume characteristics and movement from site A0 as much as plume simulations for option A1 closer inshore. This is because site A0 is located on the inner edge of the periphery of the Southland Current that drives a persistent residual current to the north and tends to dominate the flow regime.

Summary of results for the bottom layer for a predominantly silt hopper load:

- Maximum bottom-layer concentrations in the vicinity of the receiving ground are considerably higher for the predominantly-silt hopper discharge compared with the average sand/silt hopper loads reported above. For class 1 (fine silts), the increase would be 130% and 145% for light WSW and light NNE winds respectively, with equivalent increases of 140% and 150% for class 2 sediment size (medium silts) and 150% higher in both cases for class 3 sediment size (coarse silts);
- Combining all the "silt" size classes, the maximum silt-derived SSC in the bottom layer in the vicinity of the receiving ground, for the worst wind scenario (a moderate WSW wind), would increase from around 620 mg/L for an average sand/silt hopper load to around 910 mg/L for a smaller, but predominantly-silt hopper load—an increase of around 145%;
- Combining all size classes including sands, the total maximum SSC in the bottom layer in the vicinity of the receiving ground, for a moderate WSW wind, would actually decrease from around 2100 mg/L for an average sand/silt hopper load to around 1150 mg/L for a smaller, but predominantly silt hopper load—because of the much smaller sand volume in the latter;
- For shoreline areas (e.g., Otago Heads, north of Cornish Head) when the edge of the dilute edge of the plume makes contact, the maximum increase in SSC for each silt size class in the bottom layer is unlikely to be any higher for the predominantly-silt hopper discharge for light WSW or NNE wind conditions, but the area over which the silts disperse at very low concentrations is somewhat more widespread. Both these findings are indicative of the highly dispersive processes for suspended silt that operate on the Otago shelf, once they leave the receiving area.

3.7.4 Total sediment deposition on the seabed

Given the distribution of winds during the actual dredging programme are not known ahead of time, a Monte Carlo approach was used to randomly select one of the six 48-hour wind scenarios, where the chance of selection for a wind scenario is governed by the likelihood of that wind occurring. The analyses of dredge volumes and dredge turnaround times by POL indicate a continuous dredging season of around 100 days, not including downtime and weather contingencies. Therefore a sequence of 51 lots of 48-hour plume simulations was required to replicate the dredging season. The deposition pattern and magnitude from each 48-hour plume simulation is accumulated to arrive at an estimate of the total deposition.

In accumulating the deposition thicknesses, the assumption is made that once sediment is placed it remains there. This is a conservative assumption, especially for the finer sizes, which will be regularly mobilised by wave action and moved on in an ever-increasing dispersive manner. Also a conservative assumption was made that the bulk density of settled sediments would be only 1300 kg/m^3, thus erring on the higher side of deposition depths. Finally, losses of silts and sands that may overflow from the hopper into the Harbour waters during dredging were not deducted from the volumes discharged over the receiving ground. Consequently on all counts, the offshore deposition plots provide a conservative upper bound on deposition depths on which to assess environmental effects, bearing in mind the dispersive behaviour of fine sediments on an active, exposed shelf system.

The key results from the deposition distributions are:

- For the A0 receiving ground option, the deposition is predominantly on the site and to the north of it, arising from the persistent northerly residual current;
- The small degree of deposition to the south-east mainly occurs at times during light NNE breezes;
- Fine silt deposition occurs over the widest area as expected in a highly dispersive environment with slowly settling sediments. This contrasts with sand, where deposition is much more confined, occurring well offshore and to the north and north-east of the receiving ground;
- Deposition is low along coastal areas where the diluted suspended-sediment plume edge comes in occasional contact, such as Otago Heads (north of Wickliffe Bay) and the northern coast from Cornish Head north. Where deposition is predicted to occur, it would be <0.5 mm thick over the dredging programme. This is an upper-bound estimate, but in reality these “deposited” sediments, being fine and medium silts, will be mobilised by wave activity in shallow coastal waters and continue to be dispersed over a wide area. The modelling also shows that no deposition of silts or sands would occur in Blueskin Bay or at Karitane within 48 hours of disposal;
- All silt sizes would be dispersed further north than the northern boundary in the hydrodynamic model at Shag Rock, but deposition would be very small at <0.1 mm;
- The area influenced by various deposition rates is shown in Figure 3.10. The area where a deposition rate of more than 0.08 mm per day would occur (as an upper-bound) extends approximately 18 km in N-S direction (mainly to the north) and 5 km in width (Figure 3.10) covering 77 km^2. The area in which the deposition rate would be ≥0.4 mm per day would extend only to the northern terminus of the Peninsula Spit (–45.655°N) covering up to 29 km^2 while smaller areas where accumulated deposition rates would exceed 0.8 and 1.7 mm/day (Figure 3.10) could cover 18 km^2 and 11 km^2 respectively (including the disposal mound). This deposition pattern is closely aligned with the results from the sand transport modelling.

