South Otago Coast Sediment Transport: Literature Summary

Prepared for:

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Contents

Figures

1 Introduction

This report represents one of several pieces of work commissioned by the Dunedin City Council (DCC), which are being undertaken to develop a Shoreline Management Plan (SMP) for the St Clair - St Kilda beaches (Figure 1.1). While the St Clair - St Kilda beaches are the focus of the overarching project, an understanding of the larger coastal sediment transport system is imperative not only to inform decision making in the development of the St Clair - St Kilda Coastal Plan, but also support public consultation. This work considers coastal sediment transport along the southern Otago Coast from Tokatā (Nugget) Point to Kaimata (Cape Saunders) (Figure 1.1), and the implications of this regime on the long-term SMP for Coastal Plan for St Clair to St Kilda..

The aims of this work are to present data, data deficiencies and/or hypotheses on sediment transport regimes along the southern Otago coast, and the locations of sediment sources, stores and sinks; and how they may have changed over time. This has been achieved by undertaking a literature search and review of all reports pertinent to sediment transport and budgets for the area of interest (Figure 1.1).

1.1 Study Site

The coastal area from Tokatā Point to Kaimata comprises Molyneux Bay to the south and Taieri Bight in the north, divided by Quoin Point. The shoreline is characterised by sandy beaches backed by dunes, some of which are densely vegetated, and delineated alongshore by exposed cliffs and headlands, with rocky reefs scattered along the shoreline.

Carter *et al*. (1985) describes 5 major sediment facies (distinct types) that occupy the southern Otago Coast from the shoreline out to the edge of the continental shelf: Modern sand; modern mud; relict terrigenous gravel; relict/palimpsest sand; and, biogenic sand/gravel. This work is largely concerned with the *modern sand* facies that dominates the nearshore and subsequently comprises the beaches of Southern Otago.

Carter *et al.* (1985) characterise the modern sand facies as light olive-grey, fine-very fine, moderately to well sorted with a mean grain size of 0.088 - 0.23 mm (2.1 – 3.5 Φ). A modern, nearshore, sand “wedge” extends down to 70 m deep in the south, ~10 km from Tokatā Point, and only 30-40 m at Kaimata, ~1 km from the coast, where the seabed is much steeper. The modern sand wedge is dominated by Haast Schist (quartzo-feldspathic) coming from the Clutha River, however, Foveaux Strait-Western Province minerals (green hornblende and hypersthene) from the west are present. Some 10 to 25% of the sands are shell fragments (Smith, 2007).

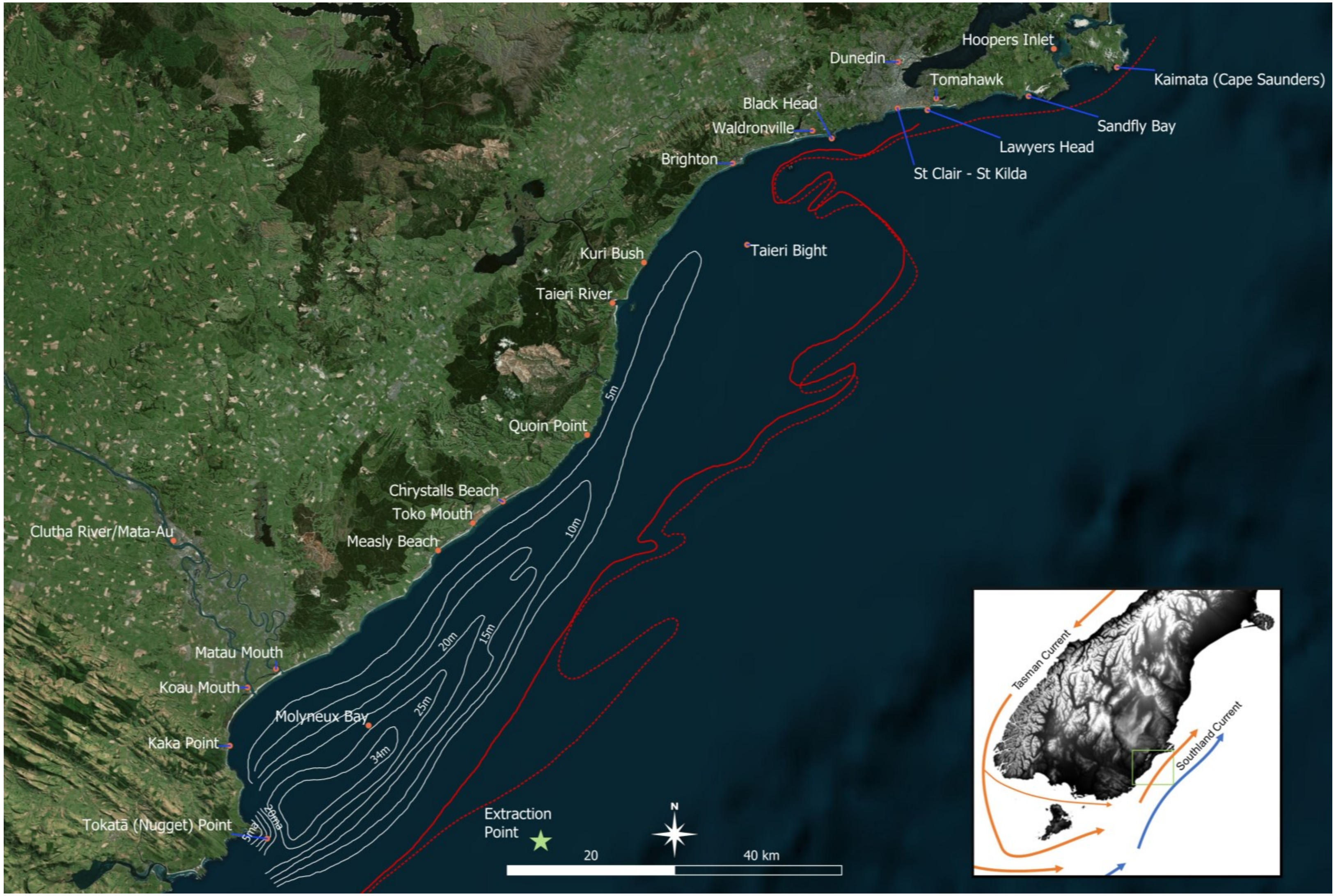

Figure 1.1. Annotated aerial photo showing: the depth of material in the modern sand wedge of Carter and Carter (1986 - white lines); seaward limit of the modern sand facies (Carter et al., 1985 (dashed red line); Carter and Carter, 1986 (solid redline)); offshore wave climate time series extraction point (green star); and prominent locations within the study site. Insert: illustration of the Tasman and Southland Currents around the southern tip of the South Island of New Zealand, and approximate study site (green box).

Most authors studying this stretch of coast have recognised the importance of the Clutha River in delivering material to the coast, some noting its influence extends well to the north of the Otago Peninsula. The Southland Current (Figure 1.1) and the wind/wave climate drive longshore transport from the southwest.

Figure 1.2 presents 40 years of wave data extracted from a point ~23 km southeast of Tokatā Point. Figure 1.2 shows the dominance of waves from the southwest. There is, however, a notable percentage of waves from the north of east. These events can setup a temporary reversal in the sediment transport system which sees material moved south and west (Carter et al., 1986; Smith, 2007). Transport to the south also occurs locally at Tokatā Point. This southerly transport is associated with a circulation of water, or anticyclonic mesoscale eddy, that occurs adjacent to Tokatā Point (Smith, 2007; Williams and Goldsmith, 2014).

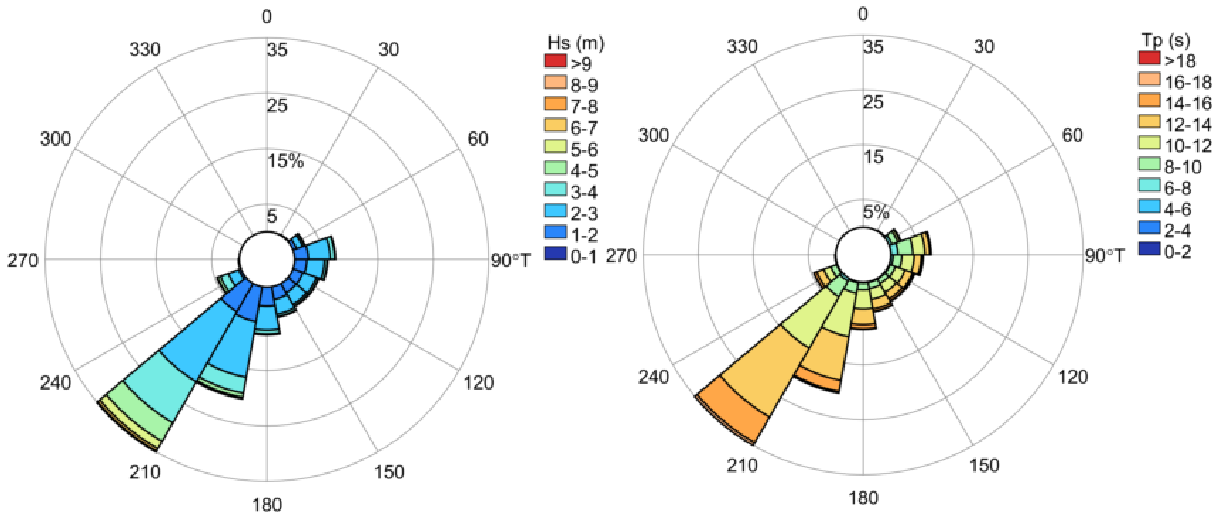

Figure 1.2: Wave roses of significant wave height (Hs; left) and smoothed peak wave period (Tp; right) from a 40 year time series extracted at 46.45°S/170.12°E (see Figure 1.1).

