7

EFFECTS ON COASTAL PROCESSES

REPORT

Tonkin+Taylor

LPC Channel Deepening Project

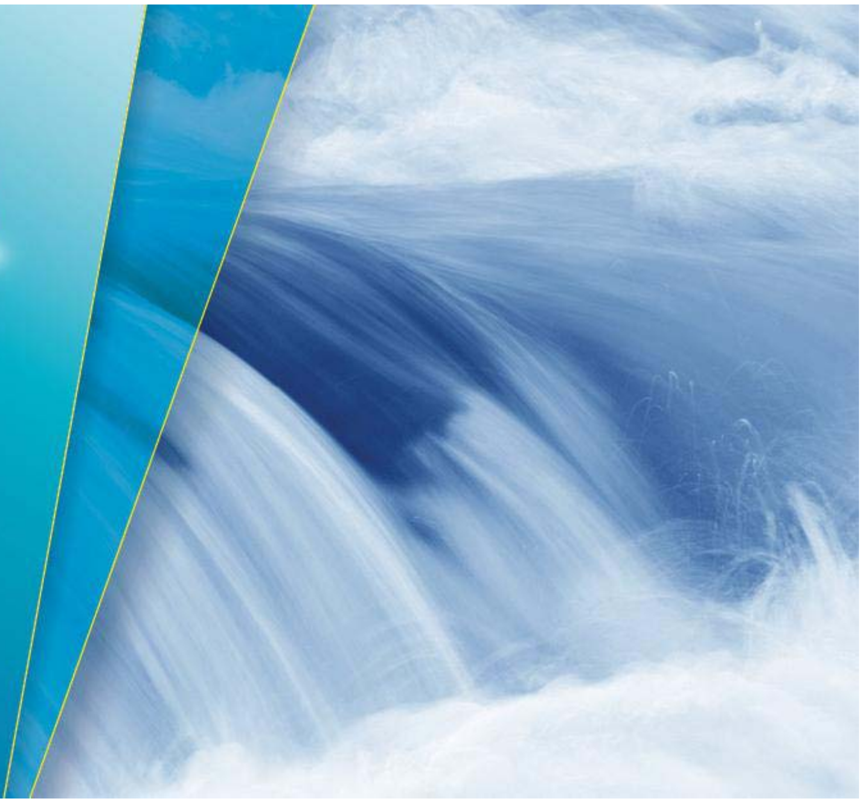
Review and summary of coastal process effects

Prepared for
Lyttelton Port Company

Prepared by
Tonkin & Taylor Ltd

Date
September 2016

Job Number
31791.v2



Exceptional thinking together

www.tonkintaylor.co.nz

Distribution:

Lyttelton Port Company	PDF
Tonkin & Taylor Ltd (FILE)	1 copy

Table of contents

Executive summary

Lyttelton Port of Christchurch (LPC) intends to deepen and extend its existing navigation channel to accommodate all tide access with vessels of a 14.5 m draught as well as deepening the swing basin, associated berths and entrance to the Inner Harbour. Up to 18M m^3 of capital dredged material will be deposited at an offshore disposal site located some 6 km off Godley Head in 20 m water depth. Ongoing maintenance dredging of some 0.9M m^3 per annum will be disposed of at the existing consented maintenance spoil disposal grounds within the harbour and/or to an offshore spoil deposition ground 3 km off Godley Head in 17-18 m water depth.

Several technical reports have been commissioned by LPC to investigate the effects of the dredging on wave, current and sediment transport processes. Tonkin & Taylor Ltd. was engaged to review these report and to evaluate whether and how both the capital and maintenance dredging will alter coastal process, specifically with reference to potential changes in shorelines position and composition and to provide recommendations for the types and locations of coastal monitoring to assist in identifying physical changes.

The principal drivers of coastal processes include waves, currents and water levels, all of which affect the location and magnitude of sediment transport. These drivers, combined with the characteristics and availability of sediment, determine form or morphology of a shoreline, its location, and its material composition. Changes in shoreline characteristics are therefore dependent on changes in the drivers or in the sediment budget.

The proposed physical works are likely to result in changes in the wave climate at the shoreline, most significantly within Lyttelton Harbour adjacent to the deepened navigation channel, but also to a lesser degree along the open coast shoreline in the lee of the capital and maintenance disposal mounds. Deepening of the channel is also likely to result in a modified tidal regime within Lyttelton Harbour. These changes are generally less than 5-10% of peak tidal flows and limited to the channels.

Modelling results indicate that suspended sediment plumes generated during dredging of the navigation channel tend to be contained within the dredged channel and do not appear to reach the shoreline. Likewise, plumes generated during offshore disposal tend to be contained at high concentrations within 500-1000 m of the disposal sites, although some particles deposited at the maintenance site may reach the entrance to Lyttelton and Port Levy. It should be noted that once dredge plume sediments have settled, they are likely to be re-entrained by waves along with existing fine seabed sediments and transported further afield.

Simulations of long-term sediment transport has shown the dredge mounds to erode, with rates being highly dependent on the assumed erosion parameter. Sediment accumulations tend to be relatively well distributed around the disposal sites with a slight skew to the west, in accordance with the predominant wave direction. Some material from the maintenance disposal site appears to migrate back into the navigation channel and into Lyttelton Harbour. Over time, the fine dredge spoil will mix with the existing 'fluid mud' layer on the seafloor and continue to be transported around Pegasus Bay. As the placed volume (18M m^3) is relatively small compared to the existing mobile mud layer within Southern Pegasus Bay (<10% of a 0.5 m thick layer spread over a 400 km^2 area), the effects of this additional sediment are unlikely to be significant.

The existing sediment sinks within Lyttelton Harbour; the navigation channel and berthing pocket, are augmented by deepening. Previously materials removed from these sinks were placed adjacent to the channel and would partially migrate back, infilling the channel and berthing pocket. As the capital and some of the maintenance dredge material is to be removed from the system to offshore disposal sites, sediment refilling the navigation channel will still occur, but from sediment in the surrounding seabed.

Effects on open coast beaches

The ***morphology*** of open coast beaches are unlikely to be modified as changes in the wave climate between New Brighton and Taylors Mistake resulting from the temporary capital dredge mound and more permanent maintenance mound are relatively minor (2-3%) and, in the case of the capital dredge mound, the changes to the wave climate will decrease over time as the spoil mound erodes.

The ***location*** of open coast beaches unlikely to be affected as the sediment regime relevant to sand beaches remains unchanged. While additional material will be added into Pegasus Bay, the fine nature of that material means that it is not compatible with the open coast beach sands and therefore will not affect the sediment budget.

The ***composition*** of the open coast beaches is unlikely to be affected as fine sediments such as the dredge spoil material will not able to settle on the higher energy environments. Seabed velocities are sufficient to prohibit settling of fine sediment here and/or would rapidly re-entrain any fine sediment on the seabed. Fine sediment would be winnowed (preferentially removed) offshore to depths where velocities allow settling. Such processes have been occurring naturally from millennia as widely graded materials from the Waimakariri River and other sources reach the coast.

Effects on harbour shoreline

The ***composition*** of the harbour shorelines within Lyttelton and Port Levy are unlikely to be affected as modelling shows that suspended sediment plumes unlikely to reach harbour shorelines. Materials re-entrained during subsequent motion are also unlikely to reach harbour shorelines as the dominant sediment transport pathway is from shallow waters, where fines are initially deposited from land sources, into deeper water.

The augmentation of the sediment sink within Lyttelton Harbour due to capital dredging has the potential to cause erosion of the surrounding seabed as this material moves to infill the deeper and wider channel. Furthermore, ongoing removal of sediment during maintenance dredging and disposal offshore would result in ongoing removal of sediment from the system (up to 31.5M m^3 over a 35 year consent term). The majority of the sediment that would infill the channel would likely be derived from the immediately adjacent seabed but, given the very flat seabed gradients (~1:1000) that exist within Lyttelton Harbour, this demand may extend further afield. It is unclear how quickly this erosion occur or to what extents but this volume equates to a 2.2 m sediment depth in the outer harbour east of Diamond Harbour. Similar erosion of the harbour seabed was reported by Curtis (1986) following initial dredging works in the mid to late 19th Century and seabed levels should therefore be monitored to detect any changes during ongoing maintenance dredging.

The harbour shorelines are typically steep and rocky and therefore unlikely to be significantly affected in ***morphology*** or ***location*** as a result in the change in wave climate or offshore seabed levels, but monitoring of the shoreline position and form would be prudent to confirm this. However, the maintenance regime could and should be modified if significant effects were detected.

Physical shoreline monitoring

Physical shoreline monitoring provides a record of changes in shoreline location, morphology or composition to allow comparison with a baseline and determination of any changes which could be related to the capital dredge project. Photo-point monitoring, sediment size analysis, beach profile survey and analysis of shoreline positions are recommended within monitoring locations at 15 locations along the open coast and within Lyttelton Harbour and Port Levy.

1 Introduction

Lyttelton Port of Christchurch (LPC) has an existing navigation channel, ship-turning basin and berth areas that need to be regularly dredged. The current navigation channel is approximately 12.2 m below Chart Datum (CD) which enables up to 12.4 m draught vessels to enter or leave the port at high tide.

In order to accommodate all tide access with vessels of a 14.5 m draught, the existing navigation channel needs to be both deepened and extended approximately 4 km beyond the harbour heads. In addition to the deepening of the main channel, the swing basin, associated berths and entrance to the Inner Harbour also need to be deepened and widened. Dredged material is to be deposited at an offshore disposal site.

1.1 Proposed works

The Channel Deepening project has four main components (refer Figure 1-1):

- Deepening of the main navigational channel and swing basin is to provide safe passage during all tides for a 14.5 m draught vessel
- Deepening of the berth pockets at Cashin Quay
- Reclamation to create the proposed container terminal at Te Awaparahi Bay
- Disposal of all capital and maintenance dredging to offshore disposal grounds.

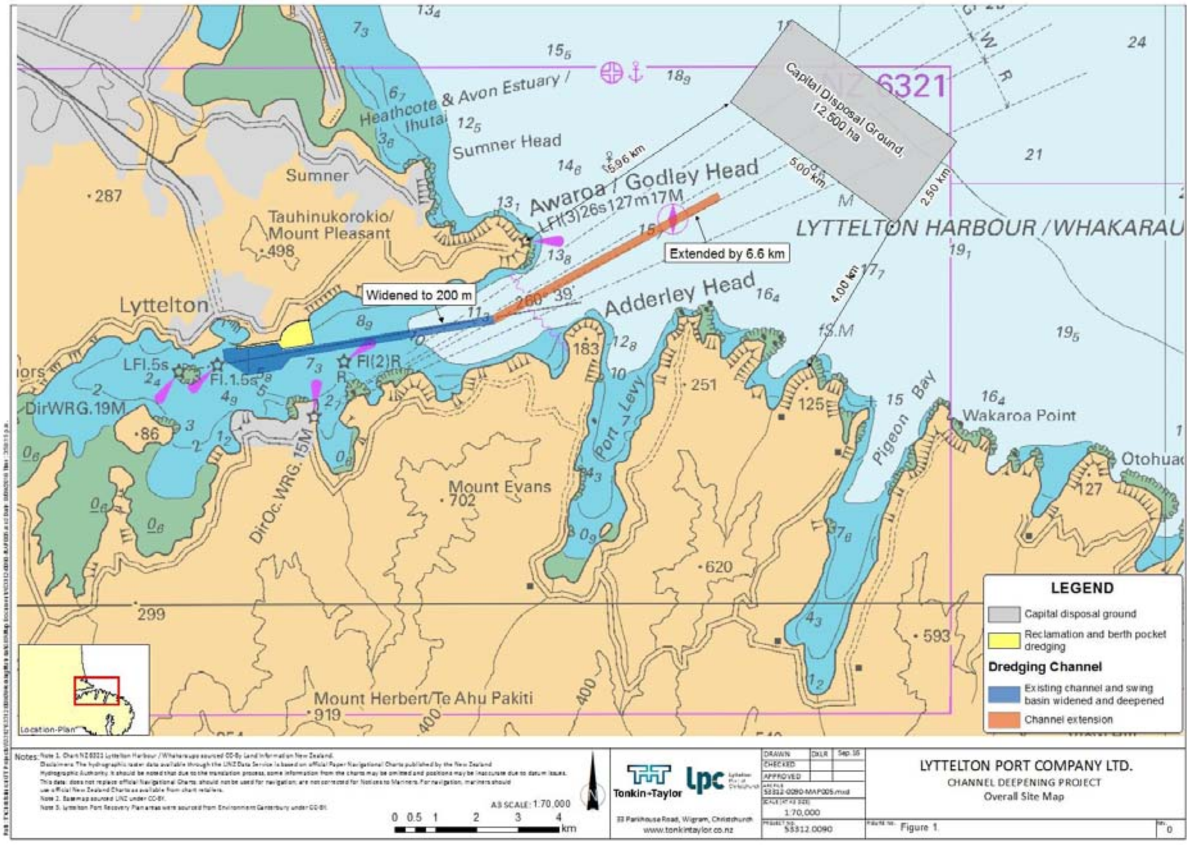


Figure 1-1 Summary of major works within the proposed Capital Dredging Project (source: LPC, 2016)

The capital dredged material is proposed to be deposited at a 2.5 x 5.0 km offshore spoil ground. This is to be located some 6 kilometres from Godley Head and 4 kilometres from Baleine Point, at an average depth of approximately twenty metres below CD. Approximately 18 million cubic metres of material will need to be dredged of in order to complete the channel, swing basin, reclamation and berth deepening. The deepening to serve a 14.5 m draught ship will occur in at least two stages over a number of years.

