Report to Environment Canterbury

Sedimentation in the Upper Lyttelton Harbour

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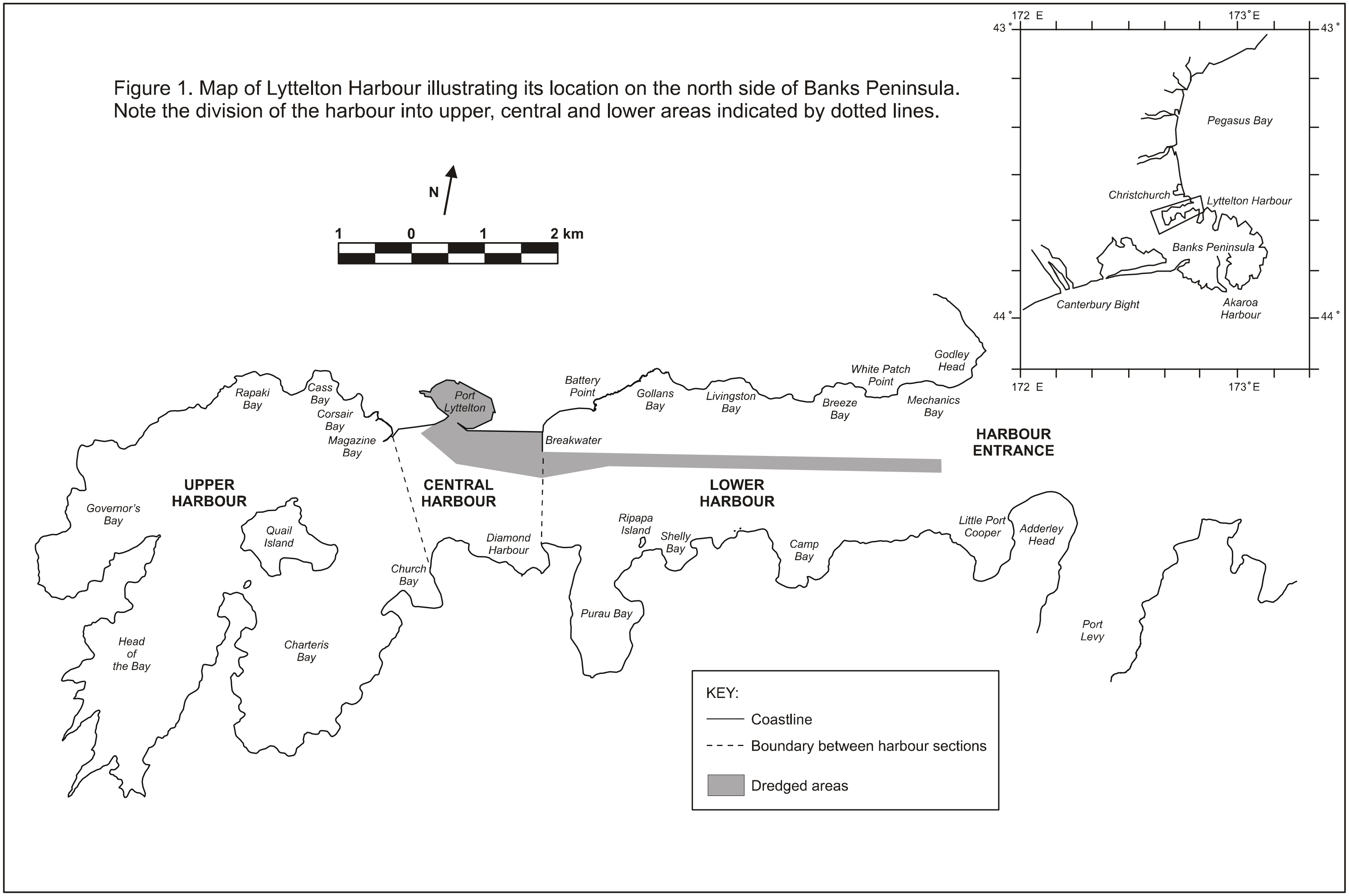
CONTENTS

Figure 1. Map of Lyttelton Harbour illustrating its location on the north side of Banks Peninsula. Note the division of the harbour into upper, central and lower areas indicated by dotted lines.



Introduction

Scope and Purpose of the Report

This report concerns the coastal processes operating in the Upper Lyttelton Harbour (43º41’ South, 172º41’ East) with particular reference to the patterns and processes of sedimentation in Governor’s Bay, Head of the Bay and Charteris Bay (Figure 1). The purpose of the report is to review current information and data on sedimentation in the Upper Lyttelton Harbour and to explore possibilities for further investigation and monitoring. Published and unpublished reports and theses have been used along with maps, aerial photographs, hydrographic charts and structural blueprints and plans. In addition, a brief field investigation was conducted on 15/12/03.