Sediment budgets were developed by Smith (2007) and T&T (2000), both of which leverage the earlier work of Carter (1986), and Smith (1999; 2000a,b). This project does not consider the coast to the northeast beyond Kaimata, so care needs to be taken in applying these sediment budgets and how they may relate to the St Clair – St Kilda beaches. Carter (1986) and Smith (2007) concur that the sediment transport system for the Otago coast is in net deficit. T&T (2000) argue that supply of material to the coast is above the losses. In terms of material moving through the sediment transport system, from Tokatā Point to Karitane, Smith (2007) quotes Gibb's (1973) along shore sediment flux of 588,888 m^3/yr. Carter et al. (1985) quotes Kirk (1980) at 450,000 m^3/yr and Gibb (1979) at 1,000,000 m^3/yr. The authors concede that the sediment budgets have been developed without validation against field data and that there remain unknowns regarding the sediment budget, largely around volume estimates associated with the Clutha River, but also time lags between when the system is perturbed and when change, if any, is manifested downstream.

2 Sources, Stores and Sinks

2.1 Sources

Sediment sources are areas, features and/or mechanisms that introduce new material to a system. Terrigenous sediments are delivered to the coast by fluvial sources (rivers and streams) and deposited to the coast through coastal erosion. From Tokatā Point to Kaimata there are 6 notable rivers/streams with permanently open tidal inlets, from south to north: Koau and Matau Branches of the Clutha River; Tokomairaro River; Akatore Creek; Taieri River; and, Hoopers Inlet. Kaikorai Stream and Tomahawk Lagoon Stream are coastally trapped water bodies with extremely low or intermittent drainage to the open sea.

Carter *et al*. (1985), Carter (1986), Carter and Carter (1986), Smith (2007) and T&T (2000) all concur that the Clutha River was the dominant fluvial source of sand and gravel prior to damming of the Clutha River. T&T (2000), who leveraged the work of Hicks *et al*. (2000), estimate pre- and post-damming input volumes of sand/gravel as 854,300 m^3/yr and 42,100 m^3/yr, respectively. Smith (2007), reviewing the work of Carter (1986), puts the pre- and post-damming input volumes of sand/gravel from the Clutha River at 594,444 m^3/yr and 69,444 m^3/yr, respectively. While there is a significant difference in the estimates of Smith (2007) and T&T (2000), both sources indicate an order of magnitude reduction in sand/gravel input from the Clutha River. An 88% reduction according to Smith (2007) and a 95% reduction according to T&T (2000), the latter being in line with Hicks *et al*. (2000).

Smith (2007) considers the trapping of material behind dams to be a store. However, the retention of material behind the Clutha River dams cannot be considered a store because it cannot readily enter the transport system at any given time by natural process. The current mechanism for release of this material is flood draw-down operations, which is an anthropogenic process. This is analogous to dredge spoil disposal (e.g. Port Otago), which Smith (2007) considered to be a source. There is currently no natural mechanism to release the material – if the material were stored in the Clutha flood plain, or in dune fields, then episodic storms and flood events could (re)introduce this material back into the system. Simply put, the Clutha source has been reduced due to capture by the Clutha River dams. The dams are a sink in-between any drawdown operations, with the material intermittently released during drawdown being an anthropogenic source that supplements the natural Clutha source. However, drawdown operations are not frequent, and beyond the regulatory control of the authorities addressing the St Clair – St Kilda Coastal plan.

The Roxburgh Dam was established in the 1950's. Smith (2007) estimates that 45 M m^3 of material had accumulated behind the dam in 30 years. In the late 80's, early 90's the Clyde Dam was constructed and commissioned. Storage rates for Lake Roxburgh of 1.5 million m^3/yr were reportedly reduced to 45,000 m^3/yr, with an estimated 33% (15,750 m^3/yr) being sand (Smith, 2007). Hicks *et al*. (2000) estimates a 95% reduction in sand and gravel material reaching the coast along the Clutha River, from 0.91 Mt/yr to 0.06 Mt/yr since the building of the hydro dams in the upper catchment.

The Taieri River delivers significantly less material (sand/gravel; Smith (2007): 17,000 m^3/yr; T&T (2000): 27,000 m^3/yr) than the Clutha prior to damming, but more than other fluvial sources along the coast, that are relatively insignificant when compared to the scale of the Clutha.

The amount of material being delivered from fluvial sources has been influenced anthropogenically through land use. Smith (2007) lists deforestation, burning, ploughing, planting, irrigation, roading, and grazing all increase erosion of material and therefore the fluvial input to the coast.

The investigations of Carter (1986), Carter *et al*. (1985), Smith (2007) and T&T (2000) all acknowledge the input of material alongshore from the southwest of Tokatā Point. These materials are Foveaux Strait-Western Province in origin. The concentration of these materials is diluted most significantly adjacent to the Clutha River, where Haast Schist input dominates. Smith (2007) states that the southwest input around Tokatā Point is 55,556 m^3/yr, while T&T (2000) state 223,300 m^3/yr, some 400% more. Both investigations considered the estimates of Carter (1986). The disparity exists because T&T (2000) included ~170,000 m^3/yr of material that is destined for the outer (offshore) flank of the sand wedge, in mid to outer shelf water depths in a littoral (nearshore) sediment budget, and Smith (1999, 2001a,b, 2007) did not. The result is that, in the present-day scenario, T&T (2000) consider the southwest alongshore transport to be the dominant sediment supply source, eclipsing that of the Clutha River (41,200 m^3/yr) by more than 400%. However, the inclusion of this material by T&T (2000) is considered here as incorrect as it is unlikely that a significant proportion of the ~170,000 m^3/yr of material transported to the mid to outer shelf water depths is incorporated into the nearshore littoral sediment budget.

Calcareous material inputs, the surplus mass of primary production in the form of discarded skeletons/shells, contributes 146,000 m^3/yr and 138,889 m^3/yr according to T&T (2000) and Smith (2007), respectively. There are other input sources, including other small streams, aeolian (windblown), coastal erosion of cliffs, etc. that are described in more detail in the references. However, these sources are several orders of magnitude less than the primary sources described above.

2.2 Stores

Stores represent areas or features that can be accounted for in the sediment budget, but not part of the consistent flux. Material can re-enter the transport system through more energetic and episodic natural process such as floods and storms. Stores include beaches, sand dunes, coastal plains (Clutha flood plain: 80,770 m^3/yr), sand spits and submarine bars. Smith (2007) considers the storage per unit coastline for Otago as 13,534 m^3/yr/km.

For this work a coastal polyline was delineated into sections capable of storage (Figure 2.2), mostly subaerial but also included were the longshore stretches of coast with estuaries and inlets that provide storage in ebb and flood tidal deltas amongst other features. The total of all sections of storage coastline is approximately 120 km. Smith (2007) refers to 148.4 km of coast when considering an inventory of coastal sand bodies including beaches, dunes, sandflats and spits from Tokatā Point to Karitane.

While material in dunes can be stored and released, this is a function of the amount and type of vegetation colonising a dune and metocean conditions, with storms being a primary delivery and redistribution mode of sediment in and out of dune systems. A healthy dune system vegetated with native dune species in the foredunes, grading to coastal shrubs, will tend towards a sink in some respects. The native species of *Spinifex sericeus* (kowhangatara) and *Ficinia spiralis* (pīngao, golden sand sedge or pikao) are salt tolerant (or halophyte) making them resilient to saltwater inundation, and they facilitate the growth of a gently sloping foredune. These features make for a more erosion resistant shoreline when compared to a dune colonised with exotic plant species such as the slat intolerant Marram Grass, which builds steep, high dunes that are susceptible to aggressive storm cut. Many of Otago's dunes are constrained either topographically or anthropogenically, which will limit long term dune storage potential.

The single largest store in the Otago sediment transport system is the modern sand wedge (Figure 1.1) comprised of 7,222 (Carter, 1986) to 8,130 Mm^3 (Smith, 2007), storing 752,291 (Carter, 1986) to 847,083 (Smith, 2007) m^3/yr. T&T (2000) estimate the annual storage rate at 719,500 m^3/yr, by averaging the rates of Carter (1986) and Smith (2007) and reducing this number for consolidation of material by, a potentially arbitrary, 10%.

A study conducted by Fleming (2012) aimed at characterising the state of the modern sand wedge, showed that no significant change in the maximum thickness of the sediment facies had occurred between 1989 and 2012. This conclusion was drawn by comparing an unpublished seismic survey conducted in 1989 to a modern 2012 seismic survey using similar equipment and interpretation methods.

Fleming (2012) did observe a maximum erosional change in the thickness of the modern sand wedge of 14 m. This is a significant change when considered in the context of Carter and Carter's (1986) maximum thickness of 34 m. Fleming (2012) does not describe the location of this 14 m deficit, but notes this amount of erosion would indicate very efficient sediment transport out of Molyneux Bay combined with limited sediment supply to the shelf, and concludes that the calculated changes are due to misplaced or poorly sighted fix points in the 1989 survey, although this is not verified. Revisiting the datasets and the collection of additional, reliable data to address this uncertainty is beyond the remit of this current study.