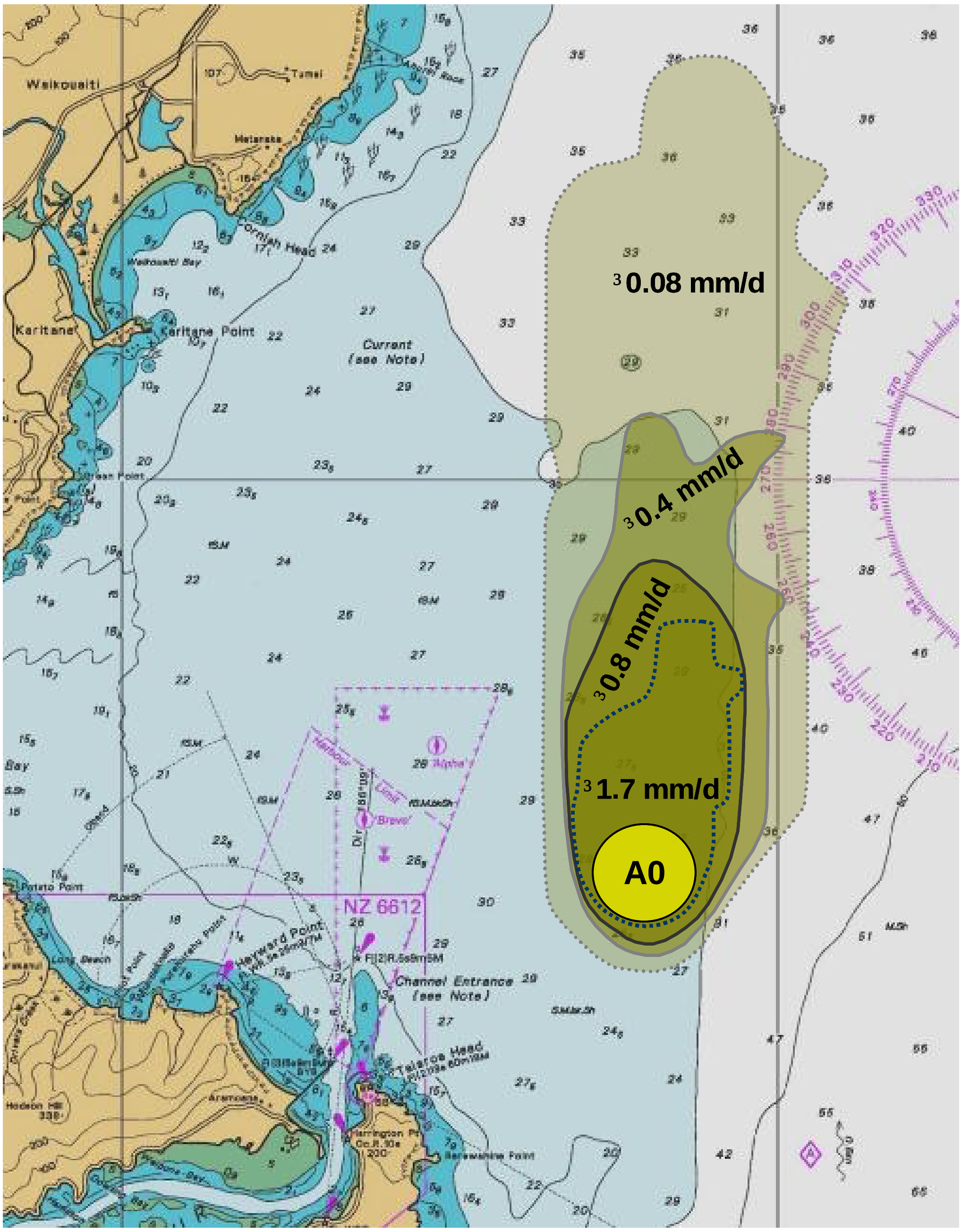

Figure 3.10 Zones within which various average deposition rates (mm per day) are exceeded for all sand/silt fractions over the entire dredging programme. The deposition rates are conservative, being applicable to a mid-size TSHD of 10,800 m^3 capacity where the dredging extends for 120 days continuously. The inner zones out to the 0.5 mm/d zone boundary are indicative of the transport pathway and extent of sand transported through the disposal mound at A0. The transport pathway also matches closely with the alignment of the incumbent geomorphological feature (Peninsula Spit) that is marked out by the light-blue 30-m depth contour shading, providing further confidence that the modelled net sediment transport direction is reliable. [*Source of background map*: Chart NZ661, LINZ] (Source: Bell *et al.* 2009, Figure 13.2).

3.8 Long term sediment transport from the receiving ground A0

3.8.1 Transport rates and deflation of the disposal mound

Based on analysis of near-bed currents and wave from the 4-month field monitoring programme at site A1 (30 m depth), currents acting alone are insufficient most of the time to resuspend fine sands with grain sizes of 0.1 mm or more. This mostly applies also to site A0, although there will be some occurrences when stronger currents are present to mobilize sands independent of waves. Therefore generally sand transport on the seabed is only possible when waves (particularly swell) generate orbital motions of sufficient strength to resuspend sands from the mound and surrounding seabed, which can then be subsequently carried short distances by the near-bed current until they settle again. Based on a 10-year hindcast of the wave climate offshore, waves are capable of suspending 0.1 mm fine sands for 55% of the time at the preferred receiving ground A0, reducing to 23% of the time for coarser 0.5 mm sands (from all wave directions). There is also a seasonal variation, with the most energetic season being winter (waves were capable of resuspending fine sand at A0 for 68% of the time) followed by autumn (61%), spring (53%) and summer (42%). These frequencies of sand mobilization will be somewhat higher again at the top of any mound at A0.

Based on an estimated height of 1.6m and bulk density of 1600 kg/m^3, a mass of approximately $8{\times}10^6$ tonnes of sediment is likely to form the initial mound. This total should be considered with regard to the estimated "net" sediment transport through a 2-km section at the A0 site. Based on Rouse and Nielsen models respectively, this would be in the range of 4,000 to 92,000 tonnes over the 2008 4-month field period for the median sand size (0.2 mm). However it should be noted that the field period was more energetic than normal in terms of significant wave height.

An analysis of potential upper and lower bounds on the deflation of the initial mound was undertaken based on transport rates determined for the 4-month 2008 field period at A0 and using the mass continuity equation, with various input and output rates relative to the mound height. The differential in local sediment transport rates on the top of the mound (in this case 1.6 m) relative to the surrounding "native" seabed at A0 are around 30% higher for the Rouse model and 37% higher for the alternative Nielsen model, which holds for all sand grain sizes. While the estimates of the upper and lower-bound estimates of the mound deflation time vary substantially between the Rouse and Nielsen sediment models, the key result from this overview of upper and lower bounds is that the mound will take many years to fully deflate back to the present seabed level at A0, based on using the median sand size of 0.2 mm. This deflation period could be as short as 21 - 580 years or 120 - 3490 years depending on the calculation method).

3.8.2 Direction of sediment movement

One of the key findings of the sediment transport analysis for sand-sized sediments placed at the A0 receiving ground is that there is very little sediment transport that would occur in any other direction apart from towards True North. There is more surety of the direction of long-term sediment transport for this site compared with sites such as A1 closer to the coast, because it would be predominantly to the north along the axis of the Peninsula Spit submarine feature. The submarine spit, has evolved over the Holocene from the prevailing sediment and hydrodynamic processes that operate in this offshore zone transporting major sediment sources from the Clutha River and to a much lesser extent the Taieri River (Carter, 1986), and will continue to build out to the north.