Numerous reports have examined patterns of circulation, sedimentation and ecology within the wider area of Lyttelton Harbour, predominantly for the purposes of assessing the impact of port dredging operations (Brodie 1955, Bushell and Teear 1975, Millhouse 1977, Curtis 1985, 1986, Knox 1983, 1988, Kirk 1992, 1993, Barter 2000). Where it pertains to the processes operating within or affecting the upper harbour environment, information from these and other studies is used throughout this report.

In the first part of this report, the physiographic settling of Lyttelton Harbour is outlined, including aspects of the geology, soils and catchment landuse relevant to the sediment budget of the inlet. Attention is also drawn to the natural process of inlet infilling. Next, the major hydrodynamic influences operating within the harbour, the waves and tides, are examined. In the subsequent two sections, sources of sediment for the upper harbour and patterns and processes of sediment transport throughout the harbour and towards the head are discussed. The final section of this report comprises an outline of possible options for further investigation of the rates of sedimentation in the Upper Lyttelton Harbour, past and present.

Physiographic Setting

Situated on the northern side of Banks Peninsula (*Hikuraki*), Lyttelton Harbour is a 15 km long, rock-walled inlet with an average width of approximately 2 km. In the upper harbour, the inlet widens to form three bays: Governor’s Bay, Head of the Bay and Charteris Bay, separated by peninsulas and Quail Island (Figure 1). The harbour has a low-tide area of approximately 43 km^2 and a central, long axis oriented in an ENE-WSW direction. The Port of Lyttelton is situated 9 km from the harbour entrance on the northern side of the harbour. Construction of the breakwater arms which enclose the inner harbour was carried out during the period 1863-1876. Port access has been maintained since 1849 through extensive channel dredging (Curtis 1985).

The wider area of Banks Peninsula comprises two large Miocene (11-8 Ma) composite volcanic cones, the central areas of which have collapsed and been eroded by streams (Neumayr 1998). Subsequent drowning by the sea led to the formation of the Lyttelton and Akaroa Harbour inlets (Speight 1917). The base of the peninsula is engulfed by the glacial outwash gravels of the Canterbury Plains, which also form the surrounding continental shelf. The underlying volcanic rocks of the peninsula are commonly mantled by thick (≤ 20 m) deposits of loess blown from the Canterbury Plains during the Pleistocene and loess colluvium (volcanic detritus). This fine sediment is readily eroded from the hill slopes and transported to the sea.

Inside Lyttelton Harbour, steep rocky slopes descend to a near-flat seabed, with an average gradient of 1 in 1000, and a maximum depth of 15.5 m below mean low water springs (MLWS) near the harbour entrance (Bushell and Teear 1975). Due to the rocky nature of the inlet sides, harbour adjustments to coastal processes are largely limited to changes in the bed. Fluvial inputs to harbour are generally small, averaging approximately 1 m^3s^{-1} annually (Heath 1976), although they and their sediment load are concentrated in the upper harbour. Catchment erosion has infilled the harbour basin to depths of up to 47 m and resulted in the formation of extensive tidal flats in Governor’s Bay, Head of the Bay and Charteris Bay, which cover a combined area of about 11 km^2 at MLWS (Bushell and Teear 1975).

During the last 150 years, vegetation cover and landuse on the peninsula have changed dramatically. Pre-1860, mixed Podocarp forests and dense tussock grasslands covered approximately two and one thirds of the Lyttelton Harbour catchment respectively. From 1860-1900, over 90% of the forests were removed as a result of timber extraction, widespread burning and agricultural land clearance (Johnston 1969). In turn, these landuse changes led to increased catchment soil erosion and stream sediment yields. Today, much of the cleared land around the Lyttelton Harbour catchment is still in grassland.

Upper Harbour Stability

It is important to recognise that the heads of coastal inlets, such as Lyttelton Harbour, are naturally infilling features. The large areas of flat land at the head of Governor’s Bay and Head of the Bay, for example, represent thousands of years of accretion, with sediment sourced from erosion of the surrounding catchment, blown from the Canterbury Plains and transported from within the marine environment. As will be detailed later in this report, the existing natural process of infilling has, since the arrival of Europeans, been influenced by anthropogenic modification of the harbour sediment supply and hydrodynamics.

Hydrodynamic Conditions

According to the classification of Heath (1976), Lyttelton Harbour is characterised by a mixture of tidal currents, wind-induced waves and currents and other motions. As detailed below, circulation and sedimentation within the harbour are atypical of estuarine and inlet dynamics, with flow and patterns in sediment texture occurring parallel to the long-axis of the harbour, along much of its length. Based on vertical stratification and salinity profiles, the harbour may be divided into three discrete compartments with exchanges of water and sediment occurring between them: the well-mixed upper and lower harbour sectors and a more stratified central area separating the two (Figure 1). The average residence time of a unit mass of water within the harbour as a whole is approximately 2.09 days (Millhouse 1977).