Fleming (2012) also mapped the distribution of Foveaux Strait-Western Province sediments offshore of the Clutha River mouth and compared the results to those of Carter (1986). It was found that Foveaux Strait-Western Province sediments in Molyneux Bay have migrated shoreward. Fleming (2012) attributes this to either: a decrease in sediment supply from the Clutha River; or, strengthening of the Southland Current, but provides no discussion or evidence around the latter theory.

Chiswell (1996), Sutton (2003) and Hopkins *et al*. (2010) present analyses on the Southland Current and its temporal variability. Hopkins *et al*. (2010) observed inter-annual variability in the strength of the current and its correlation to the El Nino Southern Oscillation, with a weakening during El Nino and a strengthening during La Nina. The authors note that the strength and sign of the correlations are seasonally dependent. Neither Chiswell (1996), Sutton (2003) nor Hopkins *et al*. (2010) report any long-term trend in the speed of the Southland Current.

2.3 Sinks

Sediment sinks can be related to anthropogenic activity (e.g. dredging, mining, damming), and natural processes (e.g. cross shore sediment transport during extreme storm events moving sediment offshore to depths beyond which it can be transported back shoreward). When considering a stretch of coast in terms of a sediment budget, material is lost to the system once it passes the alongshore boundaries of the site boundary – in this case Tokatā Point or Kaimata; and all exposed coasts have an offshore limit where sediment can be transported to a point after which it can no longer re-join the system. The diabathic transport of material from inshore to offshore and subsequent loss from the shelf is not considered to be a major sink in this case (Kirk, 1979 cited in Smith, 2007); and with the dominant south to north transport regime, alongshore losses are considered wholly to the north, at 117,778 m^3/yr (Smith, 2007) – noting this refers to loses beyond the north coast of the Otago Peninsula (not Kaimata).

Mining of sand at Tomahawk Beach (east of St Kilda) and Taieri River Mouth were consented in the late 1950's. Extraction has also occurred at Brighton, Kuri Bush and Waldronville, and possibly other locations (Smith, 2007). When considered in the greater sediment transport system and budgets, the volumes of these activities are relatively small (in the order of 10^3 m^3). However, these types of activities can have profound impacts at a local scale, both in the short and long term, especially if the activity is persistent (e.g. long-term consent) or excessive amounts are extracted.

At Waldronville, aerial photos from the 1940's through to present day show how the exposed dune field becomes entirely colonised (Figure 2.1). The impacts of this landscape transformation are not well understood and published literature relating to dune processes at the site could not be found. Considering a short to medium term sediment budget, a densely vegetated back dune and coastal forest could be considered as a sediment sink if material is locked away in a previously mobile landscape.

Figure 2.1: Beach scape at Waldronville in 1942 (source: Retrolenz) and 2016 (source: Google Earth) showing the colonisation by plant species of the previously exposed dune field

However, the open dune fields in early photographs are not likely natural. A simplified history of most of New Zealand's dune systems includes: the early introduction in the late 18th century, and mass introduction in the mid-19th century of both feral and domesticated non-native, herbivores (e.g. rabbits, sheep, goats, pigs) that consumed palatable native dune plant species, combined with slash and burn practices to clear vegetation for agriculture, left previously stored sand uncovered; the inconvenience of drifting sand was addressed by the introduction of exotic plants to re-stabilise dunes (mostly marram grass); the non-native, salt intolerant plant species formed dunes that are susceptible to coastal erosion (see 2.2), and fail to produce the same precolonial biome.

2.4 Summary

Figure 2.2 summarise the major sources, stores and sinks for the study site, and shows that:

- Prior to damming the Clutha River was the largest source of sand/gravel for the Otago coast contributing 594,444 -854,300 m^3/yr (Carter, 1986; T&T, 2000; Hicks *et al*., 2000; Smith, 2007).
- The Clutha River source has been significantly reduced to 42,100 - 69,444 m^3/yr (Carter, 1986; T&T, 2000; Hicks *et al*., 2000; Smith, 2007).
- This reduction is related to the construction of the Roxburgh and Clyde Dams.
- Other fluvial sources are relatively small and include the Tokomairaro River and Taieri River, amongst other smaller rivers and streams.
- Material entering the Otago coastal sediment transport system from the southwest around Tokatā Point ranges from 55,556 - 223,300 m^3/yr (T&T, 2000; Smith, 2007). T&T's (2000) estimates included ~170,000 m^3/yr of material destined mid to outer shelf water depths in the littoral sediment budget.
- Calcareous material inputs contribute 138,889 - 146,000 m^3/yr (T&T, 2000; Smith, 2007).
- Stores on the Otago coastline include beaches, sand dunes, coastal plains (Clutha flood plain: 80,770 m^3/yr), sand spits and submarine bars.
- The largest store in the Otago sediment transport system is the modern sand wedge comprised of 7,222 (Carter, 1986) to 8,130 Mm^3 (Smith, 2007), storing 719,500 m^3/yr 752,291 (T&T, 2000) to 847,083 (Smith, 2007) m^3/yr.
- A maximum erosion in the thickness of the modern sand wedge of 14 m was observed between 1989 and 2012 (Fleming, 2012), but may be attributed to user/instrument error. A change of this magnitude indicates net deficit.
- Between 1989 and 2012 Foveaux Strait-Western Province (from the southwest) sediments in Molyneux Bay migrated shoreward (Fleming, 2012). It is likely that this is a manifestation of reduced sediment supply from the Clutha River.
- Loss of material from inshore to offshore is not considered to be a major sink (Kirk, 1979 cited in Smith, 2007).
- Material is lost from the system to the north at ~120,000 m^3/yr (Smith, 2007).
- Sand mining has occurred at various times and places along the coast, including Tomahawk Beach, Taieri River Mouth Brighton, Kuri Bush and Waldronville; from as early as the 1950's.

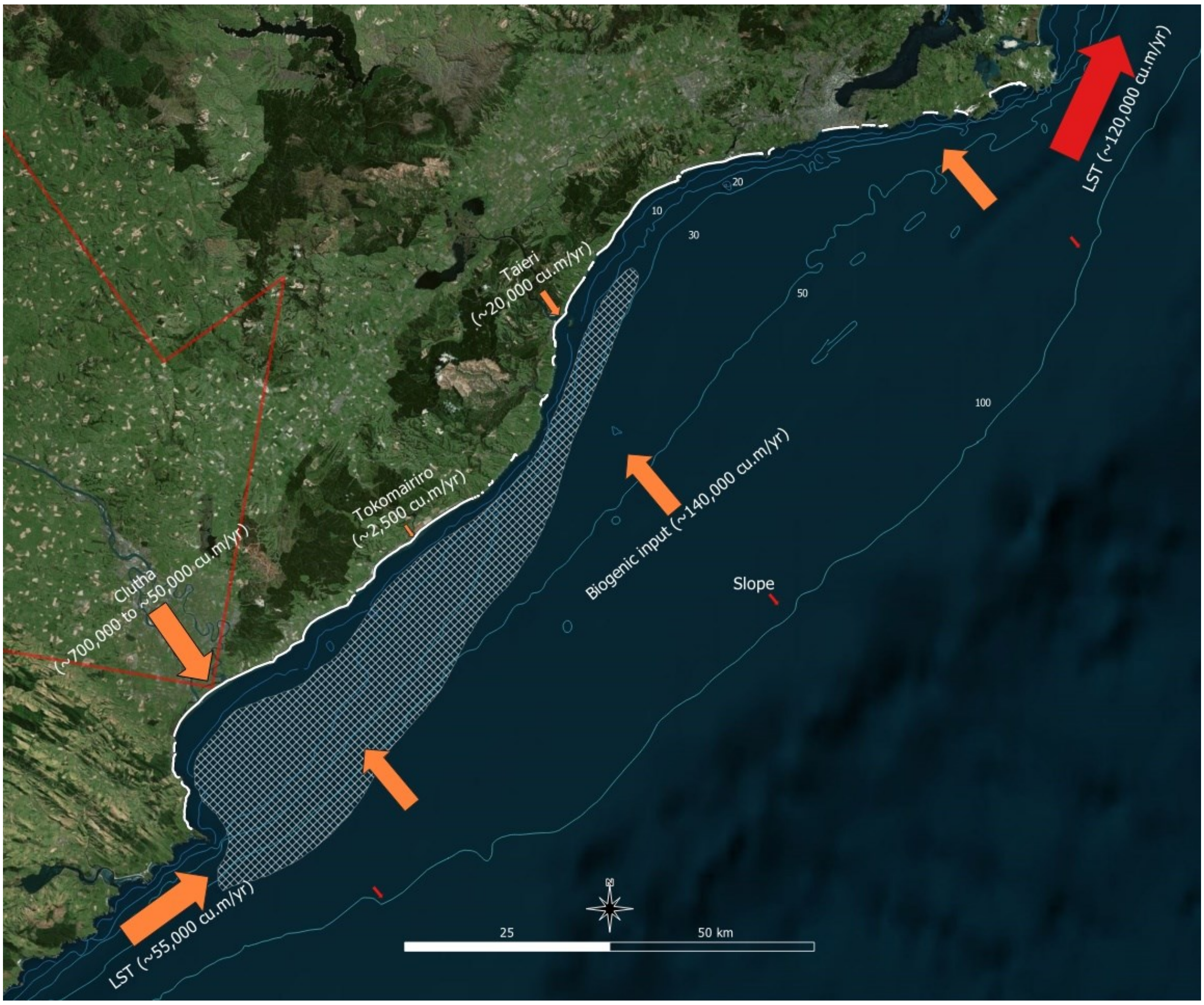

Figure 2.2: Simplified, approximately scaled annotations of primary sediment sources (orange arrows), stores (white lines) and sinks (red arrows). The large red arrowhead around the Clutha River source indicates the reduced/comprised nature of this source. The stores along the coast (white) are sections where subaerial storage is apparent (e.g. dune fields) and/or estuarine deltas (i.e. obvious storage components); the hashed white area represents where the modern sand wedge is 5 m or thicker according to Carter and Carter (1986); depth isobaths (10, 20, 30, 50 and 100 m) from LINZ Chart NZ66 (~blue lines).