A conservative indication of where sand-sized sediments (sourced from the receiving ground at A0) could move to can be inferred from the suspended-sediment plume modelling of the dredged sediment placement. After being initially deposited on the receiving ground, sand-sized material, particularly the finer sands (0.1–0.2 mm), will be re-mobilized again only by waves of sufficient height and period and then transported short distances by the near-bed current velocity operating at the time, before settling again. The larger deposition zones (50+ mm and 100+ mm) will be where most of the sands deposit, and therefore are indicative of the long-term (months to year timescales) transport pathway and extent of transported sand that has been sourced and re-mobilized from the seabed off any mound at A0. It also needs to be noted that remobilization and transport of sand particles occurs ubiquitously on the seabed during moderate to high wave events, irrespective of whether they are from the dredgings or "native" sands.

Over time periods of months and years, the mound at A0 will smooth out and deflate gradually from both consolidation and differential erosion (due to higher local wave-orbital and current velocities over the top of the mound). The evolving shape of the mound is likely to show an elongated "tail" on the northern side of the mound from the prevailing "net" sediment transport to the north, but also a smoothing of the southern side-slope of the mound as the bedload fraction of sand transport from upstream (south) is deposited on the flanks of the mound.

An optimal time of year for placement of dredged material is not obvious since the predominant transport direction to the north is independent of time or season.

Given the results from the sediment transport analysis and the above reasoning based on inferences from the plume modelling for sand-sized material and the morphology of the offshore Spit, it is very unlikely that sand-sized material, other than isolated grains from the dredgings deposited at A0 would move westwards to reach the nearshore zone (depths <15 m).

Sand already moving on the seabed in the vicinity of A0 will be indistinguishable from the placed sand sized sediment. Sand moving from A0, either the placed sand or sand moving through the area, will be subject to the same sand transport processes and will move in the same way. In essence, the placed sand sized sediment will behave the same as sand moving through the area from the surrounding seabed.

3.8.3 Comments on long-term silt transport offshore

Modelling the long-term fate of silt-size material (<0.0625 mm), especially the finer fractions (<0.02 mm), is inordinately difficult to achieve. These "deposited" sediments, especially fine and medium silts, will often continue to be re-mobilized by wave activity in shallow coastal waters and further disperse in very low concentrations over a wide area of the Otago shelf, particularly to the north.

The ultimate fate of these widely dispersed silts in terms of "permanent" deposition will be mainly in deeper waters and canyons offshore as exemplified by the deposition of fine terrigenous material from catchment run-off including the Clutha River. There are also preferential natural deposition areas for fine to coarse silts on the shelf such as off Blueskin Bay, which possibly arise from the combination of the weak counter-clockwise gyre in outer Blueskin Bay and the loss of momentum in ebb-tide sediment plumes emanating from Otago Harbour towards the north, and hence enhanced settling of coarser silts from the Harbour. Some of the silt material from the receiving ground A0 could be deposited in this preferential silt zone, but as shown by the disposal plume modelling, most of the silt material would be dispersed to the north and north-east, with virtually no suspended-sediment plumes sweeping across this preferential silt zone in central Blueskin Bay over a 48 hour period.

4. The direct and indirect effects of the proposed works

4.1 Introduction

The changes to the physical coastal environment due to the proposed dredging activity and the deeper shipping channel in Otago Harbour have been assessed in order to identify the potential effects on the physical coastal environment. These effects are discussed with regard to the following areas:

- The potential effects of the dredging operation on the <u>hydrodynamics</u> of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point as a result of the proposed dredging operation.
- The potential effects of changes to the <u>wave environment</u> on the physical coastal environment of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point as a result of the proposed dredging operation.
- The potential effects of the dredging operation and placement of dredged sediment on the <u>sedimentation processes</u> of Otago Harbour and the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point.

4.2 Effects of hydrodynamic changes

4.2.1 Hydrodynamics within the harbour

The deepened channel results in three types of changes to the hydrodynamics of the harbour. These are the tidal range, the timing of the tidal wave, and the speed of tidal currents.

The tidal range will increase by up to 0.004 m in the Harbour Entrance, between 0.004 and 0.006 m from Harington Bend to Tayler Point, by 0.006 to 0.008 m in the vicinity of Port Chalmers, and around Portobello Bay and Harwood in the Lower Harbour, and in the Upper Harbour.

The effect of the deeper channel on the tidal range is negligible, especially when considered against the background of natural variability. The change in range will not result in an increase in the incidence of inundation hazards of the harbour margins, nor expose inter-tidal areas to a significantly greater degree than at present.

The timing of the tidal wave travelling into and out of the harbour will advance, resulting in high tide arriving by up to 3 minutes earlier between the Harbour Entrance and Harington Bend, 3 to 4 minutes earlier at Port Chalmers and in the Upper Harbour. Similar but slightly smaller advances in the timing of low water would also occur. This is not a significant effect on the tide phase, but would require recalculation of tidal tables for Otago Harbour after the completion of the dredging.

There are likely to be only small changes to the speeds of tidal currents. These changes are mainly reductions in speed of less than 0.1m/s and will occur in the Lower Harbour, including within the deeper channel. Localised increases in average peak current of up to 0.02 to 0.05 m/s would occur off the groyne at Beacon 10 on the south side of Harington Bend and there would be decreases in peak current of up to 0.1 m/s in areas along the channel margins at Harington Bend and near Port Chalmers where the channel will be made wider.

These changes are less than 6% of the existing current speeds and would not result in changes to the transport of sediment within the harbour due to tidal currents. The changes in current speed would also not affect boating conditions within the shipping channel, side channels or across the shallow areas of the harbour. These small changes in velocity will have no noticeable effect.

The effects of the deeper channel on the tidal hydrodynamics would not be significantly different for different wind and tide combinations.

4.2.2 Hydrodynamics in the area offshore of Otago Peninsula between Taiaroa Head and Karitane Point

There will be small changes to the current flows in the vicinity of the Entrance Channel after dredging. There would be a resultant slight enhancement of the flood-tide flows, particularly for the mean and spring tide cycles. There would also be a slight increase in the amount of time that the flows exceeded a threshold speed such that they could mobilise fine sand. On the ebb tide sand bar, the existing bias of a dominant ebb-tide flow to the north up the axis of the sand bar would be slightly enhanced by the deepened channel. Tidal currents acting alone will still be insufficient to mobilise fine sands on the inner half of the sand bar, so wave processes play the dominant role is mobilising and transporting sediment on the bar in tandem with the net northerly tidal-flow residual.