Ongoing maintenance dredge spoil from the proposed channel, the ship-turning basin and berth pockets is proposed to be deposited:

- to the existing 36 Ha consented maintenance spoil disposal grounds within the harbour (most likely at Godley Head), and/or,
- to a new 1.6 x 1.6 km spoil deposition ground offshore of Godley Head (Figure 1-2).

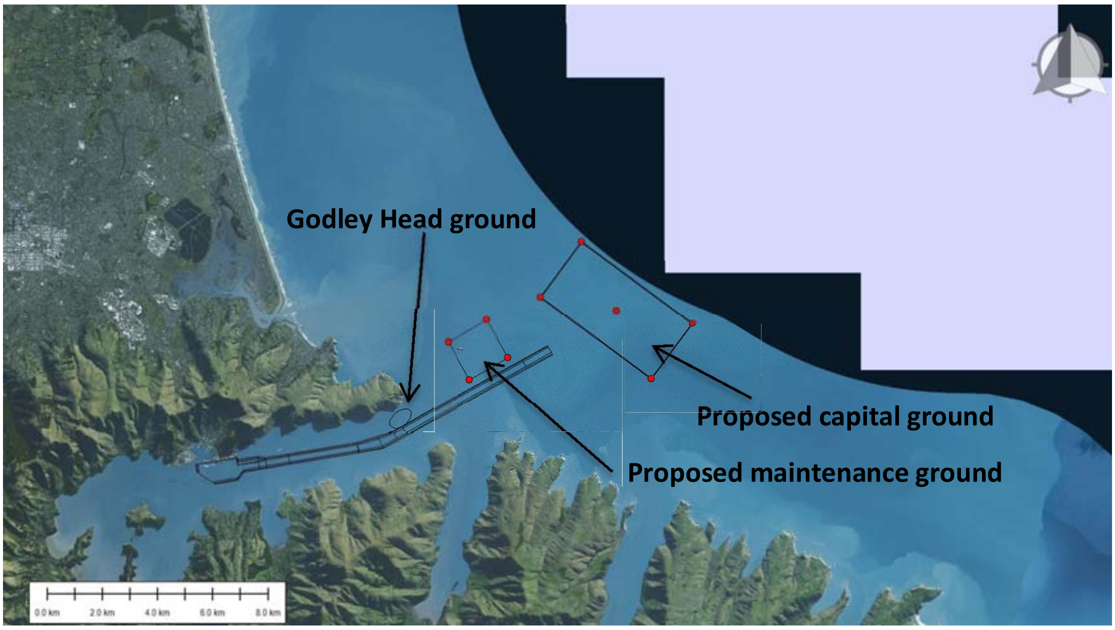


Figure 1-2 Proposed offshore disposal sites for capital and maintenance spoil disposal (Metocean, 2016e)

1.2 Assessment scope

The scope of works for this assessment is to:

1. Undertake a literature review on the current understanding of the offshore and coastal processes operating in Pegasus Bay and the harbours on the northern side of Banks Peninsula, particularly focusing on offshore sediment supply and the interaction with the littoral (i.e. shoreline) system.
2. Review of the following technical reports commissioned by LPC for this project:
    - MetOcean (2014) Pegasus Bay ROMS Hindcast: Validation Report. Report P0201-04, Version Rev C 13/03/2014
    - MetOcean (2016a) Lyttelton Port Company Channel Deepening Project - Simulations of Dredge Plumes from Dredging Activities in the Channel. Report P0201-03, Rev E 07/06/2016
    - MetOcean (2016b) Lyttelton Port Company Channel Deepening Project - Simulations of suspended sediment plumes and associated deposition from offshore disposal. Report P0201-02, Rev F 20/05/2016
    - MetOcean (2016c) Lyttelton Port Company Channel Deepening Project - Numerical modelling of sediment dynamics for a proposed offshore capital disposal ground. Report P0201-01, Rev E 19/05/2016

- MetOcean (2016d) Lyttelton Port Company Channel Deepening Project - Simulations of suspended sediment plumes generated from the deposition of spoil at proposed maintenance disposal grounds. Report P0201-06, Rev B 08/08/2016
- MetOcean (2016e) Lyttelton Port Company Channel Deepening Project - Numerical modelling of sediment dynamics at proposed offshore maintenance disposal ground. Report P0201-04, Rev C 08/08/2016
- Goring, D. (2016) Effects of Development Stages 2 and 3 on Waves and Tidal Currents in Lyttelton Harbour. Report prepared by Mulgor Consulting Ltd. for LPC. Client Report 2016/2, February 2016
- OCEL (2016) Deepening and extension of the Navigation Channel - Capital Dredging Report. Report prepared for Lyttelton Port Company, July 2016.

3 Evaluate whether and how the *Capital Dredge Project* will alter coastal process, specifically with reference to potential changes in shorelines position and composition. This assessment involves interpretation of existing information and no additional analysis or studies.

4 Evaluate whether and how the *Maintenance Dredging* will alter coastal process, specifically with reference to potential changes in shorelines position and composition. This assessment involves interpretation of existing information and no additional analysis or studies.

5 Prepare of a report detailing the above (this report).

6 Recommend locations and type of coastal monitoring to assist in identifying physical changes.

2 Existing coastal processes in Pegasus Bay

Existing coastal processes operating within Pegasus Bay have been reasonably well described by studies dating back to the 1960s, particularly through the University of Canterbury, NIWA, Environment Canterbury, Lyttelton Port of Christchurch (and formally the Lyttelton Harbour Board) and more recently by Christchurch City Council.

Seminal works which have reviewed and consolidated knowledge of Pegasus Bay coastal and shoreline processes include:

- Kirk (1979) who undertook a review of the dynamics and management of sand beaches in Southern Pegasus Bay
- Allan et al. (1999) who reviewed Coastal Processes in Southern Pegasus Bay to inform the effects assessment for the Christchurch City Council Ocean Outfall Pipeline
- Hart (2004) who reviewed Sedimentation in the upper Lyttelton Harbour for Environment Canterbury.

These studies are supplemented by the recent fieldwork campaigns (OCEL, 2016) and numerical studies (MetOcean, 2014, 2016a-e; Goring 2016) undertaken to inform the present capital dredging project. This review draws on these works to summarise existing coastal processes operating in Southern Pegasus Bay and particularly processes affecting shoreline position, form and composition.

2.1 Geological context

The geology of the southern Pegasus Bay area is a result of tectonics, glacial and interglacial erosion and localised volcanism. The entire area is underlain by 200 million year old basement sedimentary rock which have been thrust up in the east by tectonic movement forming the Southern Alps (Forsyth et al., 2008). Over time, rivers have cut gorges through these ranges and transported significant volumes of eroded materials east to form the Canterbury Plains (Figure 2-2). The coastal margin has fluctuated with successive glacial periods and sea level fluctuations of up to 120 m. The beaches of southern Pegasus Bay have formed over the last 6,000 years under relatively stable sea levels. These beaches comprise fine sands with substantial inland dune fields in the north and have enclosed the Avon-Heathcote estuary in the south.

Banks Peninsula was formed by two large, overlapping volcanoes; Lyttelton and Akaroa. These Miocene aged (8-10 million year old) volcanoes have been eroded by river systems which, as sea levels stabilised, have been drowned to form the present Akaroa and Lyttelton Harbours (Figure 2-1) and the Peninsula Bays including Sumner and Taylors Mistake on its northwest flank. Lyttelton Harbour and Port Levy are rock walled inlets with relatively flat and shallow seabeds due to ongoing infilling by fine, sediment eroded from the steep adjacent hill slopes (refer Section 2.5).

Figure 2-1 Lyttelton Harbour was formed as river valleys were drowned as sea levels rose (Forsyth et al., 2008)

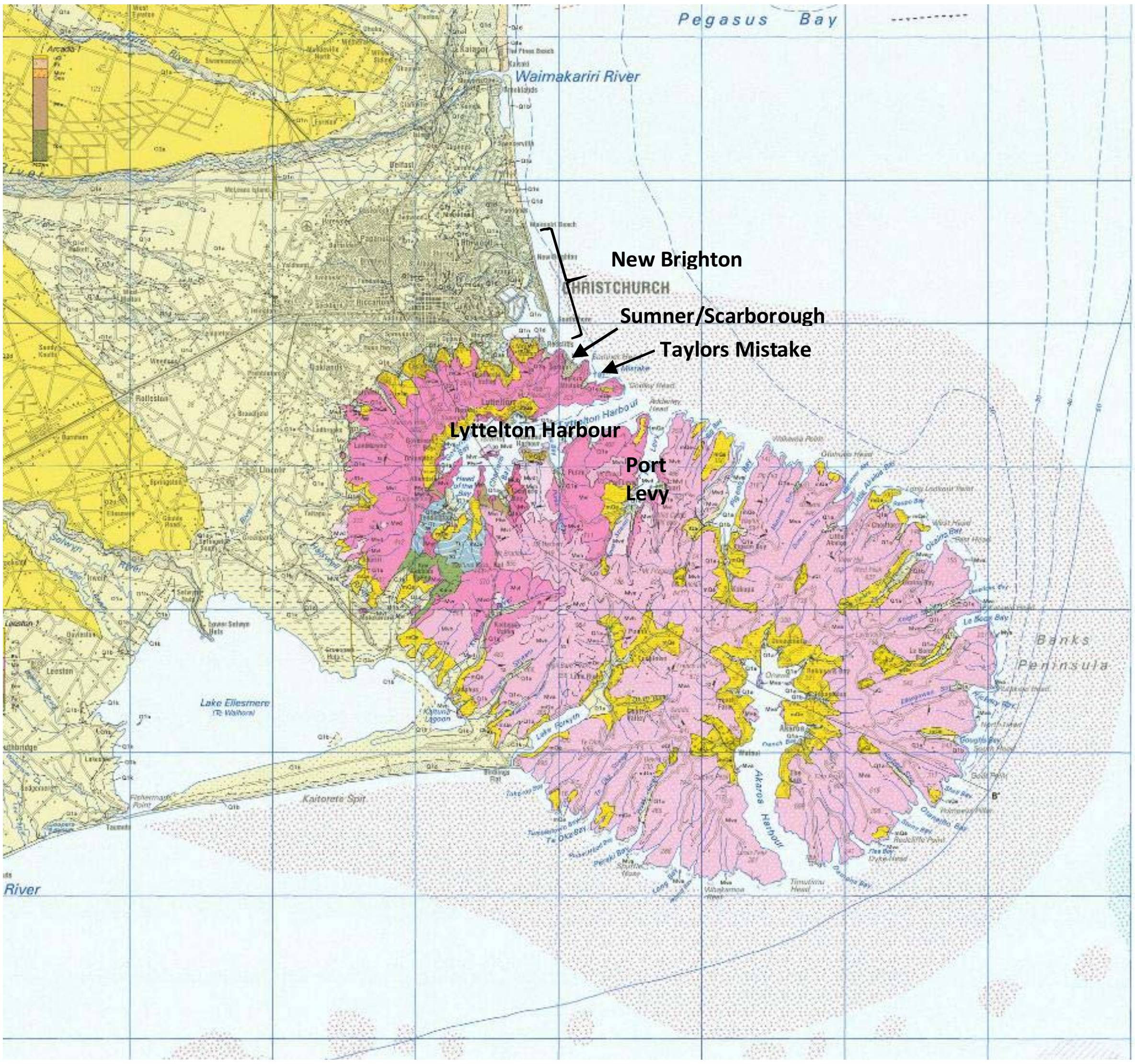


Figure 2-2 Extract from Christchurch 1:200,000 Geological Map (Forsyth et al., 2008)

2.2 Water levels

Tides off Canterbury are semi-diurnal with two similar tides occurring daily. Tidal range within Lyttelton Harbour is reported at between 1.35 and 2.35 m for neap and spring tide respectively (LINZ, 2016) with a highest astronomical tidal level of 2.7 m above CD. Tidal range at Sumner Head is slightly smaller, likely owing to the open coast. Tides vary on a monthly cycle with the apogee-perigee moon phase (Goring, 1991).