3 Shoreline Change

Otago Regional Council undertook a study (Williams and Goldsmith, 2014) of historical aerial photographs, LiDAR, nearshore bathymetric survey data and terrestrial survey data to determine shoreline change in Molyneux Bay, from Tokatā Point to Chrystalls Beach for the period 1946 – 2012. They observed:

- Accretion of the foredune and an increase in sand volume occurred between Tokatā Point and Kaka Point between 2004 and 2013, while a general retreat of the foredune occurred between Kaka Point and the Matau Mouth during the same period.
- Between Kaka Point and the Koau Mouth of the Clutha River, the vegetated foredune retreated at an average rate of 3.3 m/y between 1946 and 2012. The average rate of retreat increased between 1946 and 2012. The extent of these changes are presented in Figure 3.1, and as an aerial overlay in Figure 3.2.

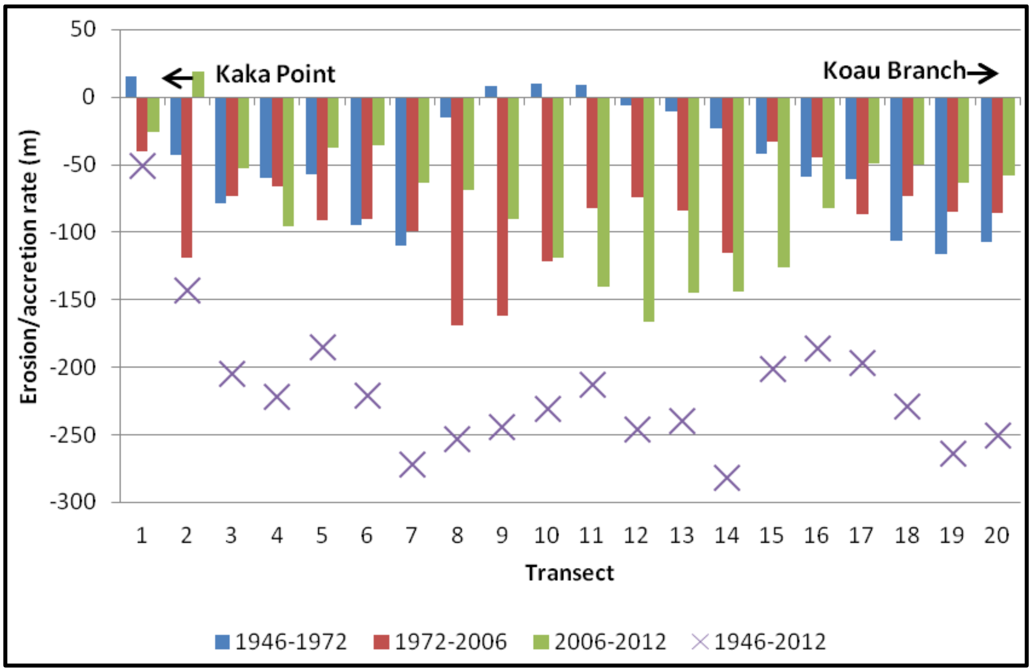

Figure 3.1: Shoreline change between Kaka Point to Koau Branch of the Clutha River from, Williams and Goldsmith (2014).

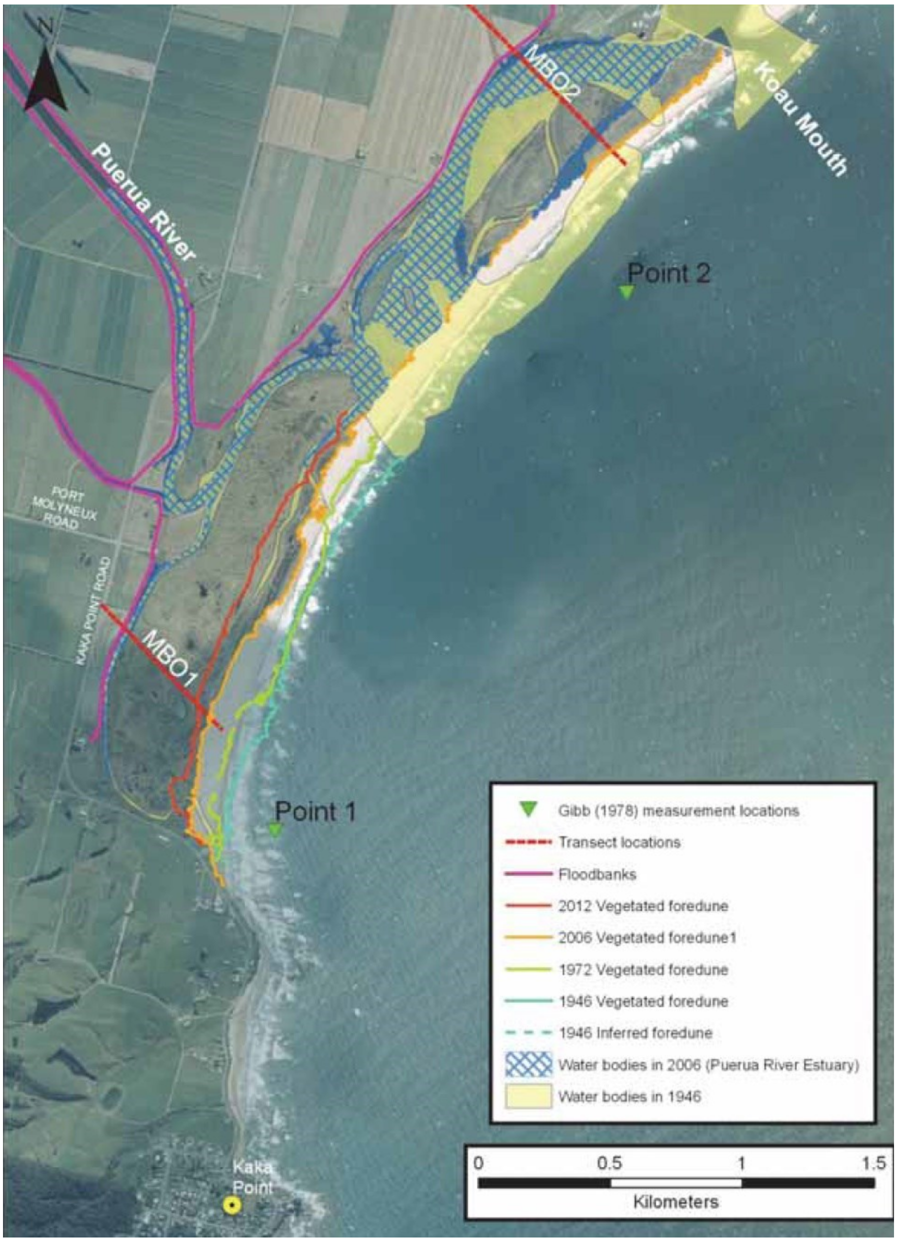

Figure 3.2. Large changes have occurred along the coast at Clutha River entrance since 1946, with retreat of over 200 m along much of this coast (replicated from Williams and Goldsmith (2014)).

- The average rate of erosion between the Koau and Matau mouths of the Clutha River between 1946 and 2012 was 0.2 m/y, with net erosion occurring at the south-western end of this beach, and net accretion towards the northeast.
- At Measly and Chrystalls beaches (to the south and north of Toko Mouth; Figure 3.4), average rates of accretion between 1946 and 2006 were 2.3 m/yr and 0.8 m/yr, respectively.