The net result may be that there is less flushing of sediments on the peak flows, and there will be preferential deposition of sediment in the dredged channel. Therefore, there may be an increase in the maintenance dredging volumes and/or frequency, and an increased need for maintaining the shape and position of the side of the channel on the eastern margin, as sediment will spill over from the east and south into the channel.

4.3 Effects of changes to the wave environment

4.3.1 Wave environment within the harbour and near the Harbour Entrance

Increases in significant wave height for a 15m channel will be small (less than a few cm) in the main channel, with negligible change outside of the proposed widened channel.

There will be a slight reduction in wave heights at some locations near the entrance. At Shelly Beach, the wave height reduction would be around 0.02-0.04m. There would be negligible effect on ship handling through the Entrance Channel, and no noticeable changes to wind waves or swell penetration in the area shoreward of the channel towards Taiaroa Head, Pilots Beach and Te Rauone.

4.3.2 Vessel wake within the harbour

Single and Pullar (2009) present an assessment of the effects of vessel movements resulting from the use of the proposed 15 m shipping channel. The assessment is based on the existing wave environment including observations of wake events at Te Rauone Beach and measurements of wake waves by Goring (2007), and the results of studies carried out for the Ports of Melbourne comparing wake from container ships in Port Phillip Bay.

Port Otago’s proposal to deepen and widen the existing navigable channel in the Lower Otago Harbour will enable vessels of a larger size and displacement to transit the channel. Concerns have been raised that this could potentially lead to increased magnitude and instances of wake from vessels that cause public nuisance and create safety concerns for fellow users of the Harbour. Wake from the largest ships (4100 class container vessels) has been measured at up to 0.150 m high (Goring 2007). The observation program of vessel wake experienced at Te Rauone beach undertaken in 2009, showed that for 22 vessel transits the highest single event resulted in a “stranding wave” of 0.35 m in height with the remainder being all less than 0.25 m. Analysis of the spit tide gauge undertaken as part of the same work showed that the maximum 1minute change in the tidal level as a result of vessels passing was 0.110 m with 99% being less than 0.040 m.

It is likely that deepening and widening of the channel will result in a reduction in the magnitude of wake generated by current commercial vessels. This is due to the reduction in blockage ratio of the vessels in relation to the channel depth and cross-sectional area. There will also be a reduction in the seabed scour beneath the vessels due to the lower blockage ratio and the greater clearance beneath the existing vessels and the proposed base of the channel.

The wake waves created by 6000 TEU vessels that could use the deeper channel will be potentially larger than those from the 4100 TEU vessels due to the greater displacement and blockage ratio of the larger vessels on a typical transit of the harbour channel. It is difficult to quantify this increase with any certainty although based on vessel observations and studies in Port Phillip Bay in Melbourne it is likely to be in the order of 10 – 15%, this range is well within the natural variability within the existing wave environment. However with the introduction of a service utilising 6000 TEU vessels, the number of transits of container vessels will be less than at present due to the larger capacity of the vessels. This will mean that the same volume of containers will be moved for less container vessel transits. Therefore the cumulative effect of wake waves in the harbour will be reduced.

There are no documented effects on the harbour ecology from wake generated by the passage of the present vessels using the harbour channel. This situation is not likely to change following the deepening and widening of the channel. Any effects from existing vessels that may exist are likely to be reduced. The wakes of the 6000 TEU vessels may disturb surficial sediments and biota but to no greater degree than current wind waves or tidal currents.

The wake events that are more likely to be adverse at the shore are those that occur within an hour or two either side of high tide. The effects on the water are limited to within two or three boat lengths away from the sailing line. As the shipping channel is “one way”, the interaction of boats with wake does not occur between ships, and smaller vessels are advised to sail at a distance from larger ones.

In conclusion, the effects of vessel passage following widening and deepening of the existing navigable channel will be similar or less than that currently existing. The cumulative effect of vessel wake, both current and in the future, is likely to be much less than the effects of natural waves and tidal currents occurring in the dynamic environment of Otago Harbour.

4.3.3 Wave environment offshore of Otago Peninsula between Taiaroa Head and Karitane Point

There is likely to be a minor focusing effect on wave patterns in the lee of the receiving ground at A0. The biggest changes would be an increase in wave height of about 3 to 5% of the wave heights for the existing situation in the vicinity of the receiving ground. There would also be a small reduction (about 0.01m) in height of waves at Aramoana Beach due to the deeper Entrance Channel.

These changes will have no persistent effects at the shoreline. There will be no noticeable effect on surfing conditions and there will be no changes to existing patterns of beach response to changes in the wave environment. In particular, there will be no increase in erosion or inundation hazards at the shore, and there will no increase in accretion due to changes in the wave environment.

4.4 Effects of changes to sedimentation processes

Sedimentation process effects include turbidity in the harbour, at the dredged sediment placement site and areas in-between, changes to wave refraction and sediment movement on the seabed as a result of placement of dredged sediment, and changes to maintenance dredging operations as a result of the deeper channel. The modelling and assessment of sediment transport and the inshore wave environment show that there will be no effects on coastal erosion and beach deposition from the proposal. Specifically in relation to areas nearest the harbour entrance channel, at the distal end of The Spit and at Te Rauone, these sites are discussed in Sections 2.4.5 and 2.4.6.

4.4.1 Turbidity

The dredging activity will result in suspended sediments being added to the water column resulting in turbidity. The immediate effect of the turbidity is to discolour the water. However suspended sediment will also travel within flowing water and disperse and settle along the harbour channel and across the inter-tidal flats, within secondary channels and shallow areas.

The modelling (suspended sediment concentrate simulation) shows that different source areas of discharges of silt from overflow and during dredging will result in areas close to the source being affected by suspended sediment plumes. Most of the deposition of fine sediment from dispersed plumes will occur in the main channel. Currents will remobilise this sediment causing some of it to flow through the main channel system up and down the harbour, and some to consolidate into the fabric of sands on the channel bed.

Turbidity resulting from transport of dredged sediment and placement at the receiving ground will be widespread but is unlikely to have an effect on the physical coastal environment.

James *et al.* (2009) discuss the effects of turbidity on the ecology of the harbour and seabed.