Storm surge results from the combination of barometric setup from low atmospheric pressure and wind stress from winds blowing along or onshore which elevates the water level above the predicted tide. The combined elevation of the predicted tide and storm surge is known as the storm tide. The 1% Annual Exceedance Probability (AEP) storm tide predicted by Goring et al. (2009) for Lyttelton Harbour is 3.07 m above CD or approximately 1.7 m above current mean sea level.

Long-term trends of historic sea level rise in New Zealand has averaged 1.7 ± 0.1 mm/year with Christchurch exhibiting a slightly higher rate of 1.9 ± 0.6 mm/year (Hannah and Bell, 2012). This higher rate may be related to subsidence of the braidplain at rates of up to 0.2 mm/year (Forsyth et al., 2008).

2.3 Waves

The wave climate offshore of Pegasus Bay consists of predominant southerly swell conditions mixed with less frequent wave events from the southeast and northeast quarters (Figure 2-3; MetOcean, 2016c). The most northerly events are generally locally generated with lower wave periods, but can still be relatively energetic in terms of wave heights (i.e. up to 3.5 m and more). Closer to shore (i.e. at the proposed disposal grounds), Banks Peninsula blocks most of the southerly wave energy with only refracted waves of substantially reduced height reaching the nearshore area (Figure 2-3). Large waves can still occur from the east to northeast however with a 100 year return period height of around 6m determined by Tonkin + Taylor (1998).

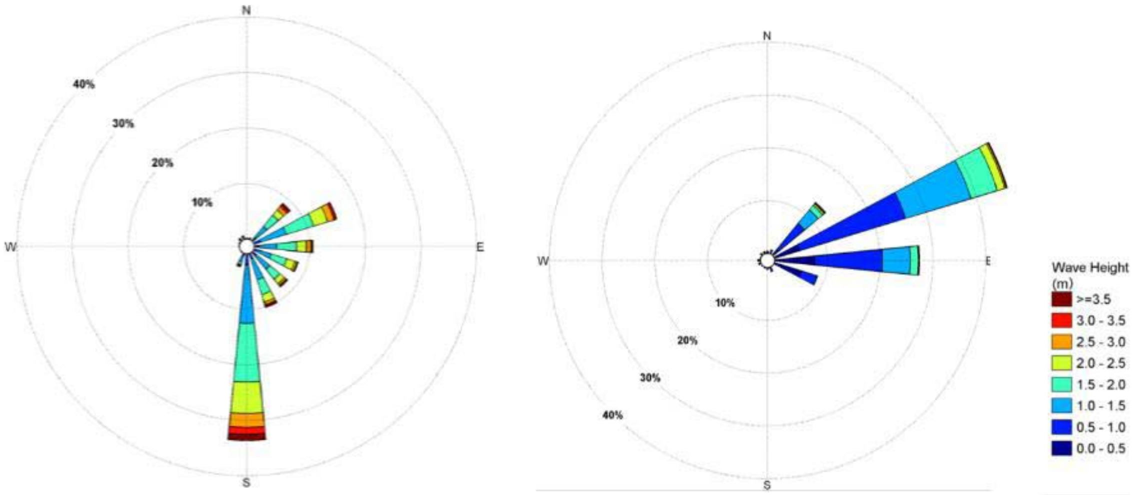


Figure 2-3 Wave roses derived from 10 year wave hindcast offshore of Banks Peninsula (left) and offshore of Godley Head (right) source: MetOcean (2016c)

Within Lyttelton Harbour and Port Levy, waves can either penetrate into the harbours from Pegasus Bay, or be generated locally within the harbour. Mulgor (2016) presents plots showing wave penetration into the harbour (Figure 2-4 and Figure 2-5). These show a relatively rapid decrease in elevation with distance from the harbour entrance, particularly for shorter period 'sea' waves. After 6 km, wave height is reduced to 10 to 25% of height at the entrance. Figure 2-4 also shows the effect of the navigation channel focussing wave energy towards the shore on either side further reducing the extent of wave penetration.

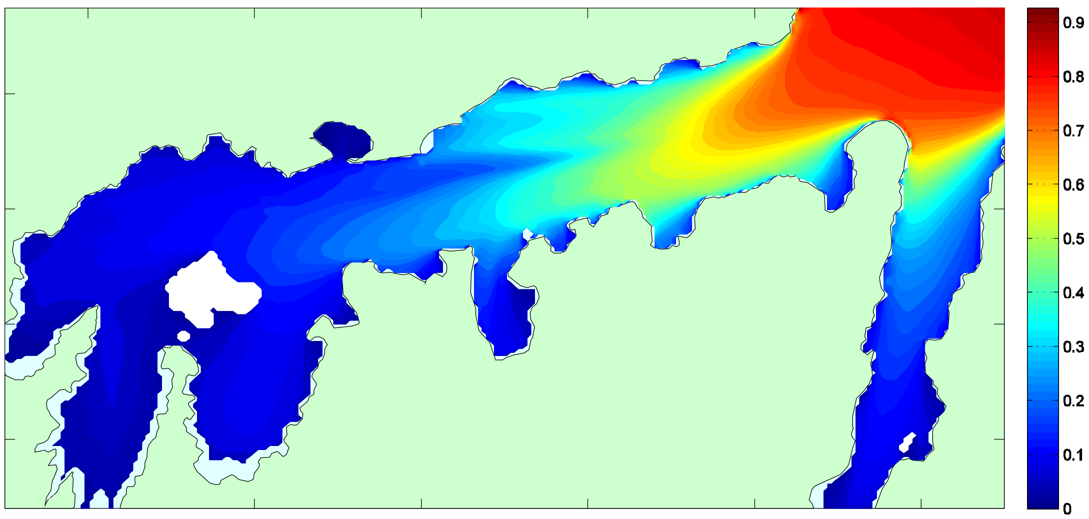


Figure 2-4 Distribution of mean significant wave height in Lyttelton Harbour and Port Levy (Mulgor, 2016)

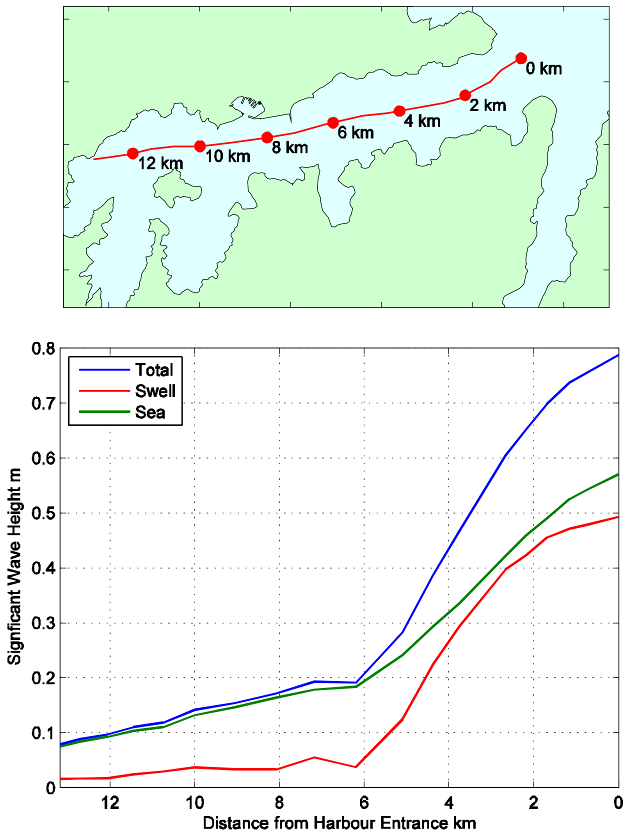


Figure 2-5 Transformation of typical sea and swell waves within Lyttelton Harbour (Mulgor, 2016)

Waves are also generated locally within the harbour as winds flow across the surface. The largest waves are generated as winds blow across the longest fetch which for Lyttelton is WSW and ENE. In parts of the harbour sheltered from swell, these waves typically dominate the energy spectrum. Wave heights in shallow bays will be significantly affected by tidal levels with depth-limited breaking at low water levels limiting the wave heights possible.

2.4 Currents

Tidal currents within Pegasus Bay setup from the south, moving northwards during the flood tide and southwards during the ebb (Goring, 1991). Current speeds offshore of Lyttelton Harbour are orientated in an ESE-WNW direction with a mean current speed of 0.1 m/s (Goring, 2009). Currents along New Brighton beach are predominantly North-South. The principal non-tidal current operating along the Canterbury coast is the Southland Current which flows northward along the east coast of the South Island but then forms a prominent reversed eddy north of Banks Peninsula which flows from north to south (Allan et al., 1999). While non-tidal residual current is usually small (<0.02m/s offshore of Lyttelton Harbour), higher currents up to 0.1 m/s directed towards the ESE can occur periodically for a day or two (Goring, 2009). This residual current is more effective at transporting sediment than tides as it is in unidirectional, rather than cyclic.

Within Lyttelton Harbour the flood tide moves water into the harbour and the ebb tide drains water out. Tidal currents are generally consistent with this, although a tidal imbalance has been noted with the ebb tide dominating the flood tide along the northern side of the harbour and the flood dominating on the south side of the harbour resulting in a slight 'clockwise' circulation. Tidal currents tend to be higher in centre of the harbour (up to 0.4 m/s; Figure 2-6) and lower within the shallow bays in either side (MetOcean, 2016a).

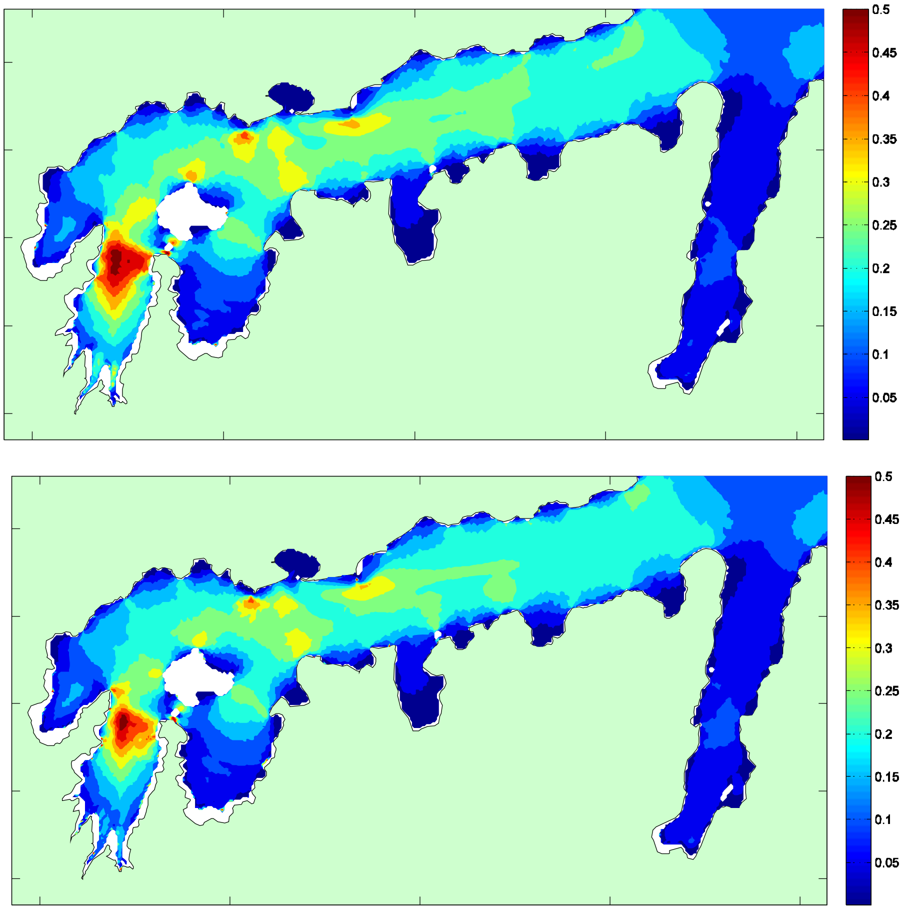


Figure 2-6 Tidal velocities (m/s) during flood (upper) and ebb (lower) tides (MetOcean, 2016a)

Waves also generate currents as they pass through water. The currents are orbital, generally returning to close to their initial position as the wave passes. The currents reduce with depth below the surface. At a certain depth, the current can reach the seabed, moving water in a forward and back motion. This depth is dependent on the wave length, with longer period waves interacting with deeper water, and on the height with higher waves inducing higher orbital velocities.