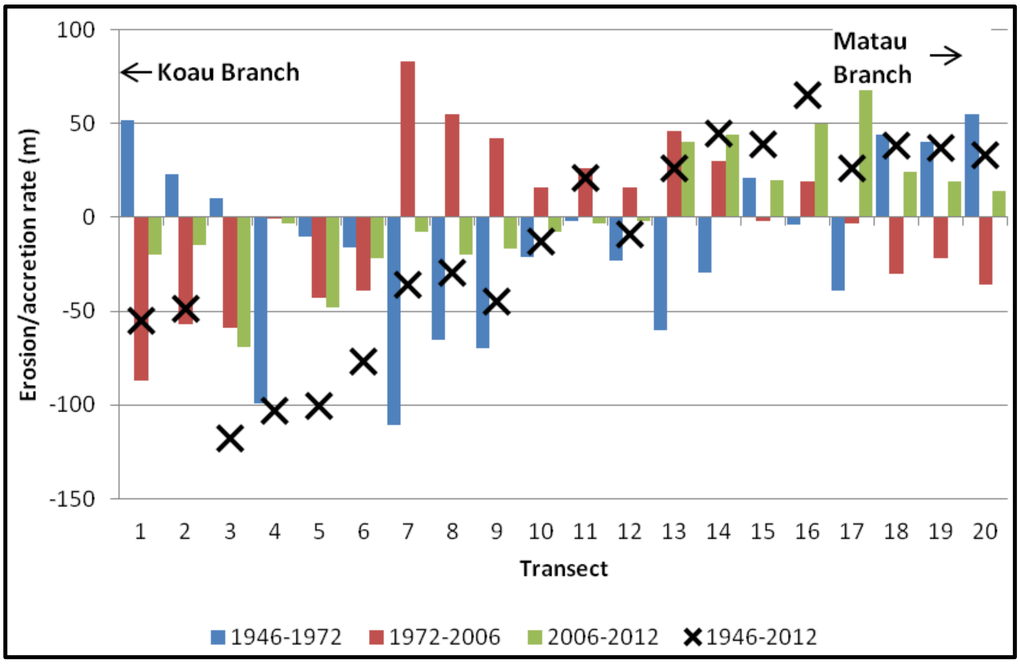

Figure 3.3: Shoreline change between Koau Branch and Matau Branch of the Clutha River, from Williams and Goldsmith (2014).

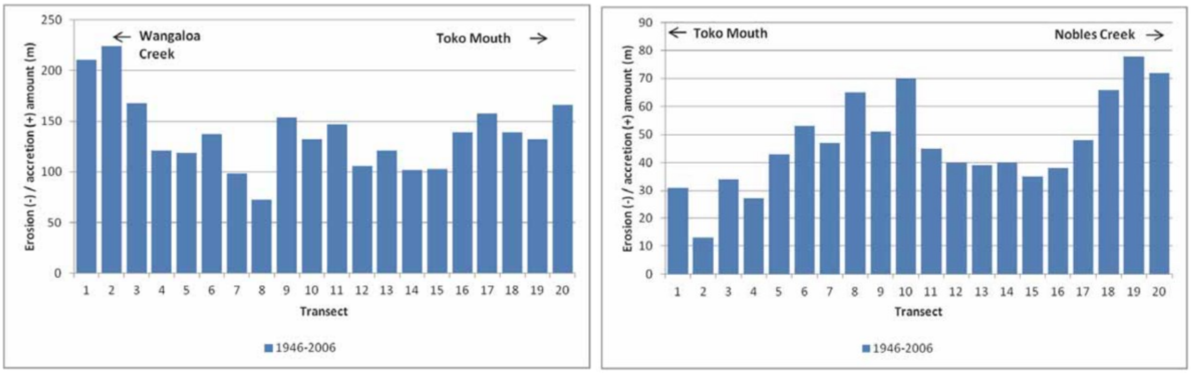

Figure 3.4: Shoreline change at Measly Beach (left) and Chrystalls Beach (right) between 1946 and 2006 at an average rate of were 2.3 m/yr and 0.8 m/yr, from Williams and Goldsmith (2014).

Figure 3.5 summarises the average (bay wide) foliage position changes compiled by Williams and Goldsmith (2014) and provides a ready comparison to the plots presented in Section 3.1.

T&T (2000) considered cadastral maps and a limited number of aerial photographs, providing ~4 data points for 14 sites between Wangola in the south and Karitane in the north. T&T (2000) concluded that there is no clear temporal trend to suggest a the long-term reduction in the rate of onshore deposition at St Clair – St Kilda beaches that could be attributed to a reduced sediment supply resulting from damming of the Clutha River. Furthermore, the report indicates that future erosion of the Otago coast will have more to do with the effects of sea level rise than sediment trapping in the Clutha River.

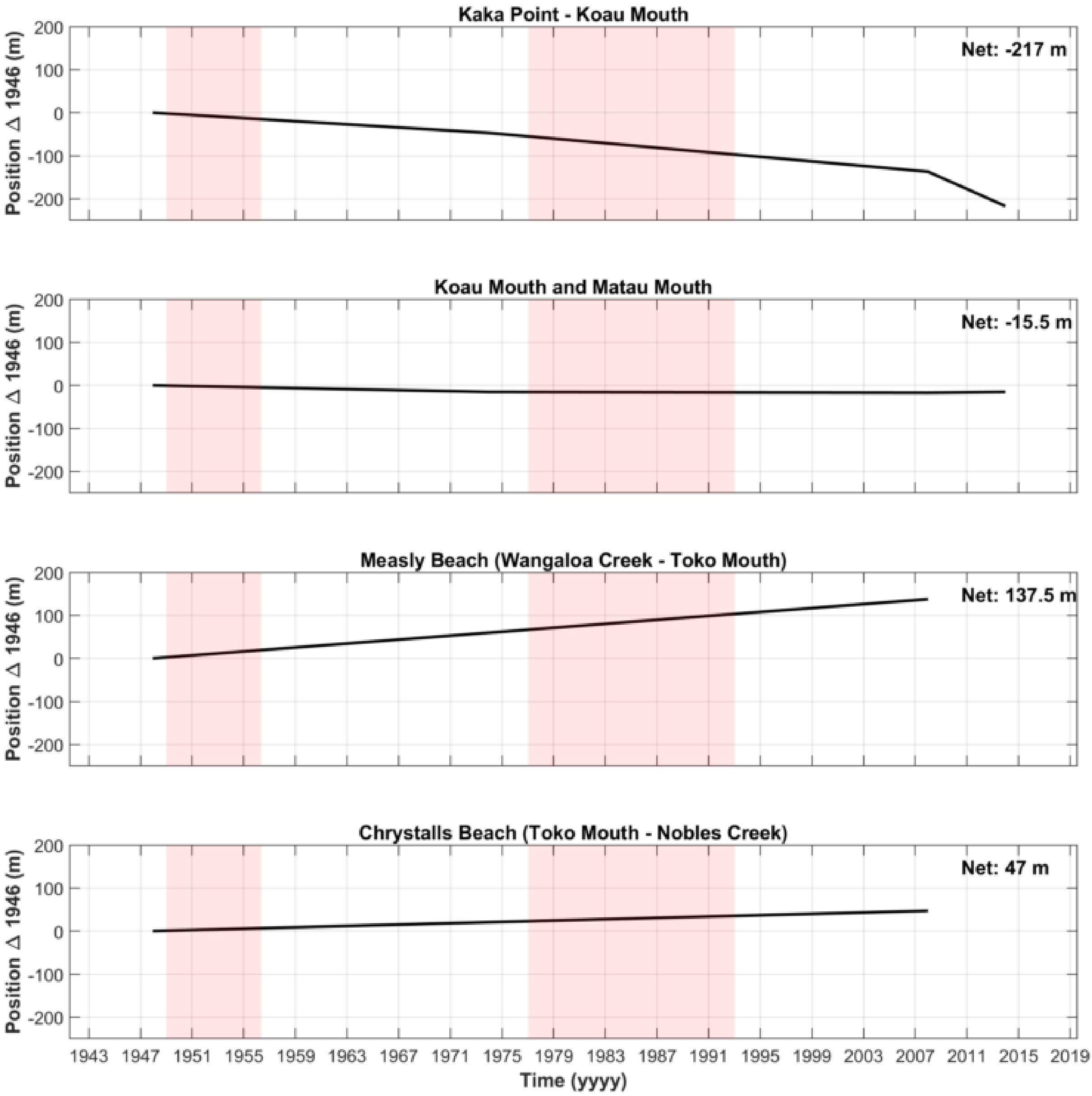

Figure 3.5. Average beach wide change from Williams and Goldsmith (2014) with Roxburgh and Clyde Dam construction periods (pink blocks). Average beach wide change are unlike the analysis in the following section, and do not provide discrete periods of coastal change.

Hilton (2010) provides a summary of studies that have considered shoreline change at along the St Clair to St Kilda coast. With the exclusion of the St Clair area, most studies indicate no clear temporal change (e.g. T&T, 2000), or an accretive trend. This is a heavily modified and anthropogenically influenced area (e.g. Duffill, Watts and King, 2002, 2004; Hilton, 2010; T&T, 2011) and may, potentially, provide a poor proxy for long term trends in sediment supply.

Taking the workings of T&T (2000), Waldronville provides a site that is a more natural setting. Waldronville is upstream in terms of sediment supply, yet still proximal to the St Clair – St Kilda beaches (separated by the Black Head cliff complex), and maintains a similar degree of wave exposure. T&T (2000) reports shoreline erosion between 1947-1982 at Waldronville of

30.2±4.6 m, and 2.6±7.7 m for 1982-1997. The earliest photo records, from 1940's, show the beach at Waldronville backed by an open dune field (see 2.3). By the late 1960's the dune field is almost entirely vegetated, the early 1980's shows that little open sand remains. Despite consistent colonisation of the dunes, this beach reportedly retreated, significantly, between 1947 and 1997.

3.1 Historical Image Analysis

To better understand the changes at Waldronville, historical aerial imagery has been georeferenced and the coastal foliage line, or cliff toe, digitized. This is also undertaken for two other representative sites within the study area, Sandfly Bay to the east of St Kilda, and Toko Moth, in Molyneux Bay to the south. The Toko Mouth analysis overlaps with the work of Williams and Goldsmith (2014) above.