Waves

The wave environment of Lyttelton Harbour comprises a mixture of locally-generated short-period wind waves (3.5 s) and long-period swell (10-20 s).

The cliffs of the harbour funnel the prevailing NE and SW winds along its length, generating the short-fetch wind waves. These short-period waves are often well developed at the head of the harbour. They suspend fine silt deposits throughout the upper harbour, facilitating their transport on the tidal and other currents present.

In addition, the harbour entrance is exposed to swell of unlimited fetch from the ENE and refracted swell from the SE. Curtis (1985) indicates that low-amplitude (1-2 m) swell waves with periods of 12 s and 20 s reach the harbour 24% and 30% of the time respectively. Higher-amplitude (>1.5 m) storm waves with periods of 11 s reach the harbour 10% of the time. The latter storm waves are more effective in terms of sediment transport. Waves which are sufficiently energetic to entrain fine sand-sized sediment in water depths greater than 7 m occur within the harbour 47% of the time (Curtis 1985).

Refraction of waves entering the harbour results from the influence of the dredged channel and spoil mounds and, to a lesser degree, the natural bathymetry. Since the 1970s, spoil mounds have been placed strategically in the outer northern bays, including Gollans and Livingston Bays, and at the northern side of the harbour entrance. The resulting outer harbour wave refraction has produced a major reduction in the amount of wave energy reaching the upper harbour as well as providing calmer conditions within the port and slowing the rate of dredge spoil re-circulation (Bushell and Teear 1975, Curtis 1986).

Tidal Circulation

Lyttelton Harbour experiences semi-diurnal tides with ranges of between 1.92 m during perigean (spring) tides and 1.64 m during apogean (neap) tides, with a maximum tidal range of 2.65 m.

Several investigations have examined tidal currents within the harbour, although almost all focus on central to lower areas. Garner and Ridgway (1955) used dye and float tracing to measure tidal circulations adjacent to the port and in the lower harbour. They found current velocities up to 0.25 ms^{-1} common in the harbour, with stronger flows in the south on the flood tide, whilst the more stratified ebb tide was stronger and of greater duration in the north. The asymmetry of tidal circulation between the northern and southern sides of the harbour was further confirmed by current-meter measurements by Bushell and Teear (1975) and Curtis (1985).

In addition, Curtis (1985) described the increasing distortion of the tide with distance up the harbour. He found that mean tidal velocities increased steadily towards the harbour entrance, varying from 0.15 ms^{-1} west of the port, to 0.22-0.23 ms^{-1} in the central harbour, to 0.26-0.27 ms^{-1} near the harbour entrance. Mean current velocities on the ebb and flood tides were 0.23 ms^{-1} and 0.22 ms^{-1} respectively.