As waves move towards shore they 'feel the seabed' and shoal, increasing in height, decreasing in wavelength (distance between crests) and reducing in speed. Velocities on the seafloor increase and larger sediments can be stirred into suspension. Eventually the waves break and move into the surf zone as turbulent bores. This movement of water induces rip currents which move water back out to sea or, if waves approach from an angle, along the shore.

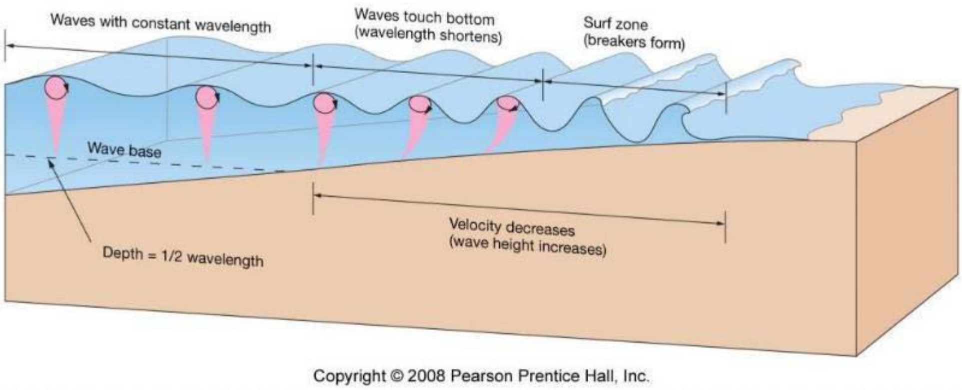


Figure 2-7 Diagram showing orbital velocities beneath a wave and interaction with the seabed

2.5 Sediments

Sediments in Pegasus Bay range from medium to fine sands on the open wave-dominated beaches, sandy muds within the harbours and finer muds within central Pegasus Bay. Kirk (1979) suggests that this sands of the open coast have been predominantly supplied by material from south of Banks Peninsula, which has moved northward around the peninsula and onto the Banner Bank before being reworked landward. Kirk considers that this reworking has now ceased and that sand supplied by the Waimakariri River is the dominant source of sediment (Figure 2-8).

Figure 2-8 The Waimakariri River transports sediment from the Southern Alps and Canterbury Plains to the coast and now supplies the majority of sediment to the Southern Pegasus Bay beaches (MetOcean, 2016a)

Fine sand makes up approximately 20% of the Waimakariri River suspended sediment load, equating to around 360,000 m^3/year based on best current estimates (Hicks, 1998). While this sand may remain in the nearshore, finer sediments cannot remain in the nearshore as velocities are too high to allow the grains to settle (Komar, 1998). Seabed sampling (Allan et al., 1999) show that sediments are coarsest within the breaker zone where wave energy is highest becoming progressively finer offshore (Figure 2-9). Finer sediments remain entrained until they are moved offshore into the deeper parts of Bay (>15-20m) where they can settle in a layer of ‘fluid mud’ (OCEL, 2016).

The underlying volcanic base of Banks Peninsula is covered by thick (~20 m) deposits of loess and loess colluvium from the Canterbury Plains (Forsyth et al., 2008). The fine loess sediment is readily eroded from the hill slopes and transported to the coast, infilling Lyttelton harbour at a rate of some 26,000 m^3/year (Hart, 2004). Lyttelton Harbour currently contains an estimated 47 m deep layer of deposition material (Hart, 2004) but drilling at Lyttelton Port indicates deposition material may extend significantly deeper. Finer sediments have tended to accumulate on the northern side of the harbour and coarser sediments along the southern margins. OCEL (2016) attribute this to the patterns of tidal asymmetry and note there is little exchange across the harbour.

The material to be dredged can be categorised as a very fine clayey silt with 45% silt, 55% clay and 1% sands (OCEL, 2016). Outside the heads, this material changes to a fine sandy silt with a predominant silt fraction. Some 0.5M m^3 per year is currently dredged from the navigation channel and placed in existing maintenance dredge dumping locations along the north side of the harbour and inside Godley Head (OCEL, 2016). A portion of the sediment is moved offshore with the dominant ebb tide and a portion (estimated by Hart, 2004 at 80%) is recirculated into the channel.

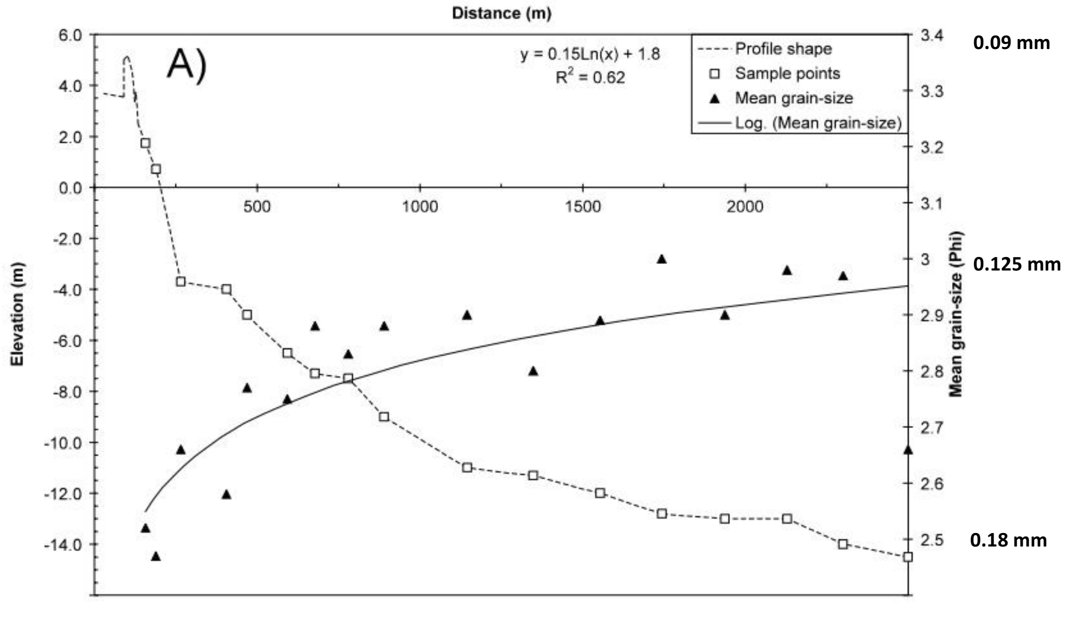


Figure 2-9 Mean grain-size for samples taken offshore from Bridge St, New Brighton (source: Allan et al., 1999)

2.6 Shoreline trends

Successive sea level fluctuations during glaciations have resulted in a stratified deposition on the Christchurch braidplain comprising fluvial gravels and sands which accumulated during lower sea levels and sand, silt, clay and peat deposits which have accumulated at higher water levels. Sea level stabilised at its present level around 6,000 years ago and inland transgression ceased (Figure 2-10). Since this time a succession of beach deposits, sand dunes, estuaries, lagoons and inter-dunal swamps accumulated resulting in shoreline advance (progradation) at an average rate of more than 2m/year (Wilson, 1976). More recently shoreline accretion has slowed, with analysis of aerial photographs since 1940 showing accretion of 0.2 to 0.5m/year, increasing towards the south (Tonkin + Taylor, 2015).

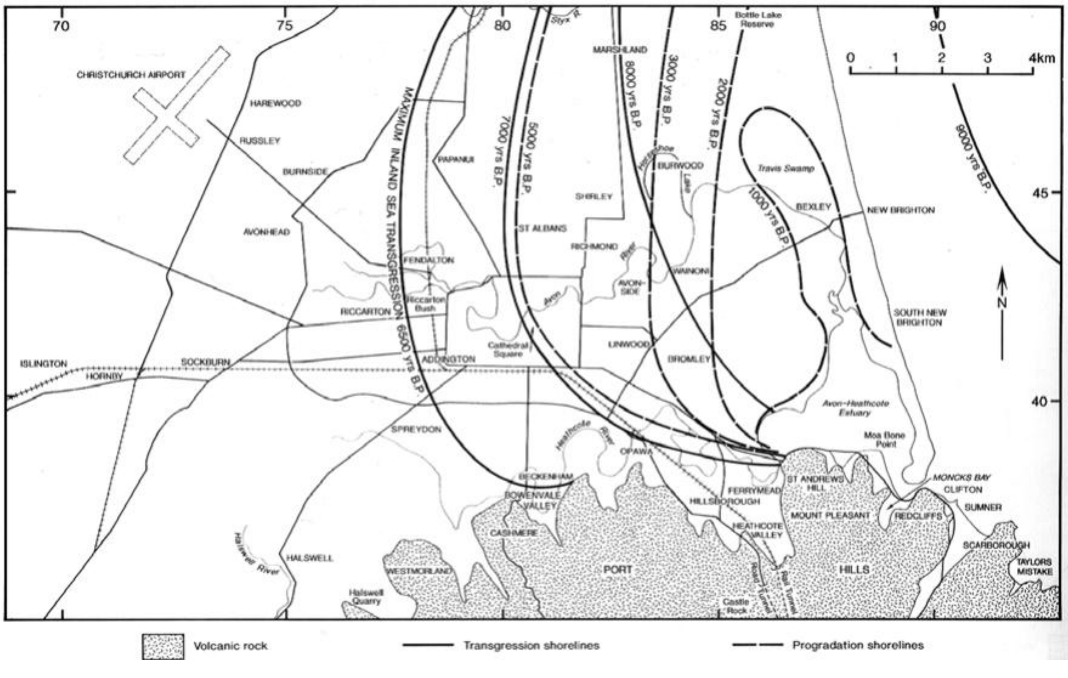


Figure 2-10 Holocene shoreline positions in Pegasus Bay (source: Campbell, 1974)

The ground around Canterbury has recently experienced regional scale tectonic movements caused by earthquakes. Beavan and Litchfield (2012) report uplift of more than 0.05 m along the coastline from New Brighton to Lyttelton Harbour and more substantial uplift within parts of the Avon-Heathcote estuary. Here there has been an increase of dry estuary area at mid tide of approximately 50 hectares or 18% with a change in the tidal prism estimated as approximately 1 million m^3 or a reduction of 14% (Measures et al., 2011). This change may result in a decrease in both the tidal current velocities and the ebb tidal delta volume (Tonkin + Taylor, 2013). This makes detection of changes in long-term beach profiles difficult due as the system has not likely reached a new post-earthquake equilibrium.

Trends within the harbours of the northern Banks Peninsula have been gradual infilling as material is eroded from the adjacent steep hill slopes. Studies quantifying changes in shoreline position have not been undertaken but are not likely significant due to the steep sides and infilling of seabed levels are the dominant process. Hart (2004) reported that examination of hydrographic charts by Curtis (1986) found periods seabed accumulation and scour over the last 150 years. Between 1849 and 1903 considerable scour occurred at the head and centre of the harbour while accretion occurred at the entrance. This was not believed to represent a 'natural' regime but rather in response to the initial dredging operations (volumes unknown) and construction of port infrastructure. From 1903 to 1951 large amounts of accretion occurred at the head of the harbour and at the entrance, which may have been a response to widespread deforestation increases in runoff and erosion, and from 1951 to 1976 smaller amounts of accretion occurred at the head and entrance and a moderate amount of scour occurred in the central harbour section. Overall between 1849 and 1976 the seabed at the head of the harbour accreted by up to 1m, the central parts scoured by up to 1.5 m and the entrance accreted by up to 1.5 m resulting in a net accumulation at a rate of approximately 30,000 m^3/year.

2.7 Summary

In summary, the sedimentation trends of Southern Pegasus Bay are accretional with the open coast beaches having prograded since the beginning of the Holocene, a trend continuing today, albeit at a lower rate. Lyttelton Harbour is infilling due to erosion of loess material, likely at a higher rate today than historically and the floor of Pegasus Bay accumulating silts and muds that cannot remain in higher energy coastal environments.