It is important to keep in mind that the results of the literature review indicate a large deficit in sediment sources due to the damming of the Clutha River. This represents a reduction of input to the system of hundreds of thousands of cubic meters of sand, although this may not be manifest along each section of the coast. For example, Williams and Goldsmith (2014) found much of the coast in the region of the Clutha River delta has been eroded by hundreds of meters since 1946, while accretion of 100 metres had occurred during the same period at Toko Mouth some 20 km to the north. The expansion of the dune field at Toko Mouth could represent a store that is reducing sediment supply to the north. As previously described, the changes to coastal dune systems/sediment stores since colonisation have likely had profound impacts on sediment supply and transport along the southern coast for the past century and a half.

Figure 3.6 shows the location of shore-normal transects at representative sites, along which the seaward foliage position or cliff toe is used as a proxy for shoreline change. For Toko Mouth, two lines were digitised, a dense foliage, seaward line and a fringe foliage seaward line, the latter of which is characterised by sparser, pioneer specimens. This approach was taken as the seaward edge of the foliage was not always clear.

At Toko mouth (Figure 3.7) the overall trend is one of progradation, which is in agreement with (Williams and Goldsmith, 2014). Through the Clyde Dam construction period, T1/T2 indicate a slowing of progradation, T3 indicates an erosional trend. This is however, followed by continued accretion to present day. For Waldronville (Figure 3.8), post ~1950, an erosional trend is evident at T1 and T2 up until 2000, while the extent of erosion is not as severe when compared to the T&T (2000) assessment, trend directions for this period are in agreement. After 2000, the cliff toe position fluctuates between progradation and erosion, but the general post 2000 trend is one of accretion. T3 shows the least variation with no strong long-term trend, the trend through the Clyde Dam construction period up to ~2000 is erosion.

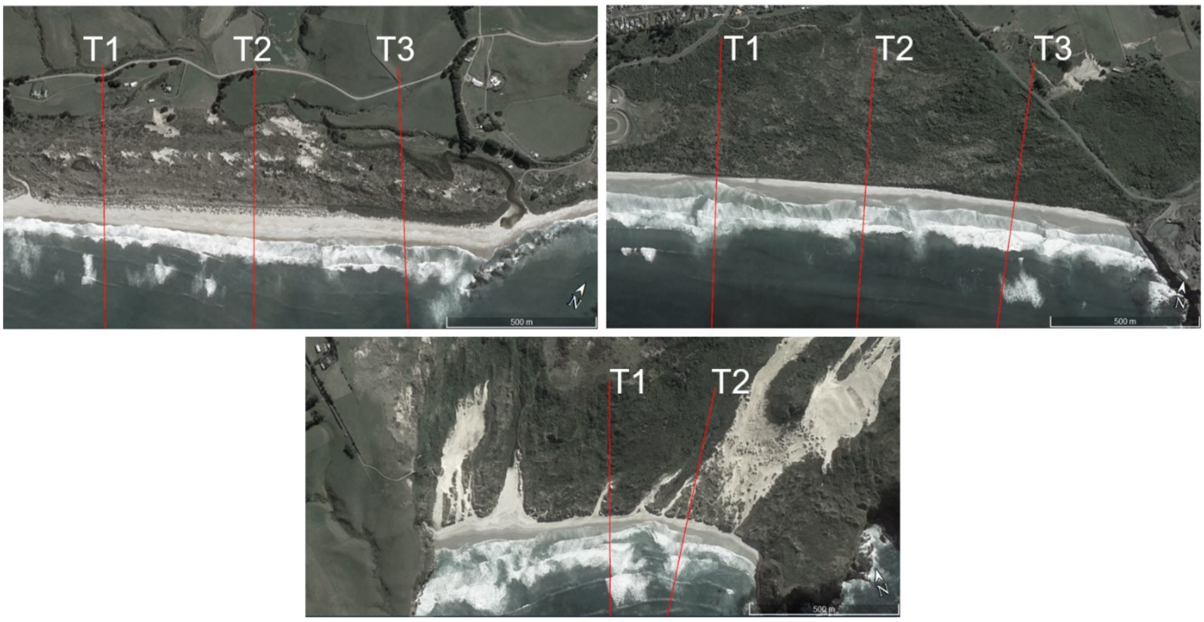

Figure 3.6: Cross-shore transect lines (red) at Toko Mouth (top left), Waldronville (top right) and Sandfly Bay (bottom). Transects are number from left to right (e.g. T1, T2, T3).

At Sandfly Bay (Figure 3.9), the overall trend for T1 is one of erosion. T1 exhibits a strong erosive trend through the Clyde Dam construction period up to ~2000, and thereafter the erosive trend is even steeper until ~2013; after which, up to 2019, the shoreline fluctuates and exhibits no distinct trend. At T2 the overall trend is accretive. T2 shows comparatively little change throughout the study period, with the exception of the last few years – after 2015 the data indicates accretion.

These results demonstrate the complex nature of the coastal dynamics along the southern Otago coastline. There is some suggestion of changes in erosion/accretion rates due to periods of damming the Clutha River, however, they are not as pronounced as those that have occurred locally at the river delta (Williams and Goldsmith, 2014), and it is noted that there are many other variables that can influence beach change (e.g. from seasonal change to beach positions, annual events just prior to sampling/photographs, hydrodynamics under different storm sources, through to medium and longer-term climatic variation (e.g. El Nino/La Nina, the Inter-decadal Pacific Oscillation (IPO), etc.). Over the period of the analysis, it is not expected that SLR will have had a measurable impact.

Many of the transects exhibit accretion and/or minimal change at the end of the observation period (i.e. present day), despite long term erosional trends in some cases. This could indicate that a new equilibrium has been reached.

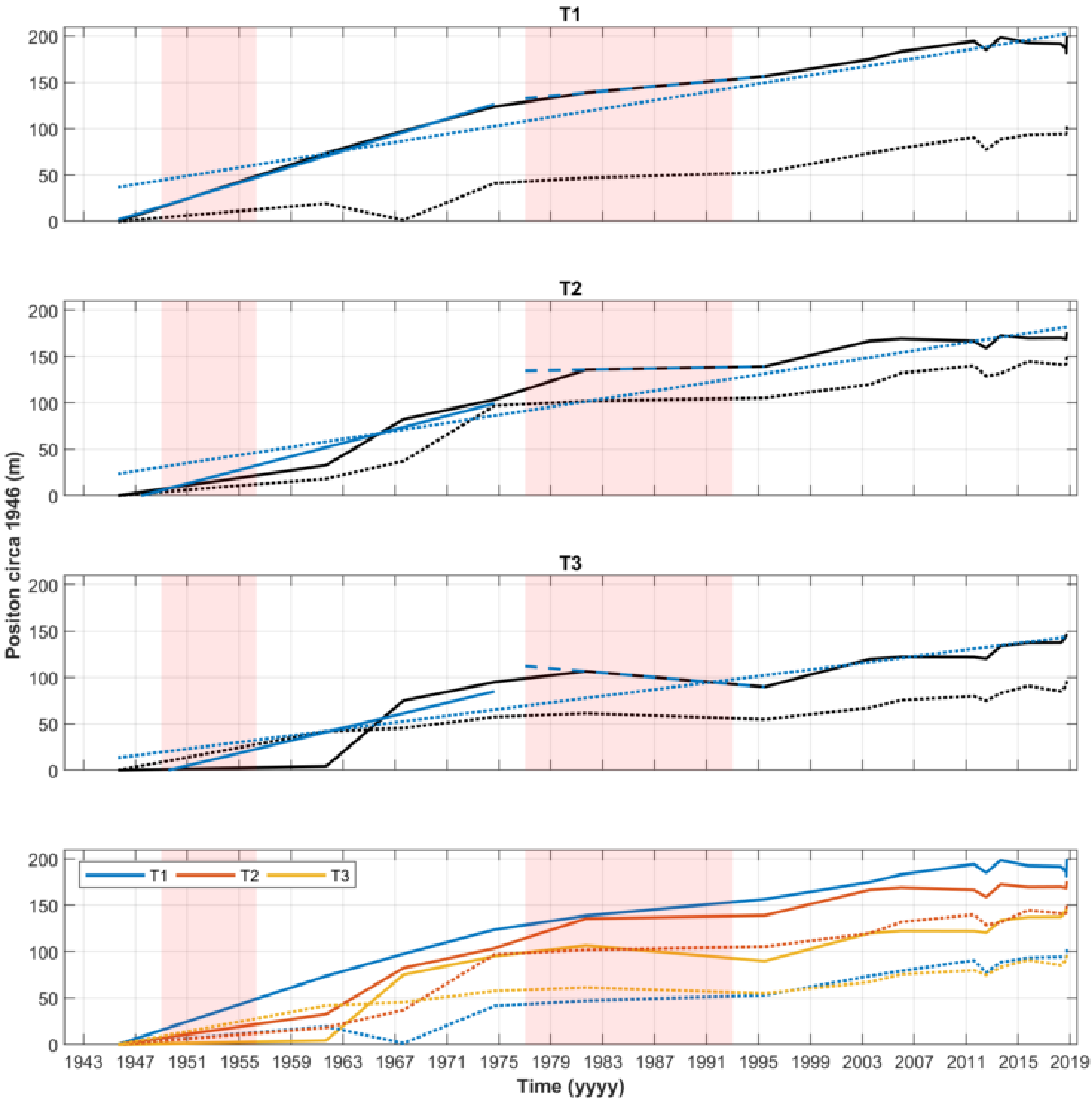

Figure 3.7: Dense (solid) and sparse (dotted) foliage position relative to 1946 at Toko Mouth with Roxburgh and Clyde Dam construction periods (pink blocks) and overall trends (blue dotted), trend from Roxburgh construction to Clyde construction (blue solid), and trend from start of Clyde Dam construction to ~2000 (blue dashed). The overall trend is one of progradation. Through the Clyde Dam construction period T1/T2 and T3 show a slowing of progradation and erosional trend, respectively.