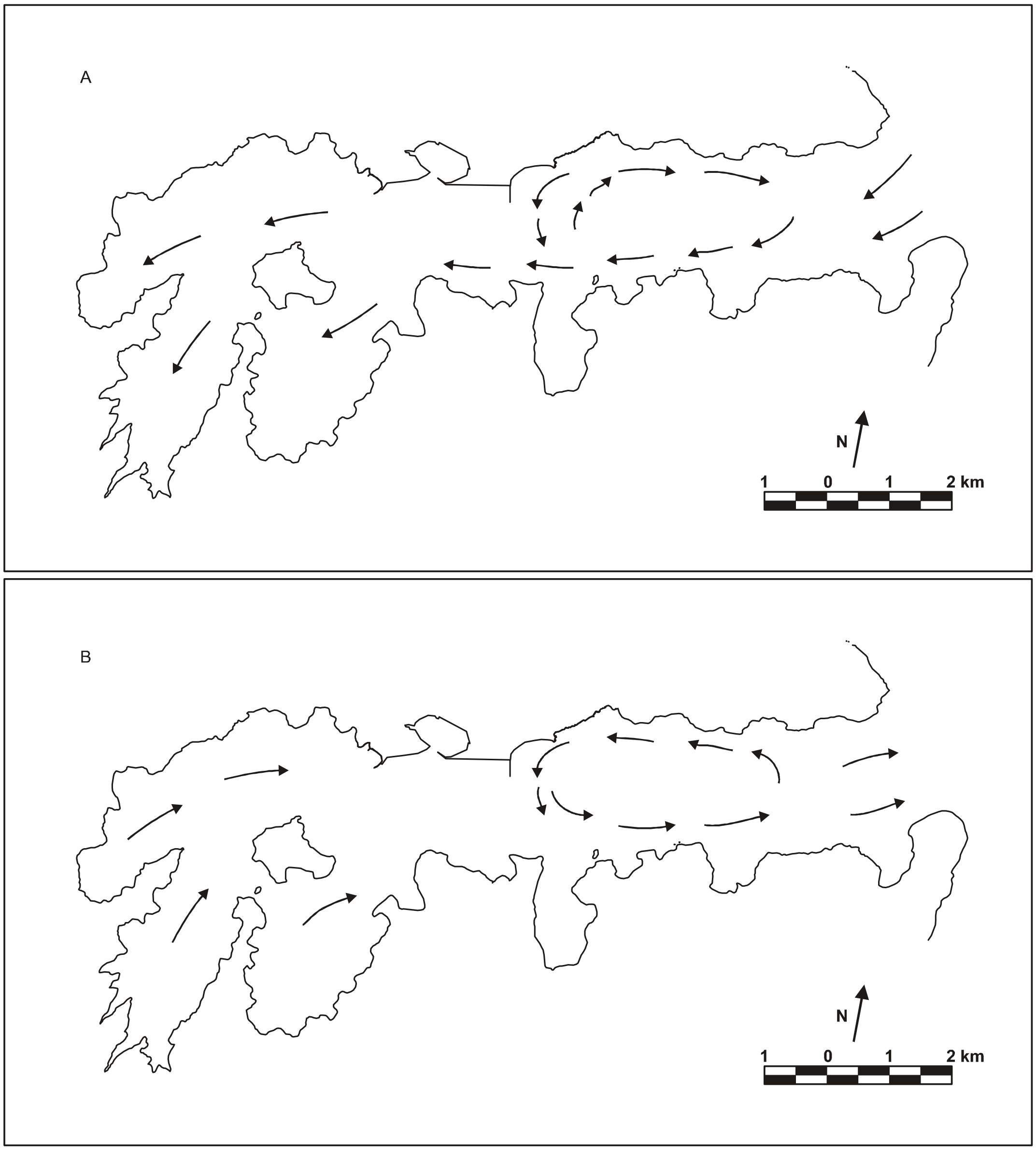


Figure 2. Harbour circulation patterns during A) the flood tide, and B) the ebb tide. Modified from Curtis (1985, 161).

Curtis (1985) suggested that the differences in tidal current velocities and durations between the two sides of the harbour gave rise to transverse, cross-harbour currents (Figure 2). Further, he postulated that the interaction of these currents with harbour topography often led to the development of a large clockwise gyre in the central to lower harbour on the flood tide and a comparable anti-clockwise gyre on the ebb tide. Gyre development was not, however, observed on every tidal cycle and, when present, the gyre operated for ≤ 50% of any given tidal cycle. Curtis (1985) suggested that the development of the gyre was a function of tidal characteristics, including amplitude and duration, and external influences, including wave and wind-induced current conditions.

Kirk (1992) observed that gyres are frequently visible in harbour waters from the air, whilst Spigel (1993a, 1993b), using dye tracing experiments, confirmed the existence of transverse flows within the central and lower harbour. Dye released from the vicinity of the port breakwater dispersed across the harbour within two tidal cycles and, later, along the length of the harbour into to the entrance of Charteris Bay in the south, and Cass and Rapaki Bays in the north.

Sediment Sources

Sedimentation within Lyttelton Harbour may comprise material sourced externally, from catchment hill slopes or Pegasus Bay, or from sources within the harbour, including the re-circulation of dredge spoil and erosion of thick bed deposits.

Catchment Erosion

On average, an estimated 44 300 t a^{-1} of loess and loess colluvium is eroded from the Lyttelton Harbour catchment (Curtis 1985) most of which is deposited within the marine environment of the inlet (Figure 3). These deposits play a major role in maintaining high levels of turbidity within the inlet as they are readily suspended by waves and tidal currents and remain in suspension for prolonged periods.

Catchment erosion rates are an order of magnitude greater in the upper harbour between Cass Bay and Head of the Bay, than along the hill slopes adjacent to central and lower areas of the harbour. This erosion is the most important source of external sediment for the upper harbour. Fluvial inputs are concentrated in this area and sink to the bottom of the water column where their sediment load settles out rapidly.

Pegasus Bay

The volume of sediment entering the harbour from Pegasus Bay is unknown (Figure 3). The lower harbour and dredged channel, however, likely operate as efficient sinks for such material, preventing any from being transported into the upper harbour.