3 Effect of capital dredge works on coastal processes

This section assesses how the Capital Dredge Project could affect coastal process leading to changes in shoreline characteristics in the vicinity of the project based on existing information and general understanding of marine processes.

The principal drivers of coastal processes include waves, currents and water levels, all of which affect the location and magnitude of sediment transport. These drivers, combined with the characteristics and availability of sediment, determine form or morphology of a shoreline, its location, and its material composition. Changes in shoreline characteristics are therefore dependent on changes in the drivers or the sediment budget. Both of these aspects are considered in assessing likely affects.

3.1 Proposed physical works

The results of the proposed physical works can be summarised as follows:

1 Intermittent generation of suspended sediment plumes into the water column along the navigation channel and within the berth pocket as fine sediments are dredged using a trailing suction hopper dredger (assumed dredge for the works)

2 Intermittent generation of suspended sediment plumes into the water column at the proposed offshore deposition site as fine sediments are deposited from the dredge hopper

3 Placement of up to 18M m^3 of fine dredged sediment in a 2.5 x 5.0 km area approximately 6 km off Godley Head to an average height of 1.44m.

4 Enlargement of the existing sediment sink within the Lyttelton Harbour navigation channel.

3.2 Modification of environmental drivers

3.2.1 Hydrodynamics

Some changes in the tidal regime are expected within Lyttelton Harbour as a result of LPC's separate proposal for reclamation which causes a construction in the harbour width. This is, however, partially offset by the deeper navigation channel (Mulgor, 2016). Overall a slight decrease in tidal currents (up to 5-10% at peak tide) is expected in the central harbour between Diamond Harbour and Lyttelton Port, and an increase of up to 10% along the navigation channel to the reclamation. No significant change in the observed tidal asymmetry is reported and changes in other parts of the harbour are expected to be negligible (Figure 3-1).

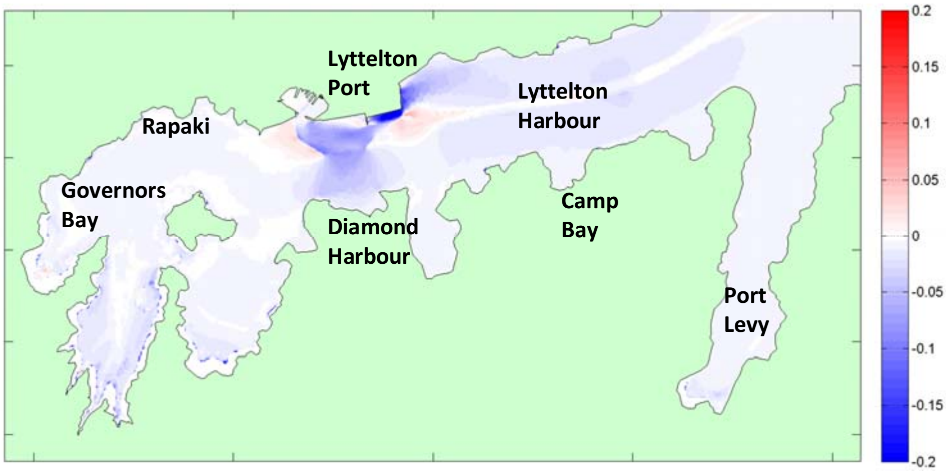


Figure 3-1 Difference in current speed (m/s) at mid-ebb tide between existing and fully developed works (Mulgor, 2016)

No significant change in tidal currents are expected within the wider Pegasus Bay area as a result of the placement of a dredge mound and no modelling of such has been undertaken.

3.2.2 Waves

A temporary change in wave transmission is expected as waves focus in the lee of the disposal site mound and defocus on either side (MetOcean, 2016c, e). Results from MetOcean (2016e) show that the area of focussing is highly dependent on wave direction with wave from NE tending to focus on the Godley Head and Taylors Mistake area, while waves from the East to Southeast tend to focus on South New Brighton Beach with reduced waves in the Taylors and Godley Head area, although these differences are typically less than 1-2%.

Figure 3-2 shows the difference in a weighted mean significant wave height (m) between the existing and with the elevated capital disposal ground and shows that overall, focussing of up to 4% may occur along South New Brighton, but mean reductions between Sumner and Lyttelton Harbour of up to 2% may occur. These change are expected to diminish as the mound is eroded and seabed returns to its previous near horizontal form.

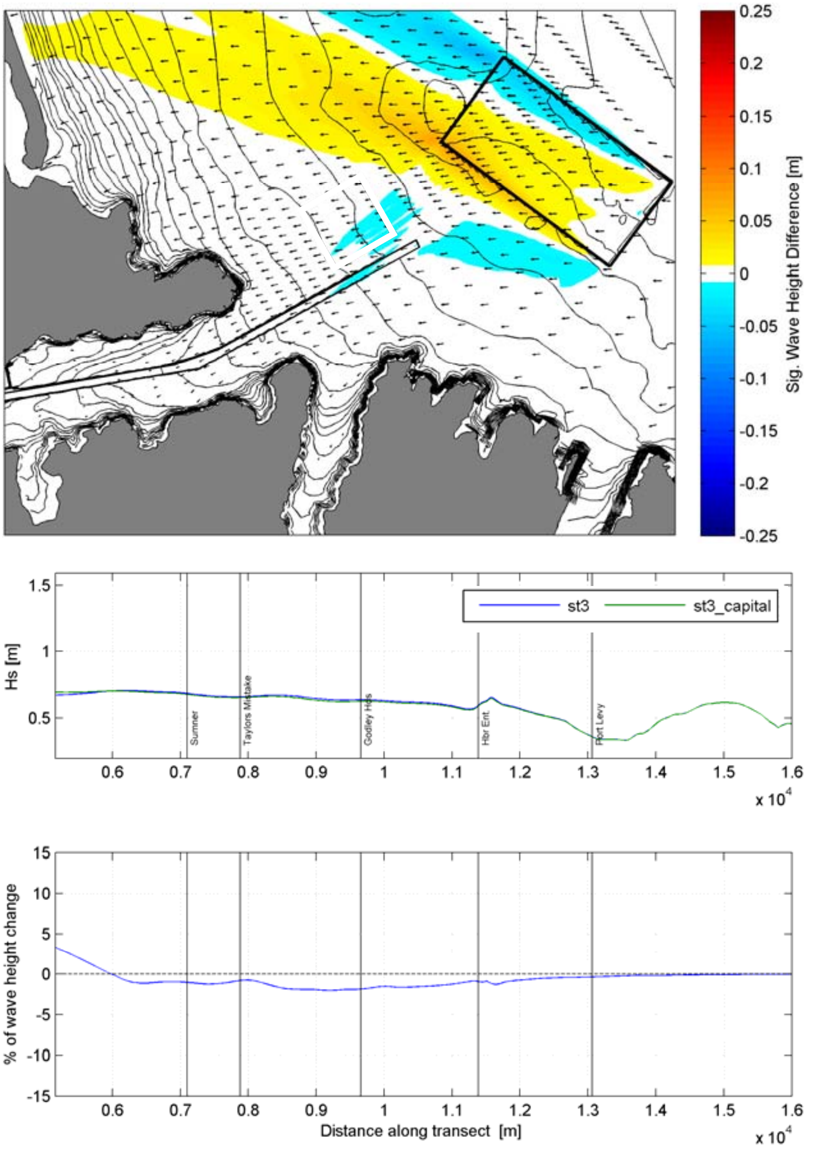


Figure 3-2 Difference in a weighted mean significant wave height (m) between the existing and with the elevated capital disposal ground (top) and height difference along a 16m depth contour (MetOcean, 2016e)

Conversely, a permanent change in wave processes is expected within the outer Lyttelton Harbour due to channel deepening. Waves entering the harbour move efficiently along the deeper channel causing waves to refract and focus on either side of the channel while decreasing in height within the channel and further up the harbour (Figure 3-3). Mulgor (2016) find decreases in mean wave height of up to 33% over the navigation channel, increases of up to 12% on either side of the channel in the outer harbour and decreases of up to 38% at Diamond Harbour and Purau, which are already very sheltered from swell waves entering the harbour. Wind waves heights are unlikely to be significantly affected by the proposed changes and, while wind-waves are likely the dominant source of wave energy reaching the shoreline in the upper harbour, they have different sediment transport characteristics with swell waves much more efficient at mobilising and transporting seabed sediments.

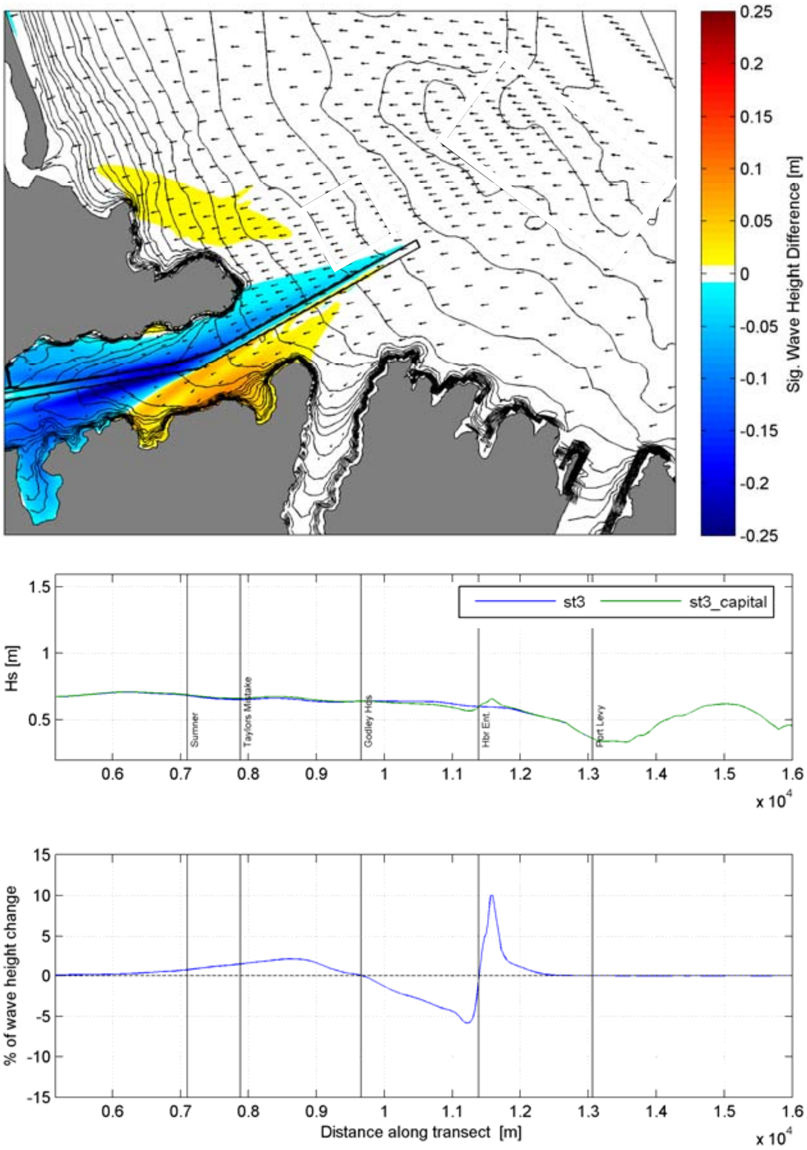


Figure 3-3 Difference in a weighted mean significant wave height (m) between existing and Stage 2 channel scenarios (top) and height difference along a 16m depth contour (MetOcean, 2016e)

3.3 Modification of sediment budget

3.3.1 Suspended sediments

Modelling of suspended sediment plumes at the dredge sites by MetOcean (2016a) indicate that plumes are likely to be more highly concentrated at lower levels than at the surface due to the dredging method. Plumes dispersal within the Harbour tends to be strongly bi-directional and contained within the dredge channel and while plume concentration may exceed ambient conditions (assumed conservatively at 10 mg/L) for up to 2 km from the dredge location, plumes are unlikely to reach the coastline (Figure 3-4).