4.4.2 Deposition of fine sediments

Modelling of deposition of fine sediments shows that deposition of up to 14 mm thick over an entire 100-day dredging season could occur within the reach of Victoria Channel to Kilgours Point, within the side channel off Quarantine Point, the southern side of the central intertidal bank and adjacent shallows that separate the shipping channel from the side channel through Ohinetu Point, the sequence of central intertidal banks adjacent to the shipping channel, and the subsidiary channel from Quarantine Island through to Latham Bay. The highest median values of deposition are likely to occur on the intertidal sandbank opposite Port Chalmers. Deposition could be as much as 82 mm over the entire dredging period, however it is intended that the management of the dredging operation will reduce these levels of deposition.

The modelling also shows that only the main channel and side channel between Quarantine Island and Portobello Peninsula would be potentially subject to high depositional thicknesses (> 10 mm). These channel silts would be reworked regularly by tidal currents and spread throughout the shipping channel. Settlement of the fine sediment will occur in quiescent sections of the channel system, but much of the fine sediment will be transported out of the harbour entrance. Wind waves will remobilise sediments deposited on the intertidal sandbanks. Currents will then transport fine sediments until further dispersed to settle elsewhere within the harbour system. Preferential settlement will occur in quiescent areas where wave activity and currents are low or sporadic such as Dunedin Basin, inlets in the Upper Harbour behind the railway embankments, sheltered sub-tidal embayments (e.g., Careys Bay and the inner Port Chalmers berths), the deep basin in Portobello Bay, and in the lee of groynes or half-tide training walls.

Although the modelling shows potential settlement of small fractions of fine sediments on broad highly elevated intertidal areas such as the Aramoana flats, this material is easily remobilised and is likely to have a short residence time before moving back into, and being redistributed via the main channel.

Fine sediments will be carried for long distances from the receiving ground, with the northern dilute edge of the suspended sediment plume reaching areas north of Karitane, and the southwestern dilute edge of the plume occasionally reaching coastal areas between Taiaroa Head and Wickcliffe Bay. This fine sediment is unlikely to settle on beaches and rocky coastal areas, as it will be readily remobilised by wave action, wind and tidal currents in the nearshore.

James *et al.* (2009) discuss the effect of deposition of fine sediments on marine biota in detail.

4.4.3 Deposition of sand in the vicinity of the receiving ground

The ideal offshore receiving site would have the same sediment in situ characteristics as the dredged material to be placed. From the investigations of the seabed sediments and the geotechnical investigations in the harbour, the modern sand and mud facies offshore of Otago Harbour, and in particular in the vicinity of the distal end of the "Peninsula Spit" are of the same character as the sediments to be dredged. Willis *et al.* (2008) do not consider the seabed in the vicinity of site A0 to be unusual nor ecologically significant. Placement of the dredged sediment would not change the composition of the seabed sediments in the long term.

The deposited sand will result in a mound being built on the seabed, and this mound will intercept and transfer sand moving on the seabed. The wave and current energy at the disposal site is not sufficient to cause mass movement of the deposited sand away from the site.

4.4.4 Sand transport patterns from receiving ground

The ideal sediment disposal site would not result in sediment transport back into the dredged channel, into Blueskin Bay estuary, or onto the rocky coast north of Warrington or south of Taiaroa Head.

Movement of sediment on the seabed was determined from seabed observations, and by assessing the predominant current directions and known sediment transport paths in the wider Blueskin Bay environment. The bed is mantled by highly mobile fine to medium sands and there is a zone in the middle of Blueskin Bay that is mantled in predominantly finer sediment (silts and mud).

The modelling studies have shown that sediment from the receiving ground would move predominantly to the north and would be masked by the existing sediment transport from south of Otago Peninsula to the north.

Bunting *et al*. (2003a) show that the beach systems from Kaikai north to Purakanui Bay have not been adversely affected by nearly 30 years of disposal of maintenance dredged sediment, and capital dredged sediment from the 1970s placed near Heyward Point. The modelled movement of the sediment from the disposal site, AO, does not indicate any change to the present situation.

James *et al.* (2008) discuss the effect of movement of sand sized sediments on benthic communities in detail.

4.4.5 Effects on the present pattern of maintenance dredging

The design of the channel sides and batter slopes replicates the existing slopes to minimise adjustment of the channel and margins after the capital-dredging programme is complete. Changes to tidal currents and waves in the harbour are unlikely to increase sedimentation from scouring of the channel margins or from erosion of the intertidal banks.

Sediment will not move from the receiving ground back towards the Harbour Entrance. However the deeper channel across the ebb-tide delta is likely to result in additional capture of sand in the Entrance Channel and will possibly result in an increase of dredging demand seaward of Harington Bend. The quantity and the duration of this increase are unknown.

It is unlikely that the total maintenance dredging demand will increase to more than the existing consent of 450,000 m^3 per year.

5. Monitoring

The proposed dredging and deeper channel will result in small changes to the physical process environment of Otago Harbour and the Blueskin Bay area. However modification of the shape and depth of the channel, and the construction of the mound of sediment at the disposal site will physically change the seabed topography.

The requirements of the Port Otago maintenance dredging consent include seabed surveying of the channel and the disposal grounds off Heyward Point, Aramoana and Spit Beach. This type of monitoring is useful in that it provides information on the dredging demand and on the retention of sediment at the disposal sites.

Monitoring of the effects of the proposed dredging operation and the deeper channel on the physical coastal environment should be of the same methodology, with annual surveys of the channel as per the maintenance dredging requirement, plus an annual survey of the disposal mound for the first five years of the project and then a five-yearly survey of the mound thereafter.

6. Conclusions

Otago Harbour is a robust, dynamic environment subject to variable wave energy and sediment supply, and to a history of human modification to the shores, the main channel and the entrance configuration. The area of Blueskin Bay between Taiaroa Head and Karitane Peninsula is subject to high-energy waves, strong tidal and oceanic currents, and a large but variable volume of sediment transfer on the continental shelf and nearshore seabed.

Feasibility studies were carried out on the proposal to deepen the shipping channel through the lower Otago Harbour, and to identify the most suitable method of sediment disposal and the offshore disposal site with the least adverse effect.

The main considerations for the effects on the physical coastal processes were:

- Potential changes to the hydrodynamics of the harbour and the entrance channel,
- Potential changes to the wave environment of the harbour, the entrance channel and the disposal site,
- Changes to patterns of sedimentation within the harbour, the entrance channel and the wider Blueskin Bay area, and
- The dispersal of fine sediments due to the dredging operation.