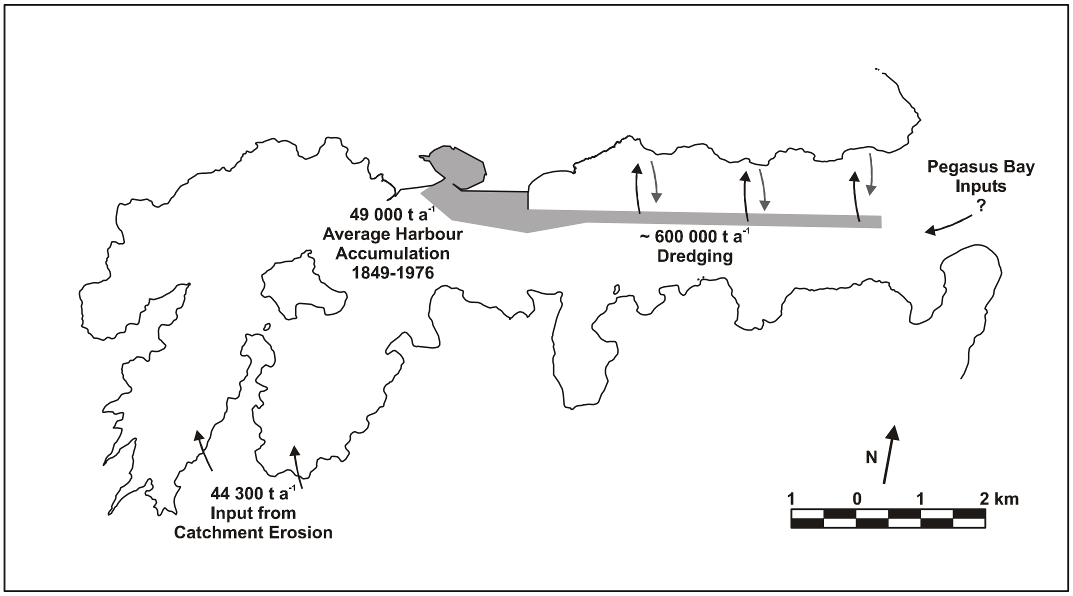


Figure 3. The Lyttelton Harbour sediment budget, including inputs from catchment erosion and Pegasus Bay, and the re-circulation of dredge spoil.

Harbour Dredging

Deepening of the inner Lyttelton Harbour bed in the form of a large-scale dredging program began in 1876. Up to 1969 dredge spoil was commonly dumped both on the southern and northern sides of the harbour at Camp Bay, in Little Port Cooper and in Gollans Bay (Figure 1). From 1969-1990 spoil was dumped predominantly on the northern side of the harbour in Livingston, Breeze and Mechanics Bays and at White Patch Point (Curtis 1985). Since 1990 all spoil dumping has been confined to the northern side of the harbour (Barter 2000).

The 7 km long harbour channel is dredged to a depth of 12 m below MLWS, at an average rate of about 600 000 t a^{-1} and maximum rate of 1 500 000 t a^{-1} of sediment (bulk density 1.68 g m^{-2}). An estimated 80% of dredge spoil is re-cycled to the channel over the long-term, with the volume of material dredged each year approximately equal to the erosion of the spoil grounds (Curtis 1985, Barter 2000).

Estimates of sediment dispersion during dredging operations range from tens of meters to beyond 3 km (Knox 1983). The dispersion of sediment from dredge plumes in Lyttelton Harbour has not been quantified. Whilst the immediate effects on turbidity levels are undoubtedly high, such plumes are likely to contribute minimal amounts of sediment to the central south and upper regions of the harbour (Kirk 1993, Barter 2000).

Based on current understanding of tidal currents and sedimentation patterns within Lyttelton Harbour, the recirculation of dredge spoil dumped on the northern bays is believed to be limited to the central and lower northern side of the inlet. Evidence as to why significant volumes of dredge spoil from the northern dump sites do not reach the upper harbour is examined in the next section of this report. Comment is also made on whether or not dredge spoil dumped in the southern bays in the past (pre-1969) is likely to have reached the upper harbour.

Patterns of Sedimentation

Sediment Texture

The Lyttelton Harbour bed sediments are generally poorly sorted and fine, ranging from clay to gravel, with a predominance of fine silt and clay.

In an early study, Brodie (1955) identified differences in the textural characteristics of bed sediments between the northern and southern sides of the harbour. He observed a well-defined boundary between mud in the north and sandier sediments in the south, attributing this pattern to spatial differences in tidal current velocities across northern and southern sides of the harbour.

Curtis (1985) observed a similar north/south division in sediment texture (Figure 4). Analysis of surface samples showed that the head of the harbour was dominated by sandy-mud with small areas of mud found in the upper reaches of Governor's and Charteris Bays, and gravels found in the upper reaches and muddy-sands found towards the centre of Head of the Bay.