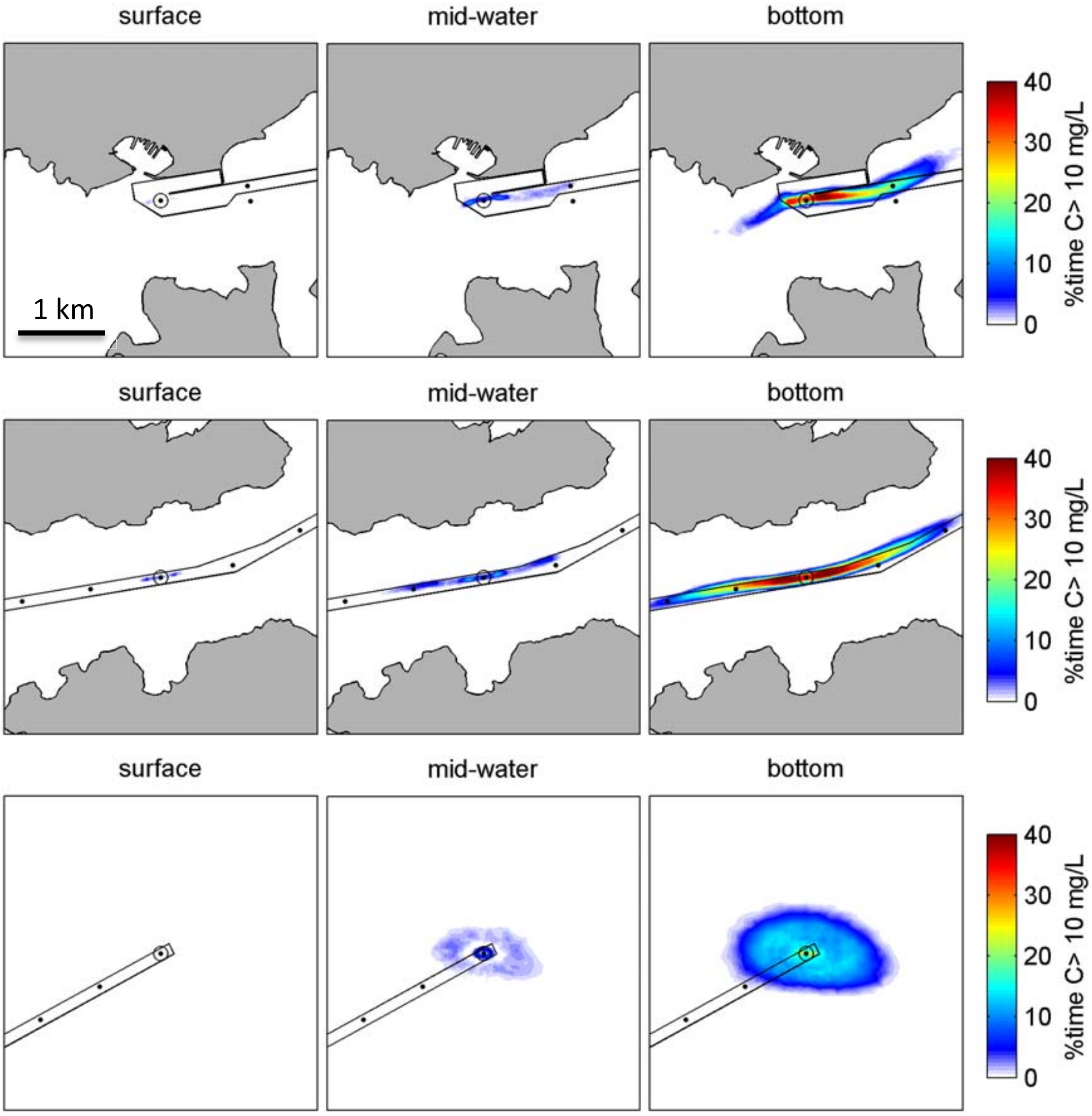


Figure 3-4 Percentage of time SSC thresholds of 10 mg/L are exceeded during dredging activities at the berth pocket, mid channel and the seaward end over a 28 day dredge cycle

Modelling of suspended sediment plumes at the offshore disposal site by MetOcean (2016b) indicate that plumes are likely to substantially settle (deposition thickness < 1mm or ambient background levels of suspended sediments reached) within 500 m of the discharge position, however individual particles may travel further. Figure 3-5 shows extreme particle excursion distances (90-99%) occurring during a 10yr hindcast simulation of continual dredge cycles placed at the disposal site corners. While the simulation is conservative, the results show the deposition footprint is contained some 2-3 km from the nearest shoreline and is elongated in the NW-SE direction due to the dominant tidal current regime. It should be noted that once dredge plume sediments have settled, they are likely to be re-entrained by waves along with existing fine seabed sediments and transported further afield.

Figure 3-5 Combined extreme excursion footprints of sediment deposition resulting from sediment disposal at the ground corners, for the Asia vessel (V=10,800 m^3). These results are derived from the 10 year hindcast simulations. Dashed circles have radiuses of 500 and 1000 m (source: MetOcean, 2016b)

3.3.2 Sediment sources

As part of the works, an additional sediment source has been created at the disposal site.

The sediment dynamics for the proposed offshore disposal site has been qualitatively modelled by MetOcean (2016c). Result show that the mound, assumed to initially be an approximately 1.5 m high mound located within the 5 x 2.5 km disposal site, to be relatively quickly eroded with the material spread across the Bay. Modelling of specific events with predominantly northwest and southeast residual flows show material distributed some 3 to 5 km in those directions (Figure 3-6).

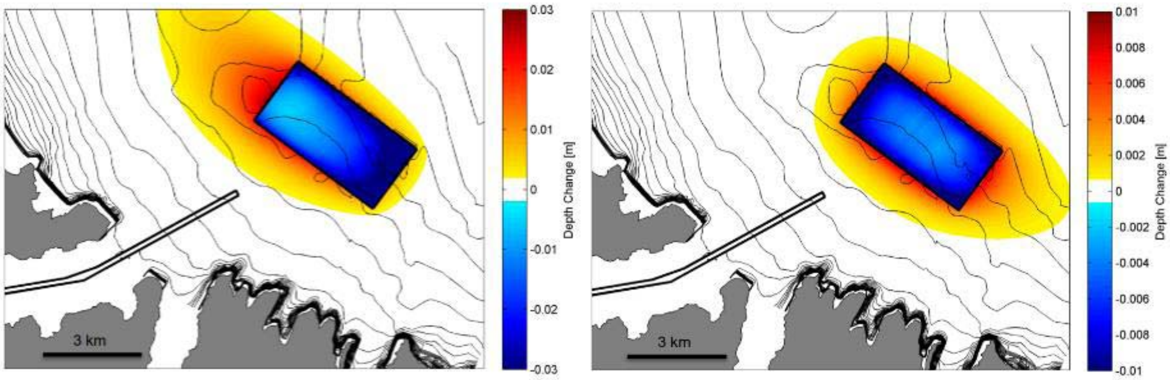


Figure 3-6 Change in depth after 4 day swell events with predominant northwest (left) and southeast (right) residual currents (MetOcean, 2016c)

Long-term modelling (Figure 3-7) shows that accumulations tend to be relatively well distributed around the capital disposal site with a slightly skew to the west, in accordance with the predominant wave direction. As expected for long-term morphological modelling, the assumed erosion parameter makes a significant difference with much slower erosion of the mound (<0.05m/year) and redistribution occurring with lower rates than the higher (up to 0.25m/year erosion of the mound).

Figure 3-7 shows only 'significant' accretion volumes (i.e. greater than 1cm) whereas significantly more material has been eroded from the deposition mound and is spread throughout Pegasus Bay. It should be noted that once materials have dispersed, they will continue to be mobilised and transported along with native materials throughout the bay.

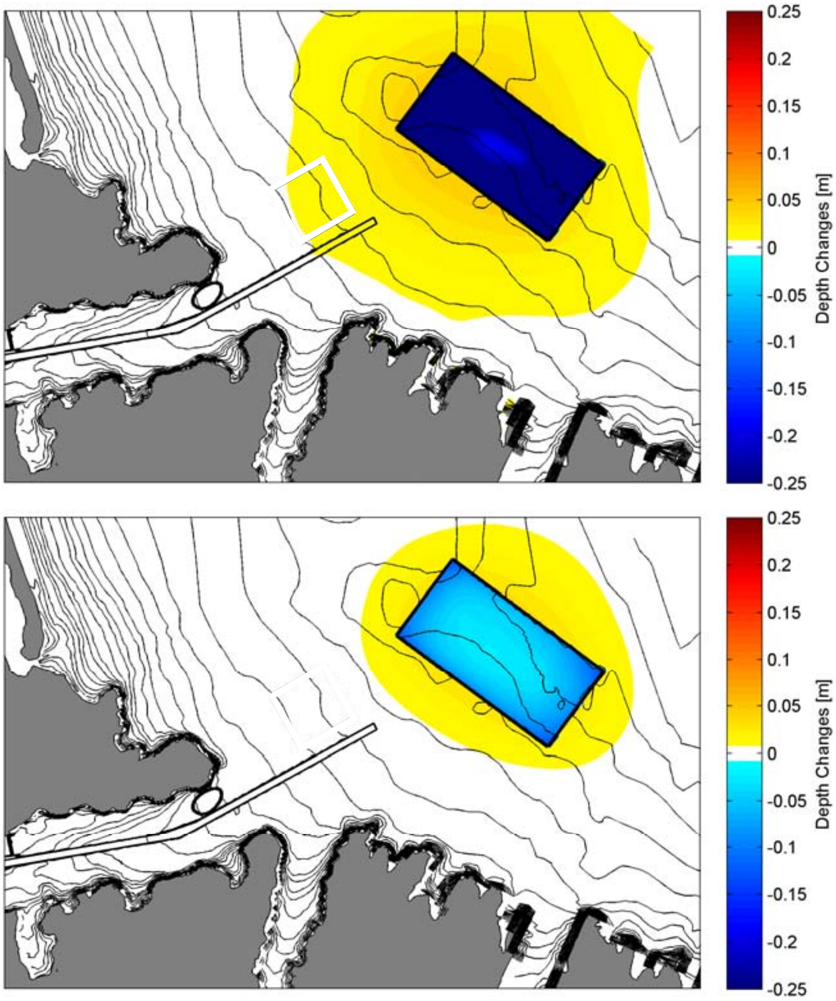


Figure 3-7 Modelled change in seabed depth resulting from the elevated capital disposal ground after 1 year morphological simulation using upper end (top) and lower end (bottom) erosion parameter (MetOcean, 2016c)

3.3.3 Sediment sinks

The existing sediment sinks within Lyttelton Harbour; the navigation channel and berthing pocket, are to be augmented by deepening. Materials previously removed from this sink were placed adjacent to the channel (OCEL, 2016) and would partially migrate back. The 18M m^3 of sediments removed during capital dredging works will be completely removed from the system.

3.4 Effects on shoreline morphology and composition

3.4.1 Open coast beaches

The ***morphology*** of open coast beaches are unlikely to be modified as changes in the wave climate between New Brighton and Taylors Mistake resulting from the temporary capital dredge mound and the permanent dredge channel are relatively minor. Figure 3-2 shows a change of less than 2 - 3% which will decrease over time as the spoil mound erodes.

The ***location*** of open coast beaches unlikely to be affected as the sediment regime relevant to sand beaches remains unchanged. While additional material will be added into Pegasus Bay, the fine nature of that material means that it is not compatible with the open coast beach sands and will not therefore affect the sediment budget.

Finally, the ***composition*** of the open coast beaches is unlikely to be affected as fine sediments such as the dredge spoil material will not able to settle on the higher energy environments. As discussed in Section 2.5, seabed velocities are sufficient to prohibit settling of fine sediment here and/or would rapidly re-entrain any fine sediment on the seabed. Fine sediment would thus be winnowed (preferentially removed) offshore to depths where velocities allow settling. Such processes have been occurring naturally from millennia as widely graded materials from the Waimakariri River and other sources reach the coast.

3.4.2 Harbour shorelines

The composition of the harbour shorelines within Lyttelton and Port Levy are unlikely to be affected as modelling shows that suspended sediment plumes unlikely to reach harbour shorelines. Furthermore, materials re-entrained during subsequent motion are also unlikely to reach harbour shorelines as the dominant sediment transport pathway is from shallow waters, where fines are initially deposited from land sources, into deeper water.

The augmentation of the sediment sink within Lyttelton Harbour has the potential to cause erosion of the surrounding seabed as this material moves to infill the deeper and wider channel. It is unclear how quickly this erosion occur or to what extents but similar erosion of the harbour seabed was reported by Curtis (1986) following initial dredging works in the mid to late 19th Century.

The harbour shorelines are typically steep and rocky and therefore unlikely to be significantly affected in morphology or location but monitoring of the seabed level and shoreline position would be prudent to confirm this.

4 Effect of maintenance dredging works on coastal processes

This section assesses, based on existing information and general understanding of marine processes, how the ongoing maintenance dredging works could affect coastal process leading to changes in shoreline characteristics in the vicinity of the project.