Studies carried out to investigate these effects have shown that they are mostly negligible, and of magnitudes within the variability of the natural environment. Table 6.1 sets out the issues and potential adverse effects of the project. Rankings of the severity of the possible consequences, the duration of the effect and the probability of occurrence are given for each effect.

Apart from the physical change to the seabed topography in and along the margins of the channel, and at the disposal site, the effects of the dredging operation on the physical coastal environment are considered to be minor.

Table 6.1 Potential adverse effects on the physical coastal environment of the proposed dredging operation and deeper channel.

POTENTIAL EFFECT	POTENTIAL CONSEQUENCES	EFFECT	SIGNIFICANCE OF EFFECT			
			SEVERITY	DURATION	PROBA-BILITY	RISK
Change to tidal hydrodynamics within the harbour.	Changes to the tidal range will include an increase by up to 0.004 m in the Harbour Entrance, between 0.004 and 0.006 m from Harington Bend to Tayler Point, by 0.006 to 0.008 m in the vicinity of Port Chalmers, and around Portobello Bay and Harwood in the Lower Harbour, and in the Upper Harbour.	Within the range of natural variability. No increase in inundation of shore and low-lying areas of Portobello Road and road to Aramoana.	Low	Long-term	High	Low
	Changes to timing of tidal wave travelling into and out of the harbour will result in high tide arriving by up to 3 minutes earlier between the Harbour Entrance and Harington Bend, 3 to 4 minutes earlier at Port Chalmers and in the Upper Harbour. Similar but slightly smaller advances in the timing of low water would also occur.	Will require recalculation of tidal tables for Otago Harbour after completion of the dredging.	Low	Long-term	High	Low
	Change in speed of tidal currents will be small with mainly reductions in speed of less than 0.1m/s and will occur in the Lower Harbour, including within the deeper channel. Localised increases in average peak current of up to 0.02 to 0.05 m/s would occur off the groyne at Beacon 10 on the south side of Harington Bend and there would be decreases in peak current of up to 0.1 m/s in areas along the channel margins at Harington Bend and near Port Chalmers.	Changes are less than 6% of existing current speeds and will result in no changes to sediment transport due to tidal currents within the harbour. No noticeable effect for boating conditions.	Low	Long-term	High	Low

POTENTIAL EFFECT	POTENTIAL CONSEQUENCES	EFFECT	SIGNIFICANCE OF EFFECT			
			SEVERITY	DURATION	PROBA-BILITY	RISK
Change to tidal hydrodynamics at the Entrance Channel area.	There will be small changes to the current flows in the vicinity of the Entrance Channel after dredging with a slight enhancement of the flood-tide flows. There would also be a slight increase in the amount of time that the flows exceeded a threshold speed such that they could mobilise fine sand.	There may be less flushing of sediments on the peak flows, and preferential deposition of sediment in the dredged channel. There may be an increase in the maintenance dredging volumes and/or frequency, and an increased need for maintaining the shape and position of the side of the channel on the eastern margin.	Low	Long-term	Medium	Medium
Changes to the wave environment within the harbour and Entrance Channel.	Small increase in wave heights (less than a few cm) within the main channel, with slight reduction in wave height outside of the channel and at Shelly Beach.	Negligible effect on ship-handling, and no changes to wind waves or swell penetration shoreward of the channel towards Taiaroa Head, Pilots Beach or Te Rauone Beach.	Low	Long-term	Medium	Low
Changes to the wave environment in Blueskin Bay.	Minor focusing of waves in the lee of the disposal site with the biggest changes would be an increase in wave height of about 3 to 5% of the wave heights for the existing situation. There would be small reduction in wave heights at Aramoana Beach for waves from south across the Entrance Channel.	No persistent effects at the shoreline. No noticeable effect on surfing conditions. No change to existing patterns of beach change in response to changes in the natural wave environment. No increase in erosion or inundation hazards at the shore, and no increase in accretion.	Low	Long -term	Medium	Low
Changes to sedimentation processes.	Additional turbidity during the dredging activity.	Discolouration of water in the vicinity of the dredge, and dispersal of suspended sediment within flowing water, and settling along the harbour channel, across inter-tidal flats, within secondary channels and shallow areas. Most of the deposition of fine sediment from dispersed plumes will occur in the	Medium	Short to Medium-term	Medium/ High	Medium

POTENTIAL EFFECT	POTENTIAL CONSEQUENCES	EFFECT	SIGNIFICANCE OF EFFECT			
			SEVERITY	DURATION	PROBA-BILITY	RISK
		main channel. Currents will remobilise this sediment causing some of it to flow through the main channel system up and down the harbour, and some to consolidate into the fabric of sands on the channel bed. Turbidity resulting from transport of dredged sediment and placement at the receiving ground will be widespread but is unlikely to have an effect on the physical coastal environment				
	In the harbour, deposition of fine sediments in a layer of up to 14 mm thick over an entire 100-day dredging season could occur within the reach of Victoria Channel to Kilgours Point, within the side channel off Quarantine Point, the southern side of the central intertidal bank and adjacent shallows that separate the shipping channel from the side channel through Ohinetu Point, the sequence of central intertidal banks adjacent to the shipping channel, and the subsidiary channel from Quarantine Island through to Latham Bay. The highest median values of deposition of up to about 82 mm could occur on the intertidal sandbank opposite Port Chalmers. Channel silts would be reworked regularly by tidal currents and spread throughout the shipping channel.	Settlement of the fine sediment will occur in quiescent sections of the channel system, but much of the fine sediment will be transported out of the harbour entrance. Wind waves will remobilise sediments deposited on the intertidal sandbanks. Currents will then transport fine sediments until further dispersed to settle elsewhere within the harbour system. Preferential settlement will occur in quiescent areas where wave activity and currents are low or sporadic such as Dunedin Basin, inlets in the Upper Harbour behind the railway embankments, sheltered sub-tidal embayments (e.g., Careys Bay and the inner Port Chalmers berths), the deep basin in Portobello Bay, and in the lee of groynes or half-tide training walls.	Medium	Short to Medium-term	High	Low