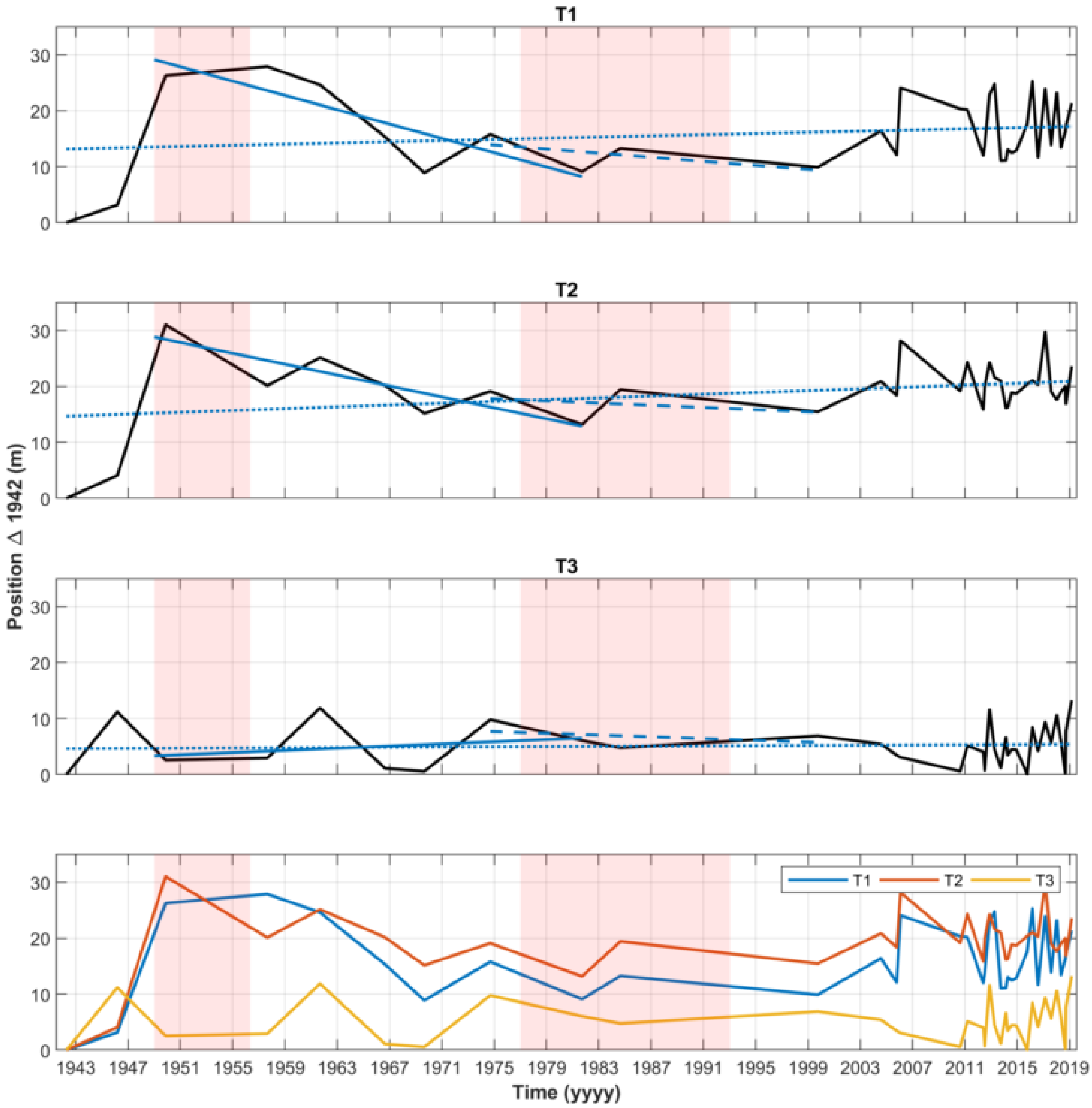

Figure 3.8: Dune/cliff toe position relative to 1942 at Waldronville with Roxburgh and Clyde Dam construction periods (pink blocks) and over all trends (blue dotted), trend from Roxburgh construction to Clyde construction (blue solid), and trend from start of Clyde Dam construction to ~2000 (blue dashed). There is no clear trend for the whole data set. Post ~1950, an erosional trend is evident at T1 and T2 up until 2000; after which the toe position fluctuates between progradation and erosion, but the general post 2000 trend is one of accretion. T3 shows the least variation.

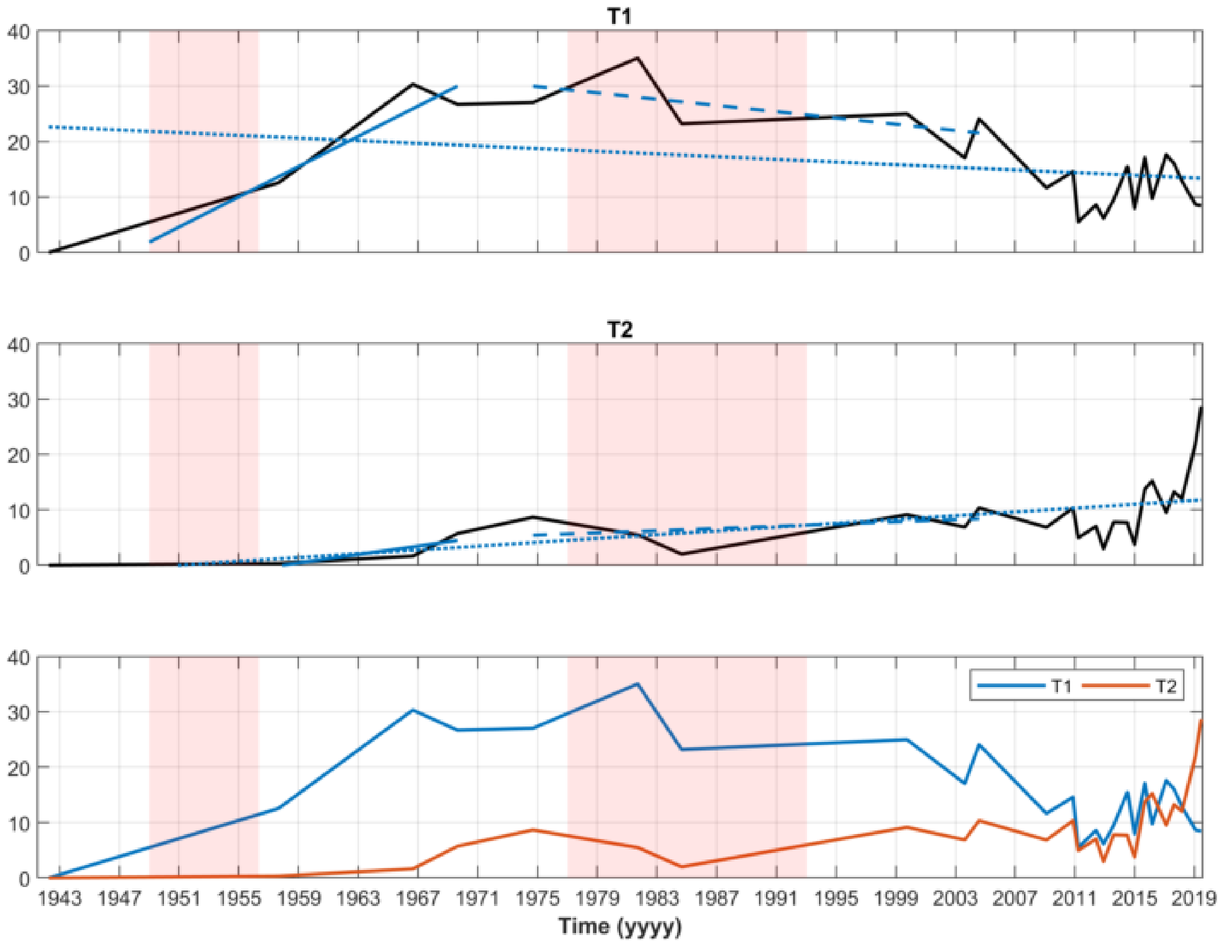

Figure 3.9: Foliage position relative to 1942 at Sandfly Bay with Roxburgh and Clyde Dam construction periods (pink blocks) and over all trends (blue dotted), trend from Roxburgh construction to Clyde construction (blue solid), and trend from start of Clyde Dam construction to ~2000 (blue dashed). The overall trend for T1 is one of erosion, at T2 the overall trend is accretive. T2 does show little change throughout the study period, with the exception of the last few years.