4.1 Proposed physical works

The effect of the proposed physical works can be summarised as follows:

1. Intermittent generation of suspended sediment plumes into the water column along the navigation channel and within the berth pocket as fine sediments are dredged using a trailing suction hopper dredger (assumed dredge for the works)
2. Intermittent generation of suspended sediment plumes into the water column at the proposed offshore maintenance deposition site as fine sediments are deposited from the dredge hopper
3. Placement of approximately 0.9 M m^3 of fine dredged sediment annually in a 1.6 x 1.6 km area approximately 3 km off Godley Head (Figure 1-2) to an average height of 0.35m (if placed at once).
4. Ongoing removal of sediment from an enlarged sediment sink within the Lyttelton Harbour navigation channel.

4.2 Modification of environmental drivers

4.2.1 Hydrodynamics

Maintenance dredging is not likely to have any additional effects on either the harbour or Pegasus Bay hydrodynamic processes beyond those described in Section 3.2.1 for the Capital Dredging unless deepening of the adjacent seabed occurs in response to the capital dredging and ongoing maintenance (refer Section 4.3.3). The magnitude of changes would depend on the modified seabed form.

4.2.2 Waves

A semi-permanent change in wave transmission is expected as waves focus in the lee of the maintenance disposal site mound and defocus on either side (MetOcean, 2016e). Results from MetOcean (2016e) show that the area of focussing is highly dependent on wave direction with waves from the northeast tending to focus on the Godley Head area, while waves from the east to southeast tend to focus on the Sumner to Taylors Mistake area, although these differences are typically less than 1-2% and will depend on the actual height of the mound at any time.

Figure 4-1 shows the difference in a weighted mean significant wave height (m) between the existing situation and with the elevated capital disposal ground. Results show that focussing of up to 3% may occur near Taylors Mistake, with mean reductions of up to 2% around the Lyttelton Harbour mouth. These changes would generally be undetectable compared to daily changes in wave height, although would be permanent as long as material continues to be placed and form at mound at the disposal site.

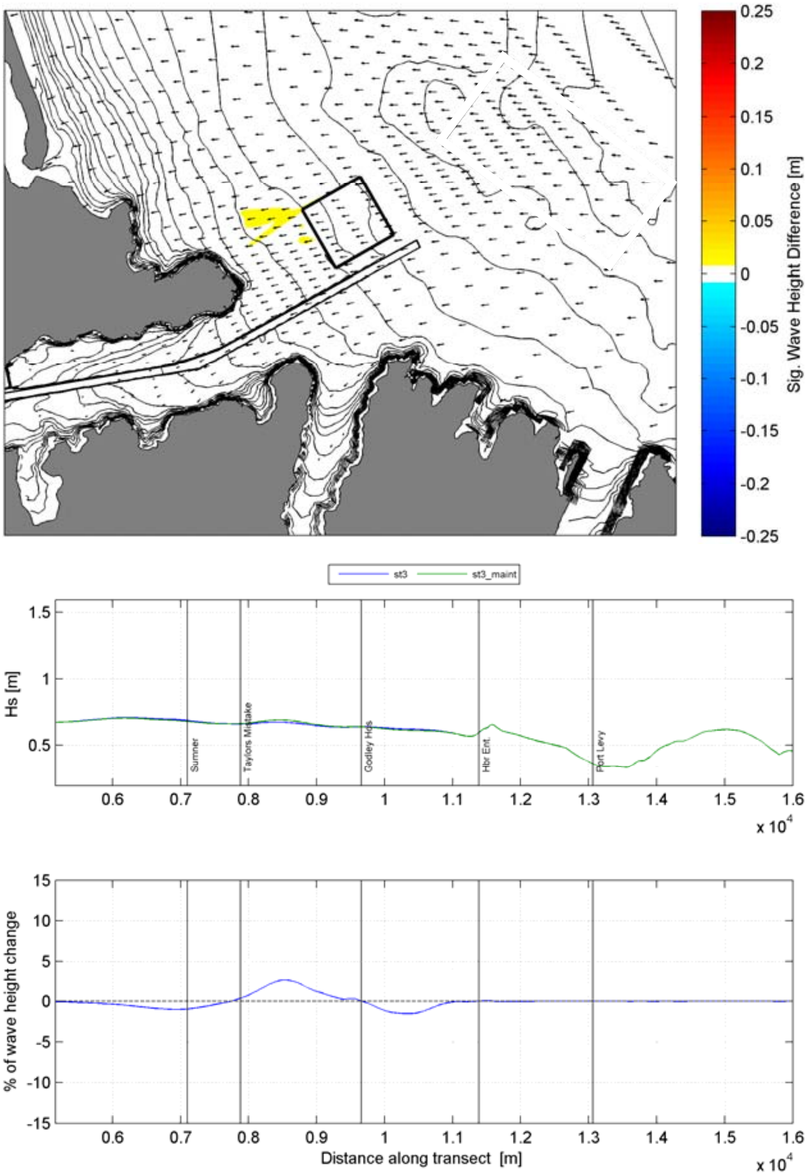


Figure 4-1 Difference in a weighted mean significant wave height (m) between the existing and with the elevated maintenance disposal ground (top) and height difference along a 16m depth contour (MetOcean, 2016e)

4.3 Modification of sediment budget

4.3.1 Suspended sediments

The dynamics of suspended sediment plumes resulting from maintenance dredging along the navigation channel are expected to be similar to those for the capital dredging reported in Section 3.3.1; that is, they are likely to be contained substantially within the dredge channel and unlikely to reach the coastline (MetOcean, 2016d).

Modelling of suspended sediment plumes at the offshore disposal site by MetOcean (2016d) indicate that plumes are likely to substantially settle (deposition thickness < 1mm or ambient background levels of suspended sediments reached) within 1km of the discharge position respectively, however individual particles may travel further. Figure 4-2 shows extreme particle excursion distances (90-99%) occurring during an annual hindcast simulation of continual dredge cycles placed at the disposal site corners. While the simulation is conservative, the results show the deposition footprint extends towards Godley Head and the entrance to Port Levy. It should be noted that once dredge plume sediments have settled, they are likely to be re-entrained by waves along with existing fine seabed sediments and transported further afield.

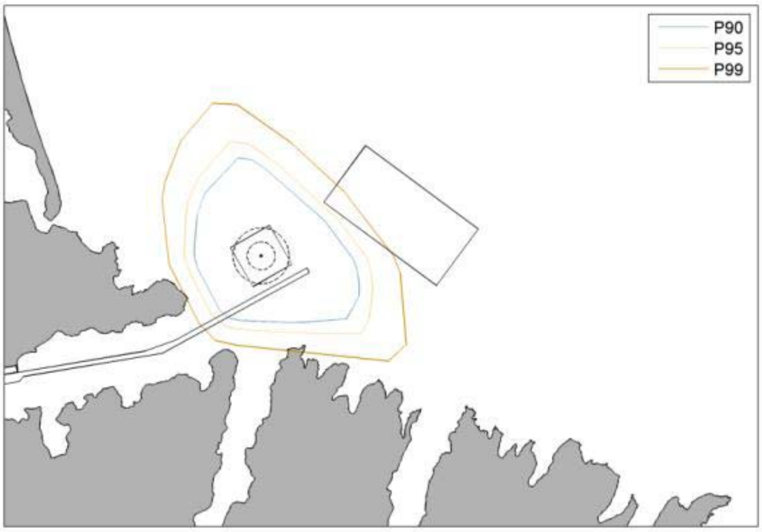


Figure 4-2 Combined extreme excursion footprints of sediment deposition resulting from sediment disposal at the maintenance ground corners, for the Mahury vessel (V=1,840 m^3). These results are derived from an annual hindcast simulations. Dashed circles have radiuses of 500 and 1000 m (source: MetOcean, 2016d)

4.3.2 Sediment sources

As part of the ongoing maintenance dredging, an additional sediment source has been created at the disposal site in the form of a 1.6 x 1.6 km mound. This mound would extend approximately 0.35 m high based on the estimated 0.9M m^3 dredged annually if placed all at once.

The sediment dynamics for the proposed offshore maintenance disposal site has been qualitatively modelled by MetOcean (2016e). As expected for long-term morphological modelling, the assumed erosion parameter makes a significant difference with much slower erosion of the mound (less than 0.05m/year) and redistribution occurring with a lower selected parameter than with a higher parameter (up to 0.25m of erosion/year).

Results (Figure 4-3) show that accumulations tend to be relatively well distributed around the offshore maintenance disposal site and may extend to the navigation channel, resulting in partial infilling. Figure 4-3 shows only ‘significant’ accretion volumes (i.e. greater than 1cm) whereas significantly more material has been eroded from the deposition mound. This material is spread throughout Pegasus Bay but with accretion levels of less than 1 cm. It should be noted that once materials have dispersed, they will continue to be mobilised and transported along with native materials throughout the bay.

Note that if maintenance dredging is undertaken at greater than yearly intervals then the placed could become higher and resulting rates of sediment erosion and distribution wider. Likewise, if erosion rates are slower than expected then the following year’s maintenance dredging will be placed on the remainder of the previous extending the mound higher which may have more effect on the inshore wave climate than modelled.

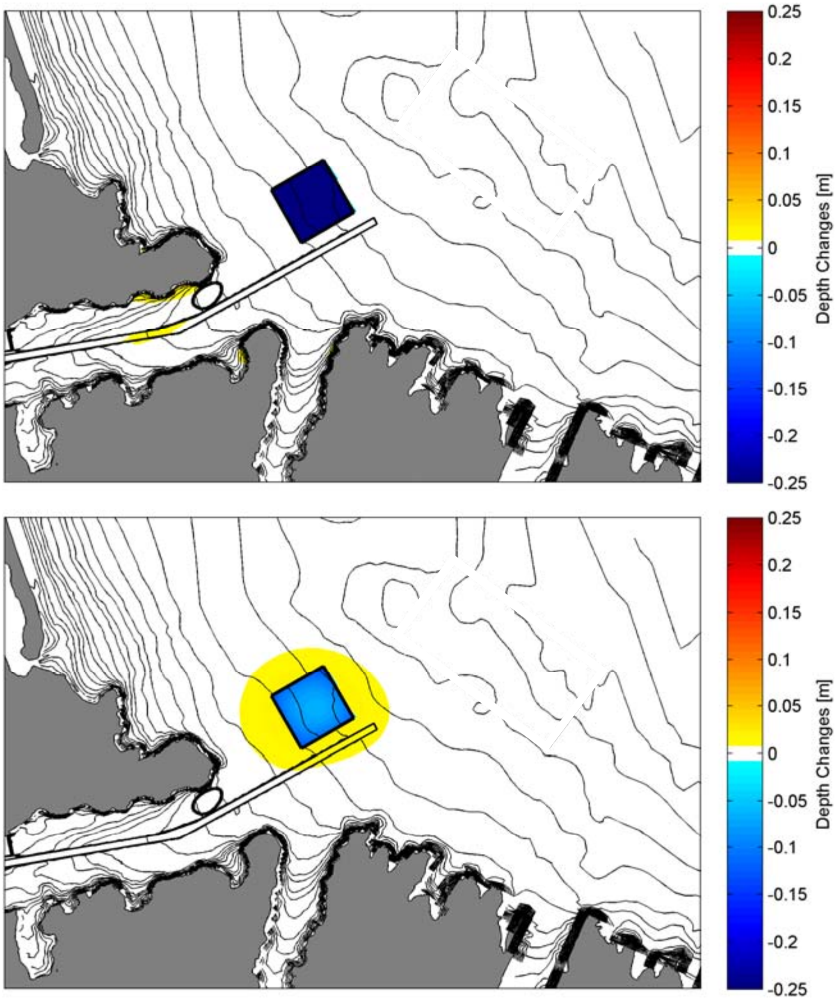


Figure 4-3 Modelled change in seabed depth resulting from the elevated offshore maintenance disposal ground after 1 year morphological simulation using upper end (top) and lower end (bottom) erosion parameter (MetOcean, 2016c)

4.3.3 Sediment sinks

The existing sediment sinks within Lyttelton Harbour; the navigation channel and berthing pocket, are to be augmented by deepening. Previously materials removed from this sink were placed adjacent to the channel (OCEL, 2016) and would partially migrate back. If dredged sediment is removed from the system to the offshore disposal site, sediment refilling the navigation channel will be derived from the surrounding seabed. Based on annual maintenance dredging of 0.9M m^3, over a 35 year consent term up to 31.5M m^3 of sediment could be removed from the outer harbour.