POTENTIAL EFFECT	POTENTIAL CONSEQUENCES	EFFECT	SIGNIFICANCE OF EFFECT			
			SEVERITY	DURATION	PROBA-BILITY	RISK
	Fine sediments will be carried for long distances from the receiving ground, with the northern dilute edge of the suspended sediment plume reaching areas north of Karitane, and the southwestern dilute edge of the plume occasionally reaching coastal areas between Taiaroa Head and Wickcliffe Bay.	This fine sediment is unlikely to settle on beaches and rocky coastal areas, as it will be readily remobilised by wave action, wind and tidal currents in the nearshore.	Low	Short to Medium term	High	Low
	The deposited sand at the disposal site will result in a mound being built on the seabed, and this mound will intercept and transfer sand moving on the seabed.	The wave and current energy at the disposal site is not sufficient to cause mass movement of the deposited sand away from the site.	Low	Long-term	High	Low
	Sand-sized sediment from the disposal site will move slowly and predominantly to the north. However it would be masked by the existing sediment transport from south of Otago Peninsula to the north.	Sand is unlikely to reach the shores of Blueskin Bay, and will not move south and be intercepted by the Entrance Channel.	Low	Long-term	Low	Low
	The channel margins will be stable, but the deeper channel across the ebb-tide delta is likely to result in additional capture of sand in the Entrance Channel.	This will possibly result in an increase of dredging demand seaward of Harington Bend. It is unlikely that the total maintenance dredging demand will increase.	Low	Medium to Long-term	High	Low

7. References

Andrews PB (1973): Late Quaternary continental shelf sediments of Otago Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics* 16 (4): 793 -830.

Andrews PB (1976): Sediment transport on the continental shelf, east of Otago – a reinterpretation of so-called relict features: Comment. *New Zealand Journal of Geology and Geophysics* 19 (4): 527-531.

Baird V (1997): Trace metals in some marine sediments. MSc thesis (Chemistry, Otago University). 100p.

Bardsley WE (1977): Dispersal of some heavy minerals along the Otago-Eastern Southland Coast. *New Zealand Geographer* 33 (2): 76-79.

Barn`ett AG, Victory SJ, Bell RG, Singleton AL (1988): Otago Harbour hydrodynamic model study. Report to Otago Harbour Board. Barnett Consultants Ltd. 152p.

Bell RG, Hart C (2008): Offshore ADCP deployments (Otago Peninsula) for Port of Otago dredging project. NIWA Client Report HAM2008-178 prepared for Port Otago Ltd, 75 p.

Bell RG, Oldman JW, Beamsley B, Green MO, Pritchard M, Johnson D, McComb P, Hancock N, Grant D, Zyngfogel R (2009): Port of Otago dredging project: Harbour and offshore modelling. NIWA Client Report HAM2008-179 prepared for Port Otago Ltd, 349 p.

Bell J (2007): Te Rauone Coastal Erosion Hazard. Report to Engineering and Hazards Committee. ORC, File: EN7005, May 2007.

Benn J, Single MB (2007): Annotated bibliography: Coastal and continental shelf processes of Otago Harbour and Blueskin Bay. Report for Port Otago Ltd. Shore Processes and Management Ltd, November 2007, 52 p.

Bunting K; Single MB; Kirk RM (2003a): Sediment transport pathways around Otago Harbour and north to Karitane Peninsula. Report for Port Otago Ltd. Land and Water International Ltd. 75p.

Bunting K, Single MB, Kirk RM (2003b): Effects of dredge spoil at Shelly Beach, Otago Harbour. Report for Port Otago Ltd. Land and Water International Ltd. 31p.

Carter L (1986): A budget for modern-Holocene sediment on the South Otago continental shelf. *New Zealand Journal of Marine and Freshwater Research* 20: 665-676.

Carter L, Carter RM (1986): Holocene evolution of the nearshore sand wedge, South Otago continental shelf, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 29: 413-424.

Carter L, Heath RA (1975): Role of mean circulation, tides, and waves in the transport of bottom sediment on the New Zealand continental shelf. *New Zealand Journal of Marine and Freshwater Research 9* (4): 423-448.

CIRIA (2000): Scoping the assessment of sediment plumes from dredging. *Eds.* John, S.A.; Challinor, S.L.; Simpson, M.; Burt, T.N.; Spearman, J. Construction Industry Research and Information Association (CIRIA) Report C547, London, UK. 188 p.

Cournane S (1992): Seismic and oceanographical aspects of Lower Otago Harbour. MSc thesis (Marine Science, Otago University). 216p.

Davis RM (2008): Short History of Otago Harbour Development and Dredging. Report to Port Otago Ltd. Duffill Watts Ltd, July 2009. 23p plus Appendices.

Elliot EL (1958): Sandspits of the Otago Coast. *New Zealand Geographer* 14: 65-74.

EnviCom Working Group 10 (2006): Environmental risk assessment of dredging and disposal operations. EnviCom report 10 – October 2006, PIANC.

EnviCom Working Group 100 (2009): Dredging management practices for the environment – a structured selection approach. EnviCom report 100 – January 2009, PIANC.

EnviCom Working Group 104 (2009): Dredged material as a resource. EnviCom report 104 – January 2009, PIANC.

Goring D (2007): Waves and Currents in Te Rauone Bay. Report to Otago Regional Council. Mulgor Consulting Ltd, Client Report 2007/1, April 2007.

Hewson PA (1977): Coastal Erosion and beach dynamics in South Canterbury – North Otago. Unpublished M.A> Thesis, University of Canterbury, 185p.

Hodgson WA (1966): Coastal processes around the Otago Peninsula. *New Zealand Journal of Geology and Geophysics* 9 (1/2): 76-90.

James M, Probert K, Boyd R, John A (2007): Summary of existing ecological information and scoping of further assessments for Port Otago dredging project. NIWA Client Report HAM2007-156, Project POL08201. 58 p.

James M, Probert K, Boyd R, Sagar P (2008): Biological resources of Otago Harbour and offshore: assessment of effects of proposed dredging by Port Otago Ltd. NIWA Client Report HAM2008-152 prepared for Port Otago Ltd.

Johnstone N (1997): Consequences of breaching of Aramoana Spit sand dunes. Unpublished memorandum to the Otago Regional Council. 4p plus appendices.

Kirk RM (1980): Sand transport processes at the entrance to Otago Harbour: Report to the Engineer's Department, Otago Harbour Board. 57p.