3.1.1 Limitations

This addendum has not included error estimates, relies on a largely linear approach to georeferencing, uses manual (by hand) digitisation, and assumes that the foliage line is a suitable proxy for shoreline change at these sites. Seasonal changes, specific storm events and medium and long-term variations have not been considered and are inherently difficult to consider with aerial image analysis. The analysis has also focussed on only 3 sites along over ~100 km of coast, the sampling frequency (number of images) is variable, and sparse in some cases.

4 Summary

An understanding of the larger coastal sediment transport system for the southern Otago Coast, from Tokatā (Nugget) Point to Kaimata (Cape Saunders), is considered imperative to the development of the Coastal Plan for St Clair to St Kilda, since sediment supply will influence the potential management options. This document provides a review of the findings of previous studies that have considered sediment transport on the Otago coast. It has considered the sources, stores and sinks of the sediment transport system, and historical shoreline change.

Identifying sediment sources and sinks, together with transport rates, is non-trivial without measurements (Goodwin et al., 2020), which is a challenge faced when attempting to quantify sediment transport for the south Otago Coast due to the lack of data. As concluded by Goodwin *et al*. (2020), the short-term challenge presented by the urgency for coastal adaptation is to determine the modern natural sediment budget for all coasts, as sand extraction can induce a long-term sediment deficit, leading to exacerbation of coastal recession over the next century.

While a detailed literature review was undertaken, much of our understanding is drawn from a limited number of seminal reports (Carter *et al*., 1985; Carter, 1986; T&T, 2000; Smith 2007), that largely supersede previous work. The authors of the main literature cited in this report concede that the sediment budgets have been developed without any validation against field data and some of the values attributed to sources, stores and sinks are educated guesses relying on a range of assumptions. There are still unknowns regarding the sediment budget, and Smith (2007) summarises these. They are largely related to material volume estimates associated with the Clutha River, but also time lags; that is, when the system is perturbed (e.g. reduce fluvial input), at what point will this be manifested downstream, along the coastline?

There is a certain degree of confidence in our understanding of some elements of this system:

- The sediment transport system that affects our primary area of interest (St Clair - St Kilda) extends along the Southland coast and up to the mountain lakes of Wakatipu, Wanaka and Hawea.
- The Clutha River is by far the largest source of sand and gravel for the Otago coastline, contributing 594,444 -854,300 m^3/yr prior to damming, with only an additional 55,556 m^3/yr being supplied from the coast southwest.
- Damming of the Clutha River at Roxburgh in 1956 and Clyde in 1992 substantially reduced the amount of sand/gravel material reaching the coast (i.e., by approximately 95% - Hicks *et al*., 2000).

- The construction of both the Roxburgh Dam and Clyde Dam has had a profound impact on the sediment transport system due to the large reduction in the major sediment source to the coast.
- Other primary sources of material for the littoral system are longshore transport from Southland and biogenic inputs, although these are/were previously a relatively small percentage of the overall sediment budget due to the extensive deepwater, cliffs and headlands between Papatowai and Kaka Point.
- The coastal landscape, especially dune areas, have fundamentally changed in the last 70-80 years.
- The single largest store in the Otago sediment transport system is the modern sand wedge, and there is ~120 km of subaerial storage potential between Tokatā Point and Kaimata; with storage in submarine bars unevaluatable.
- Neither Chiswell (1996), Sutton (2003) and Hopkins *et al*. (2010) report any long-term trend in increasing current speeds for the Southland Current, so this is unlikely to be affecting the storage of the modern sand wedge.
- It is estimated that ~600,000 m^3 of sediment could be in transit at any one time between Tokatā Point and Karitane, with an average, transport volume is 5,346 m^3/y/km.
- The colonisation of the dunes by plant species from the 1940's through to present day is quite evident. A short history of dune management is provided in Section 2.3. Large parts of this coast will have likely transitioned from a precolonial vegetated dune, to open sand, to vegetated dune likely occupied by exotic plant species, but also some native specimens.
- Three different beach sections in the study site have all exhibited a degree of erosive behaviour, and/or change in progradation rate, that temporally correlates to the construction periods of the Roxburgh Dam and/or the Clyde Dam.

There is less certainty around other elements of the system:

- T&T (2000) consider that the ~95% reduction in Clutha River source material is insignificant with respect to the overall sediment budget and not likely to be having an impact on distal beaches, including the St Clair – St Kilda beaches. However, this conflicts with the work of most studies of this system.
- Mining of sand has occurred at many places along the coast. While the volumes accounted for are small in comparison to the sources and stores of the system, the affect these activities have had in both space (local, further afield) and time (consent length) is not known.

- The interconnectivity of the coast and how readily material is transport at different parts of the coast and the volumes/rates of sediment being transported, is not fully understood.
- Despite repeat surveys, it is not known if the modern sand wedge is changing in time – the work of Fleming (2012) states little change in the thickness of the modern sand wedge, but also observes erosion of 14 m (of a possible ~35 m); Fleming suggests that the large observed erosion is more likely user/instrument error than actual erosion, although no evidence is supplied to support this. Given loss of hundreds of thousands of cubic meters of sand following the damming of the river (Hicks *et al*., 2000), the presence of southwestern sediment closer to the shore today and the loss of ~200 m of dunes in the Clutha mouth area (Williams and Goldsmith, 2014)), there is a high likelihood that the modern sand wedge has been eroded.
- The shoreline change analysis presented here as an addendum considers 2-3 transects at 3 beach sections and it is not known if this is representative of other beach compartments in the study site, especially St Clair to St Kilda. This analysis provides trends that indicate a relationship between the construction of the dams and a reduction in progradation rates and/or coastal erosion. There is, however, a large deficit of modern information pertaining to how the various beach compartments up the coast are trending (i.e. eroding, accreting or in dynamic equilibrium).
- The modern sand wedge diminishes to the north and east which may leave the distal beaches (relative to the Clutha) more sensitive, while beaches adjacent to the wide sand wedge benefit from a plentiful local source of material. If correct, the sensitivity of the distal beaches will likely be exacerbated by SLR.
- Other than around the Clutha delta there is a paucity of data pertinent to the sediment transport system between Tokatā Point and Kaimata
- While construction of the Roxburgh Dam and Clyde Dam has had an impact on the sediment transport system, the time scale of impacts are unknown.

4.1 Recommendations

From the review, it is clear that the construction of the Roxburgh Dam and Clyde Dam have had an impact on the sediment transport system of the south Otago coast due to the prior volumes of sediment input to the system being reduced by some 95%. This is manifested in the chronic and continued erosion of the Clutha River entrance and delta area that has occurred since the 1950's. Since Clutha River sediment was previously the major input/source for the south Otago coastal system, it is very likely that there have been, and/or will be, consequent impacts to this coast, including the St Clair to St Kilda beaches.

A concurrent piece of work to this literature review is the development of an indicative sediment transport model for the section of coast in question. Sand moves at different rates along different section of coast based on wave exposure, aspect of the coast to the wave climate (the Otago coast is at an oblique angle to the dominant wave climate (Figure 1.2), which increases sediment transport potential) and sediment grain size. It also varies significantly due to the differences in wave height, period and direction from event to event. For example, during an extreme event, a grain of sand can be moved from the beach to more than 10 m deep offshore in a matter of minutes, or it can be moved several kilometres along the coast in several hours, depending on the characteristics of the event. A numerical model can take the long-term wave climate and simulate sediment transport along the coast between Tokatā Point and Kaimata to improve our understanding on the connectivity of the system.

With a view towards the development of a sustainable Coastal Plan for St Clair to St Kilda, *preliminary* recommendations for the next steps, prior to the results of the sediment transport modelling, include:

- Expansion of the historical aerial analysis, including error margins, from 1946 to present to fill in the information gaps between the Toko Mouth/Measley Beach and Waldronville. This information will help to inform and interpret the results of the proposed alongshore sediment transport modelling by further detailing stores and sinks along the coast.
- A field campaign to validate the transport quantities between Waldronville and St Clair and out of the St Clair to St Kilda cell (i.e. round Lawyer's Head) to provide an understanding of inputs and losses to the beach system in the context of the present findings (i.e. there is very likely a net deficit of sediment input into the southern coast system):
    - Sediment traps
    - Hydrographic transects
    - Wave/current meter deployment
- Expansion of the existing model to accommodate for high resolution hydrodynamics capable of accounting for the distinct infrastructure and geomorphological differences St Clair, St Kilda and the Lawyers head end of this stretch of coast. While a holistic approach should be taken with respect to the management of St Clair to St Kilda, there are clearly 3 distinct areas of the beach that require different management approaches:
    1. St Clair with its highly modified shoreline (seawall, swimming pool, geotextile container protection (and associated end-effects) and surfing amenity.
    2. The central stretch and landfill/contaminated soil in the vulnerable dune area, and.

3. The steep St Kilda dune system back and capped by the John Wilson Ocean Drive.

High resolution numerical modelling supported by field data collection is likely the best way to develop a long-term solution for the situation at St Clair due to the complexity of the site. In the absence of these data and information with respect to the local coastal processes, most interventions are likely to be full-scale experiments, which are not recommended due to chance of failure and potential knock-on impacts. It is likely that different approaches will be required for the sustainable management of the different beach areas of the St Clair to St Kilda embayment. Consideration of the potential and likely impacts of sea level rise will also need to be incorporated into any strategies.

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