4.4 Effects on shoreline morphology and composition

4.4.1 Open coast beaches

The ***morphology*** of open coast beaches are unlikely to be modified as changes in the wave climate between New Brighton and Taylors Mistake are relatively minor as a result of the maintenance dredge mound. Figure 4-1 shows a mean change of less than 2-3% with slightly larger waves expected between Sumner and Taylors Mistake.

The ***location*** of open coast beaches unlikely to be affected as the sediment regime relevant to sand beaches remains unchanged. While additional material will be added into Pegasus Bay from

Lyttelton Harbour, the fine nature of that material means that it is not compatible with the open coast beach sands and will not therefore affect the sediment budget.

Finally, the ***composition*** of the open coast beaches is unlikely to be affected as fine sediments such as the dredge spoil material will not able to settle on the higher energy environments as described in relation to the Capital dredge works (Section 3.4.1).

4.4.2 Harbour shorelines

The ***composition*** of the harbour shorelines within Lyttelton and Port Levy are unlikely to be affected as modelling shows that suspended sediment plumes may reach the mouth of the harbours but are unlikely to penetrate into the harbours to reach harbour shorelines.

As described in Section 4.4.3, the removal of sediment from outer Lyttelton Harbour has the potential to cause erosion of the surrounding seabed as this material moves to infill the deeper and wider channel and is continually removed from the system. Over a 35 year consent term up to 31.5M m^3 of sediment could be removed from the outer harbour. Assuming no recycling of the dredge spoil, this material would be derived from the adjacent seabed. The equivalent change in average seabed level in the outer harbour (east of Diamond Head) is 2.2 m. While the majority of this sediment would likely be derived from the immediately adjacent seabed (leading to greater local elevation change), given the very flat seabed gradients (~1:1000) that exist within Lyttelton Harbour (OCEL, 2016), this demand may extend further afield. ***Sea bed levels*** should therefore be monitored to detect any changes during ongoing maintenance dredging.

The harbour shorelines are typically steep and rocky and therefore unlikely to be significantly affected in ***morphology*** or ***location*** as a result in the change in wave climate or offshore seabed levels, but monitoring of the shoreline position and form would be prudent to confirm this and the maintenance regime modified if significant effects detected.

5 Physical shoreline monitoring

Physical shoreline monitoring provides a record of changes in shoreline location, morphology or composition to allow comparison with a baseline and determination of any changes which could be related to the capital dredge project or ongoing maintenance dredging (if disposed at new offshore site).

5.1 Programme

The following programme is recommended to monitor potential changes:

Name	Description	Monitoring requirement	Frequency[1]			
			Baseline	During capital	Following capital	During maintenance
Photo-point monitoring	Photographs taken from fixed locations and aspects	Visually assess beach level change or fine sediment deposition.	3 monthly	3 monthly	3 monthly for 2 years 6 monthly to 5 years	Annually
Sediment size analysis	Particle size analysis of sediment samples from the intertidal beach face (3 locations on surface)	Quantifies sediment size on beach to determine changes in texture and composition	6 monthly	6 monthly	6 monthly for 2 years Annually to 5 years	N/A – *effects not likely if not observed during capital works*
Beach profile survey	Beach profile survey from established benchmark[2]	Quantifies changes in profile geometry and/or location	6 monthly	6 monthly	6 monthly to 5 years	Annually[3]
Seabed survey	Profile survey across seabed or seabed depth at specific locations	Quantified change in seabed level over time	Annually	Annually	Annually to 5 years	5 yearly
Shoreline analysis	Digitise and compare shoreline positions from aerial photographs/Satellite imagery	Determines change in shoreline position	Baseline assessment of historic shoreline (Lyttelton harbour only)	Annually (or as aerial photographs/ satellite imagery become available) to 5 years following dredging project		5 yearly

[1]Monitoring frequency is broken into three stages,
- ***Baseline*** before capital dredging begins
- ***During*** capital dredging project
- ***Following*** capital dredging project
- ***Maintenance*** during maintenance dredging (if disposed offshore)

[2]Survey requirements,
- *Survey* using staff and level, total station or RTK GPS
- *Survey during spring low tide, pick up all changes in grade*
- *Required horizontal accuracy +/- 0.1m, vertical accuracy +/- 0.05m*

[3]Assume profiles at Brighton and Sumner will continue to be monitored at 6 month intervals by ECan.

5.2 Locations

Monitoring is recommended at the locations shown in Figure 5-1 with the types of monitoring shown below:

Location		Capital Dredging Project			Maintenance Dredging (if disposed offshore)		
		Photo-point monitoring	Sediment size analysis	Beach profile survey	Photo-point monitoring	Sediment size analysis	Beach profile survey
1.	New Brighton ECAN C0815 (Rodney Street)	✓		✓[1]	✓		✓[1]
2.	South New Brighton ECAN C0513 (Hasley Street)	✓		✓[1]	✓		✓[1]
3.	Southshore ECAN C0362 (Tern Street)	✓	✓	✓[1]	✓		✓[1]
4.	Sumner ECAN CCC0190 (Main Rd)	✓		✓[1]	✓		✓[1]
5.	Sumner ECAN CCC0112 (Hardwicke St)	✓	✓	✓[1]	✓		✓[1]
6.	Taylors Mistake	✓	✓	✓	✓		✓
7.	Gollans Bay	✓	✓				
8.	Corsair Bay	✓	✓	✓			
9.	Cass Bay	✓					
10.	Rapaki Bay	✓		✓	✓		✓
11.	Purau Bay	✓	✓	✓			
12.	Pile Bay	✓					
13.	Camp Bay	✓	✓	✓	✓		✓
14.	Little Port Cooper	✓					
15.	Port Levy	✓	✓		✓		

[1] ECAN currently collect profile data here and are likely to continue (Cope pers. comm. Sept 2016)

5.3 Reporting

Photo-point monitoring should be assessed as collected with major observed changes triggering requirement for additional sediment size analysis or beach profile surveys. Formal reporting should be undertaken at the end of the 12 month baseline, at 6 month intervals during dredging and for two years after and annually from two to five years following dredging. Reporting should be undertaken at 5 year intervals during maintenance dredging if material is placed on the offshore disposal site.

Notes:

A4 SCALE 1:125,000

0 1 2 3 4 5 (km)

N

Tonkin+Taylor

105 Carlton Gore Road, Auckland
www.tonkintaylor.co.nz

DRAWN	PPK	Aug.16
CHECKED		
APPROVED		

ARCFILE
Figure 5.1.mxd

SCALE (AT A4 SIZE)
1:125,000

PROJECT No.
31791

LYTTELTON PORT COMPANY

LPC Channel Deepening Project

Review and summary of coastal process effects

Proposed Monitoring Locations

FIGURE No. Figure 5.1

Rev. 0

Path: P:\31791\WorkingMaterial\GIS\Map Documents\Figure 5.1.mxd Date: 30/08/2016 Time: 4:38:57 p.m.

6 Applicability

This report has been prepared for the exclusive use of our client Lyttelton Port Company, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
Dr Tom Shand	Richard Reinen-Hamill
Senior Coastal Engineer	Project Director

Tom Shand
p:\31791\workingmaterial\r090916.lpc dredge coastal processes.docx

7 References

Allan, J. C., Kirk, R.M., Hemmingsen, M. and Hart, D. (1999). Coastal processes in Southern Pegasus Bay: A Review. A report to Woodward-Clyde New Zealand Ltd. and the Christchurch City Council.

Beavan, R.J., Litchfield, N.J. (2012) Vertical land movement around the New Zealand coastline: implications for sea-level rise. GNS Science Report 2012/29. 41p.Burgess, J.S., (1968) Beach morphology in southern Pegasus Bay. Unpublished M.A thesis, in Geography, University of Canterbury, N.Z. 98pp.

Campbell, J.R., (1974) Processes of littoral and nearshore sedimentation in Pegasus Bay. Unpublished M.A thesis, in Geography, University of Canterbury, N.Z. 97pp.

Carter, L.; Herzer, R.H., (1986) Pegasus sediments. 2nd Ed., New Zealand Oceanographic Institute Chart, Coastal Series, 1:200,000.

Cope, J; Flatman, M; Howes, A; Young, B., (1998) A summary of monitoring and investigations on the Pegasus Coastline, 1993-97. Unpublished Canterbury Regional Council Report, No. U98/30. 49pp.

Curtis (1986) An assessment of sedimentation and dredging effects in Lyttelton Harbour. Unpublished report to the Lyttelton Harbour Board.

Duns, R.M., (1995) A sediment budget analysis of Pegasus Bay. Unpublished M.Sc thesis, in Geography, University of Canterbury, N.Z. 156pp.

Forsyth, P.J. Barrell, D.J.A. and Jongens, R. (2008) Geology of the Christchurch Area. Institute of Geological & Nuclear Sciences Ltd. 67p + Map.

Goring, D. (2009) Design Extreme Sea Levels for Parsons Rock Beacon. Technical report prepared for Port of Lyttelton.

Hannah, J. and Bell, R.G. (2012) Regional sea level trends in New Zealand. Journal of Geophysical Research: Oceans. 117 (C1)

Hart, D.E. (2004) Sedimentation in the Upper Lyttelton Harbour. Report to Environment Canterbury.

Hicks (1998) Sediment budgets for the Canterbury Coast – a review, with particular reference to the importance of river sediment. NIWA Client Report No. CHC98/2.

Kirk, R.M., (1979) Dynamics and management of sand beaches in southern Pegasus Bay. Unpublished report to Christchurch Area Metropolitan Authorities, Morris and Wilson Consulting Engineers Ltd, Christchurch. 121pp.

Komar, P.D., (1998) Beach processes and sedimentation. 2nd Ed., Prentice Hall, Inc. Englewood Cliffs, New Jersey. 544pp.

LINZ, 2016. New Zealand Nautical Almanac (NZ 204)

Measures, R. Hicks, M. Shankar, U., Bind, J., Arnold, J. and Zeldis, J. (2011) Mapping earthquake induced topographical change and liquefaction in the Avon-Heathcote Estuary. Report prepared for Environment Canterbury by NIWA. Report No. U11/13. 28p.

MetOcean (2014) Pegasus Bay ROMS Hindcast: Validation Report. Report P0201-04, Version Rev C 13/03/2014

MetOcean (2016a) Lyttelton Port Company Channel Deepening Project - Simulations of Dredge Plumes from Dredging Activities in the Channel. Report P0201-03, Rev E 07/06/2016

MetOcean (2016b) Lyttelton Port Company Channel Deepening Project - Simulations of suspended sediment plumes and associated deposition from offshore disposal. Report P0201-02, Rev F 20/05/2016

MetOcean (2016c) Lyttelton Port Company Channel Deepening Project - Numerical modelling of sediment dynamics for a proposed offshore capital disposal ground. Report P0201-01, Rev E 19/05/2016

MetOcean (2016d) Lyttelton Port Company Channel Deepening Project - Simulations of suspended sediment plumes generated from the deposition of spoil at proposed maintenance disposal grounds. Report P0201-06, Rev B 08/08/2016

MetOcean (2016e) Lyttelton Port Company Channel Deepening Project - Numerical modelling of sediment dynamics at proposed offshore maintenance disposal ground. Report P0201-04, Rev C 08/08/2016

Goring, D. (2016) Effects of Development Stages 2 and 3 on Waves and Tidal Currents in Lyttelton Harbour. Report prepared by Mulgor Consulting Ltd. for LPC. Client Report 2016/2, February 2016

OCEL (2016) Deepening and extension of the Navigation Channel - Capital Dredging Report. Report prepared for Lyttelton Port Company, July 2016.

Okayasu, A.; Shibayama, T.; Mimura, N. (1986), "Velocity field under plunging waves", in Edge, B.L., Proceedings of the 20th International Conference on Coastal Engineering, 1, Taipei: ASCE, pp. 660–674

Reis, H.A, and Gama, C. (2010) Sand size versus beachface slope. Geomorphology 114, pp276-283.

Tonkin + Taylor (1998) Christchurch coastal dune wave run-up study. Part C: Modelling of dune erosion and wave run-up heights. Unpublished Tonkin & Taylor Report, 27p.

Tonkin + Taylor (2013) Effects of Sea Level Rise for Christchurch City. Report for Christchurch City Council

Tonkin + Taylor (2015) Coastal Hazard Assessment Stage One – Review. Report for Christchurch City Council

Wilson, D.D. (1976) Hydrogeology of metropolitan Christchurch. NZ Journal of Hydrology. 15: 101 – 120.

www.tonkintaylor.co.nz