Lauder GA (1991): Otago Harbour: Coastal Inlet and Shoreline Processes**.** Report to the Physical Systems and Ecosystems Working Group of the Otago Harbour Planning Study. Department of Conservation, Southland. 20p.

Lusseau D (1999): Port Otago Ltd. Dredge spoil relocation: A literature review. Report for Port Otago Ltd. Zoology Department, Otago University. 38p.

Leon JP (2005a): Coastal evolution of Shelly Beach, Otago Harbour: A composite approach to examining the morphodynamic behaviour of a human-modified sand spit. MSc Thesis (Geography, Canterbury University). 216p.

Leon JP (2005b): Changes in seabed elevation of dredge spoil sites at Heyward Point, Aramoana and Shelly Beach Otago Harbour. Report to Port Otago Ltd. Geography Department, Canterbury University. 26p plus appendices.

Lockerbie L (1959): Anthropology in the South Seas, New Plymouth: 75.

McLintock AH (1951): The Port of Otago. Whitcombe & Tombs Limited: Dunedin. 428p

Murdoch RC, Proctor R, Jillet JB, Zeldis JR (1990): Evidence for an eddy over the continental shelf in the downstream lee of Otago Peninsula, New Zealand. *Estuarine, Coastal and Shelf Science* 30: 489-507.

Nicholson DC (1979): Sand beaches in southern Blueskin Bay. MA thesis (Geography, Canterbury University). 185p.

Old CP (1998): Otago Harbour tidal jet and channel flow. Report for Port Otago Ltd. Marine Science Department, Otago University. 80p.

Old CP (1999): The structure and dynamics of an ebb tidal jet. PhD thesis (Marine Science, Otago University). 277p.

Old CP, Vennell R (2001): Acoustic Doppler current profiler measurements of the velocity field of an ebb tidal jet. *Journal of Geophysical Research – Oceans:* 106 (C4): 7037 - 7049.

Oldman, J.W.; Bell, R.G.; Stephens, S.A. (2008): Port of Otago dredging project. NIWA: Preliminary hydrodynamic modelling and scoping further work. NIWA Client Report HAM2007-152 prepared for Port Otago Ltd. 55 p.

Opus International Consultants (2008): Factual report of geotechnical investigations: Port Otago–Project Next Generation. Opus International Consultants Ltd client report #1230, prepared by Shane Greene for Port Otago Ltd. August 2008. 9 p. + appendices.

Opus International Consultants (2009): *Geotechnical Advice "Next Generation" Project – Interpretation of Geotechnical Data and Quantity Survey.* OPUS International Consultants, prepared by Markus Hanz, September 2009, 2p + appendices.

Pattle WN (1974): Coastal Processes and beach development – Cape Wanbrow to Shag Point. Christchurch. Unpublished M.A. Thesis, University of Canterbury.

Purdie J, Smith AM (1994): Heavy metals and hydrocarbons in Otago Harbour sediments. Report to Otago Regional Council. Department of Marine Science, Otago University. 51p.

Port Otago (2004): Te Rauone Beach Erosion. Internal report, Ocober 2004. 11p plus drawings

Pullar A, Hughes S (2009): Project Next Generation: Dredging Methodology and Disposal Aleternatives. 53p.

Quinn J (1979): Report on further studies on the hydrology of Otago Harbour. Report to Otago Harbour Board. Marine Science Department, Otago University. 6p plus figures.

Ramsay D (2006): Review of erosion at Te Rauone Beach (Otago Harbour). Report prepared for Otago Regional Council. NIWA Client Report HAM2005-024, January 2006.

Royds Garden Ltd (1990): Environmental impact assessment: Dredging and dredge spoil relocation; Port Otago. 43p.

Sanford South Island Ltd (2001): Brinns Point Marine Farm – Resource consent Applications and Assessments of Environmental Effects. Unpublished report.

Scott GL, Landis CA (1975): Ecology of Aramoana: Geological development of Aramoana. Report to Dunedin Metropolitan Regional Planning Authority. Geology Department, Otago University. 23p.

Single MB (2007): Te Rauone Beach coastal resource management. Unpublished report to Port Otago Ltd and Otago Regional Council.

Single MB, Benn J (2007): Port Otago project next generation summary of existing physical coastal environment information and scoping for further studies. Port Otago Ltd. 65 p

Single MB, Kirk RM (1994): Impact of dredge spoil discharge at the entrance to Otago Harbour – sand transport processes. Report for Port Otago Ltd. Land and Water Studies International Ltd. 35p.

Single MB, Pullar A (2009): Vessel effects as a result of a deeper channel in the Lower Otago Harbour .Shore Processes and Management Ltd, Dec 2009. 30p.

Single MB, Stephenson WJ (1998): South Spit Beach assessment of erosion mitigation. Report for Port Otago Ltd. Land and Water Studies International Ltd. 10p.

Skinner HD (1953): Stratification at Long Beach, Otago. Journal of Polynesian Society, 62(4): 400-402

Skinner HD (1959): Murdering Beach: collecting and excavating: the first phase: 1850 – 1950. Journal of Polynesian Society, 68(3), 219 – 235.

Stevenson M (1998): An investigation into sediment of the upper harbour basin and Andersons Bay inlet. Otago Regional Council. 137p.

Thomson P (1870): On the sand hills, or dunes, in the neighbourhood of Dunedin. Read before the Otago Institute, May 31 1870.

Todd D (2002): Dunedin City Council Coastal Dune Conservation Works Programmes. Report prepared for Dunedin City Council. DTec Consulting Ltd, Client Ref: 1051.122DCC, July 2002.

Tonkin and Taylor (1998): Dunedin City Council Coastal Dune Investigations: Te Rauone Reserve. Report prepared for City Consultants. Tonkin and Taylor Reef: 50214, July 1998.

Williams JJ (1979): Quaternary Sedimentation of the North Taieri Bight, Otago Continental Shelf. Unpublished thesis, University of Otago, Dunedin. 111p

Willis TJ, Bradley A, Handley SJ, Paavo B, Page MJ, James M (2008): Benthic offshore surveys of proposed dredge spoil disposal sites off Otago Peninsula. NIWA Client Report NEL2008-024, Project POL08401. 53 p.

Wilson G (1989): A two dimensional numerical model of Otago Harbour. ME thesis (Canterbury University, Civil Engineering). 176p.