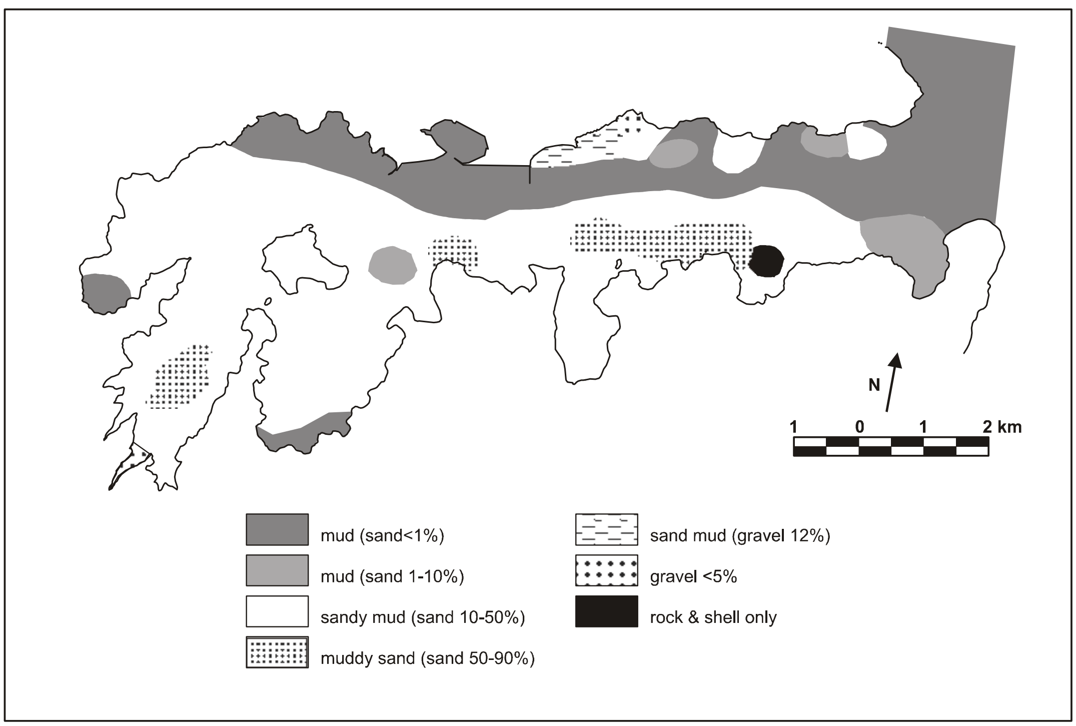


Figure 4. Surface sediment textures across the harbour (after Curtis 1985, 58).

Visual observations conducted during the course of this investigation indicate that sediments comprising a high proportion of mud are now present in the upper areas of Head of the Bay and Governor's Bay.

Changing Bed Levels

Comparisons between the structural plans archived by the Lyttelton Port Company and contemporary bed levels around the Governor's Bay jetty indicate that approximately 2.5 m of vertical accretion has occurred at the head of this bay since the early 1900s.

Patterns of sedimentation throughout the wider area of the harbour have been described by Curtis (1985) who examined hydrographic charts from 1849, 1903, 1951 and 1976. He found the following distinct phases in harbour sedimentation.

- From 1849-1903 considerable scour occurred at the head and in the centre of the harbour, whilst accretion occurred towards the entrance. Averaged over the entire harbour, erosion of the bed occurred at rates of 209 000 t a^{-1}.

- From 1903-1951 a large amount of accretion occurred at the harbour head and entrance, whilst a small degree of scour occurred in the central section. Averaged over the entire harbour, accretion of the bed occurred at rates of 351 000 t a^{-1}.

- From 1951-1976 small amounts of accretion occurred at the head and entrance to the harbour and a moderate amount of scour occurred in the central section. Averaged over the entire harbour, accretion of the bed occurred at rates of 73 000 t a^{-1}.

Over the entire period from 1849-1976, bed levels at the head of the harbour accreted up to 1 m of sediment vertically, the central harbour underwent up to 1.5 m scour, and bed levels towards the harbour entrance accreted up to 1.5 m of sediment. Averaged over the length of the harbour, accumulation occurred at a rate of 49 000 t a^{-1}, totalling 3.74×10^6 m^3 of deposition.

At the time of Curtis' (1985) investigation, moderate accretion was still occurring in the upper and entrance areas of the harbour, while erosion was ongoing in central areas. Sedimentation was occurring at a rate of $<6 \times 10^5$ m^3 throughout the harbour, the bulk of which was re-circulating dredge spoil in the central and lower harbour.

The significant bed erosion that occurred in the central and upper harbour, and the accumulation that occurred in the lower harbour from 1849-1903, is not believed to represent a 'natural' regime. Rather, this pattern of bed level change is thought to have been a response to the initial dredging operations and construction of port infrastructure (Brodie 1955, Curtis 1985).

Change from the regime of predominant bed erosion during the late 1800s, to one of predominant accretion during the early 1900s, was a direct response of the harbour to the increases in erosion and runoff that resulted from major forest clearance and landuse change around the harbour catchment up to 1900.

Although substantially reduced from the initial rates post-clearance, the moderate rates of accumulation occurring in the upper harbour since 1951 are probably higher than those that existed pre-1849. This is because higher rates of erosion result when a catchment is covered in grassland as opposed to forest. Since catchment erosion is the number one source of sediment inputs to the upper harbour, similar rates of sediment accumulation will continue here, whilst large areas of the catchment remain in grassland and/or until substantial wetland and watershed management is undertaken.

Sediment Transport

Rollability and textural analyses performed by Curtis (1985) indicate that sand transport systems along each side of the harbour operate independently so that there is no transfer of sand laterally across the inlet. These analyses also show that the along-harbour transport of sand is bidirectional. That is, due to variation in tidal and other currents within the harbour, sediment transport may occur in both up- and down-harbour directions over the short-term.

In the long-term, flood-tide currents and wave-induced currents combine to produce a net transport of fine sand towards the head along the south side of the harbour, with coarser sediment being eroded from opposite the port to Camp Bay. Fine sediment is deposited in the three upper harbour bays, with coarser material being deposited throughout the area west of the port. Sediment transport towards the head of the harbour along the south side of the inlet is enhanced by storm waves which are effective in inducing rapid sand transport.

Along the northern side of the harbour, the dumping of dredge spoil acts to maintain high mud concentrations in the form of near-bed fluid mud layers and bed deposits. Using a ‘dynamic trap’ concept, Curtis (1985) explains how material from these northern dumping grounds is contained on the north side of the harbour and re-circulated into the dredged channel whilst low concentrations of mud are maintained on the south side of the harbour.

The dynamic trap concept involves the transport and deposition of sediment according to flux gradients, where flux is defined as increasing with increasing current velocity and sediment concentration. According to this model, suspended fine sediments are transported away from areas of low flux, such as the upper or south side of the harbour, towards areas of high flux, such as the northern side of the harbour and channel, primarily by advection and diffusion normal to current flow paths. This movement of fines across the harbour is believed to be the cause of the south to north cross-harbour gradation in sediment texture from coarse to fine.

These flux gradients operate in combination with the rotational currents of the harbour so that dredge spoil from the northern bays is re-circulated into the channel, thus preventing spoil from reaching the south side of the inlet. It is suggested here that prior to 1969, when significant volumes of dredge spoil were dumped on both sides of the harbour, flux gradients would not have been sufficient to prevent spoil from the southern bays being transported along the south side of the inlet, resulting in the deposition of fines in the upper and lower harbour.

Conclusions

- The main source of material for sedimentation in the Upper Lyttelton Harbour is from catchment erosion. Patterns of sedimentation in the upper harbour over the past century have been dominated by accretion. The tendency to accrete and infill is a natural characteristic of the heads of coastal inlets.

- Pre-European rates of sedimentation have, however, been accelerated through anthropogenic modification of the catchment cover and erosion rates. Current rates of upper harbour sedimentation are expected to persist as long as the catchment remains in grassland.

- It is commonly accepted that the present dredging regime contributes minimal amounts of sediment to the upper bays and south side of the harbour. Investigation of the textural properties of surface sediments within the harbour by Curtis (1985) supports this argument, showing that the re-circulation of dredge spoil is limited to the northern side of the harbour and channel, and that the resultant flux gradients induce the northward transport of fine sediments from the south side of the harbour. There is less evidence as to how change in the wave environment, resulting from the dumping of spoil mounds towards the entrance, has affected sedimentation in the upper harbour.

Options for Further Investigation

Several options exist for further investigating the rates and causes of sedimentation in the upper Lyttelton Harbour. Following is a brief outline of these options.

Marker Stakes

One of the simplest ways of monitoring future change in the upper harbour bed levels would be to install a number of marker stakes and monitor the level of the bed relative to the top of the stakes. The height of the stakes should be surveyed to a fixed benchmark at the time of each measurement so as to correct for vertical movement in the stake. Due to the coarseness of this technique, a record of several to tens of years may be required to assess the rate of bed level change. Stakes should be designed to minimise scour of the surrounding bed and signposted adequately to avoid creating a marine hazard.

Artificial Marker Horizons

Feldspar or ceramic tile marker horizons could be used to determine rates of sedimentation at the head of the upper harbour bays. Tiles are installed at or below the surface, while feldspar is spread across the surface. Core samples are collected of the material that has accumulated above the horizon at biannual or shorter time scales. While this is an inexpensive option, it requires time to be spent in the field sampling at repeat intervals. In part, the accuracy of results will depend on the rate of sedimentation occurring, with faster, uninterrupted accumulation providing clearer results. See Reed (2002) for an outline of techniques.

Bathymetric Surveys

Changes in the shoreline position and bed levels within the upper harbour could be monitored via a program of annual or biannual bathymetric surveys similar to that currently commissioned by the Lyttelton Port Company for the central and lower harbour. A few transects along the length of each of the upper harbour bays would provide sufficient coverage. Note that a considerable record is required before trends can be quantified. Also, the cost of this option may be prohibitive if surveys are not carried out in conjunction with other harbour works.

Surface Sediment Analysis

A one-off program of surface sediment sampling and textural analysis, such as that conducted by the Lyttelton Port Company annually for Resource Consent purposes (e.g. Gillespie, Asher and Handley 1992, Barter 2000), could be undertaken in the upper harbour. Results could then be compared to those of Curtis (1985), in order to determine if recent changes have occurred. To examine longer-term changes in sediment, texture core sampling is recommended.

Core Sample Analysis

Changes in the texture and rate of accumulation of bed deposits in the three upper harbour bays could be investigated through the analysis of core samples. Cores could be used to establish decadal rates of accretion in the upper harbour over the last century, and at coarser time scales since the arrival of humans. It is recommended that the analysis include dating of ^{210}Pb and ^{137}Cs isotopes, as well as pollen and textural analyses. Techniques are outlined in Goff, Dunbar and Barrett (1998), Kirchner and Ehlers (1998) and Allgire and Cahill (2001). This is an expensive option with an estimated cost of around $15 000, including $4 000 for isotope sample testing (2 cores, 10 samples each) and $2 500 for carbon dating (2-3 samples in total). The results would, however, a) be immediate and b) cover a far longer timescale than other types of investigation.

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References

Allgire, R.L. and Cahill, R.A. (2001) Benchmark sedimentation survey of the Lower Cache River Wetlands. Report to the Illinois Department of Natural Resources, No. 2001-17.

Barter, P. (2000) Environmental monitoring of impacts of dredging and dumping in Lyttelton Harbour - 1999. Unpublished report to the Lyttelton Port Company by the Cawthron Institute, Nelson, No. 574.

Brodie, R.G. (1955) Sedimentation in Lyttelton Harbour, South Island, New Zealand. *New Zealand Journal of Science and Technology* 36(b): 306-321.

Bushell, J.B. and Teear, G.C. (1975) Lyttelton Harbour – Bottom Sediments, dredging and regime improvement. *Proceedings of the Second Australian Conference on Coastal and Ocean Engineering.* Queensland Institute of Engineers, Australia National Conference Publication 75(2): 53-68.

Curtis (1985) Sedimentation in a rock-walled inlet, Lyttelton Harbour, New Zealand. Unpublished PhD Thesis, Department of Geography, University of Canterbury.

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

Garner and Ridgeway (1955) A note on the tidal circulation in Lyttelton Harbour. *New Zealand Journal of Science and Technology* 37(1)B: 47-52.

Gillespie, P.A., Asher, R.A. and Handley, S. (1992) Environmental monitoring of impacts of dredging and dumping in Lyttelton Harbour. Unpublished report to the Lyttelton Port Company by the Cawthron Institute, Nelson, No. 200.

Goff, J.R. Dunbar, G.B. and Barrett, P.J. (1998) Monthly to decadal sediment accumulation rates in a semi-enclosed embayment. *Journal of Coastal Research* 14(2): 461-471.

Heath, R.A. (1976) Broad classification of New Zealand inlets with an emphasis on residence times. *New Zealand Journal of Marine and Freshwater Research* 10(3): 429-444.

Johnston, W.B. (1969) Modification of the natural environment by Man. *In:* G.A. Knox (ed) *The Natural History of Canterbury.* pp77-94.

Kirchner and Ehlers (1998) Sediment geochronology in changing coastal environments: Potentials and limitations of the ^{137}Cs and ^{210}Pb methods. *Journal of Coastal Research* 14(2): 461-471.

Kirk, R.M. (1992) Sedimentation in Port Levy, (Potiriwi) Banks Peninsula and its relationships with dredging in Lyttelton Harbour. Unpublished report to the Lyttelton Port Company.

Kirk, R.M. (1993) Dredging and dumping in Lyttelton Harbour – submission by the Minister of Conservation. Unpublished report to Lyttelton Harbour Board.

Knox, G.A. (1983) The ecological impact of proposed reclamation in the inner Lyttelton Harbour. University of Canterbury Department of Zoology Estuarine Research Unit Report No. 28.

Millhouse, D. (1977) The fertility of Lyttelton and Akaroa Harbours, Banks Peninsula, New Zealand. University of Canterbury Department of Zoology Estuarine Research Unit Report No. 7.

Neumayr, R.E.E. (1998) The geology of Lyttelton 1 Volcano. Unpublished Masters Thesis, Department of Geology, University of Canterbury.

Reed, D.J. (2002) Understanding tidal marsh sedimentation in the Sacramento-San Joaquin Delta, California. *Journal of Coastal Research Special Issue* 36: 605-611.

Speight, R. (1917) The geology of Banks Peninsula. *Transactions and Proceedings of the New Zealand Institute* 49: 365-392.

Spigel, R.H. (1993a) Flushing capability of Lyttelton Harbour: review of existing knowledge and suggestions for future work. Unpublished report submitted to Royds Garden Ltd in relation to water right applications for the proposed Lyttelton sewage outfall.

Spigel, R.H. (1993b) Continuous dye release: Lyttelton Harbour 30 August 1993. Unpublished report submitted to Royds Garden Ltd in relation to water right applications for the proposed Lyttelton sewage outfall.