The Vulnerability of Tuhaitara Coastal Park to Rising Sea-levels

S. Whitelaw

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The New Zealand Coastal Policy Statement 2010 directs regional and district policy makers to identify hazards associated with sea-level rise (SLR) over a minimum 100 years. Under current emission scenarios the planet is committed to a global SLR of 0.9–2m and temperature increase of 3–7˚C by 2100. Tuhaitara Coastal Park's current Restoration Plan does not take SLR into consideration. This paper identifies several ways in which the Park is vulnerable to SLR. An overview of SLR and the geomorphology and coastal processes of the setting are reviewed. Topographic surveys maps generated from LiDAR are used to identify vulnerabilities, and recommendations are made.

Background

Tuhaitara Coastal Park is on the coast of the Waimakariri River delta in Canterbury. An abundance of sand from the Waimakariri combined with dynamic coastal process built transverse dunes as the delta prograded ~1m/year for the last 4,500 years. These dunes are the Park's only defence against rising sea-levels. Several drivers, some episodic and exacerbated by climate change, cause SLR. When the planet warmed at the end of the last glacial, evidence suggests that once certain critical thresholds were reached, sea-levels rose several centimetres/year before stabilising ~4,500 years ago. Processes leading to similar critical thresholds are being observed worldwide. Areas of Tuhaitara Coastal Park presently undergoing restoration are very likely to be inundated by rising sea-levels within the time frames set out by its current Management Plans. Further, SLR is expected to continue over the coming centuries.

Discussion

The Tuhaitara Coastal Park coastline shows evidence that it has ceased prograding. While sand is still accumulating on dunes, non-native marram grass and radiata pine has caused the dunes to develop exceptionally steep profiles, making them preternaturally vulnerable to blowouts and undercutting, affording the park no substantive protection against sea-level rise. Recent earthquakes have caused subsidence in some areas of the Park, increasing its vulnerability to inundation, particularly where the transverse dunes terminate at the mouth of the Waimakariri River. Before a problem can be managed it must be recognised. Sea-level rise is commonly viewed as a long-term problem or disregarded where coastal areas have historically prograded, such as at Tuhaitara Coastal Park. This is a deeply flawed assumption. The planet is committed to rising sea-levels regardless of what action is taken to reduce carbon emissions. Acting to mitigate the impact sooner rather than later will prove far less costly and result in a far better outcome.

Recommendations

If the Park is to be preserved for future generations, it is strongly advised that:

- A three-dimensional topographic profile of the Park and surrounding areas including Brookland's Lagoon spit be generated from the most recent LiDR data.
- Research be undertaken to determine the most suitable sand-stabilising native plants given the projected rise in temperatures and increasing exposure to salt water.
- Priority be diverted from restoring native vegetation in low lying areas likely to be permanently inundated within the 200-year time frame of the Draft Restoration Plan, to restoring native vegetation on upper beach faces and dunes. Urgent priority should be given to areas most vulnerable to inundation and erosion, identified in this report and confirmed by a 3D topographic profile.

1. Introduction

The New Zealand Coastal Policy Statement 2010 (NZCPS 2010) (Department of Conservation, 2010) directs regional and district policy makers to identify hazards associated with sea-level rise (SLR) over a minimum 100 years. Under current emission scenarios the planet is committed to a global SLR of 0.9–2m and temperature increase of 3–7˚C by 2100 (Allison *et al*., 2010; Arctic Monitoring and Assessment Program, 2011). Tuhaitara Coastal Park's current Restoration Plan (Simcock *et al*., 2008) does not take SLR into consideration. This paper identifies several ways in which the Park is vulnerable to SLR. An overview of SLR and the geomorphology and coastal processes of the setting are reviewed. Topographic survey maps generated from LiDAR are then used to identify vulnerabilities, and recommendations are made.

2. Background

2.1 Tuhaitara Coastal Park

On the east coast of the South Island, Tuhaitara Coastal Park, hereinafter referred to as the Park, in Pegasus Bay, North Canterbury, encompasses 575ha and stretches some 15km along the coastline between the Waimakariri River and Ashley Rivers. It is managed with Waikuku Beach by the Te Kōhaka o Tūhaitara Trust and Waimakariri District Council under the joint Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan 2006 (Fig. 1) (Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan, 2006). Policy provision 7.3.1 of this joint Plan relates to coastal protection: 'To manage the dune plant communities to reduce risks of dune blow-out and storm damage while enhancing and preserving the dune area as habitat for native plants and animals' (op. cit.:30).

The Park was established by the Te Kohaka o Tuhaitara Trust in 1998 as one of the outcomes of the Ngai Tahu settlement with the Crown under the Treaty of Waitangi (Ngai Tahu Claims Settlement Act, 1998; Ngai Tahu Tutaepatu Lagoon Vesting Act, 1998). Under the terms of the settlement the Tutaepatu Lagoon and Wetlands Draft Restoration Plan (Simcock *et al*., 2008) was formulated to restore the lagoon and wetlands 'for the benefit of future generations' (op. cit.:9). Tutaepatu Lagoon and wetlands have significant importance to the Ngäi Tahu as a mahinga kai and urupa and potential kainga nohoanga (*ib id*), and are a habitat for the endangered Canterbury mudfish (*Neochanna burrowsius*) (Hitchmough *et al*., 2007) regarded as taonga by iwi (Department of Conservation, 2003).

The Tutaepatu Lagoon and Wetlands Draft Restoration Plan includes a vision that the Park's ecosystems will, within the bounds of natural cyclic variability and planned restoration programmes, remain in their approximate location for the next 200 years. Neither the Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan 2006 nor the Tutaepatu Lagoon and Wetlands Draft Restoration Plan contain provisions to assess hazards posed by SLR and climate change in compliance with the NZCPS 2010. Without this assessment the Park cannot make provision for the effects of SLR. The Ministry for the Environment (Ramsay & Bell, 2008) suggest SLR will be a minimum of 0.8m until the 2090s and 2m by 2190 respectively, and continue rise thereafter. Research post-dating the Ministry's report, discussed in section 2.4 in of this report, suggests SLR may be faster. Crucially, restoration plans for the Park extend into the twenty-third century, and, 'it is clear global sea-level rise will continue far beyond the 21st century irrespective of future greenhouse gas emissions' (Nichols *et al.*, 2010:21).

Fig. 1 Tuhaitara Coastal Park (red—approximate), and waterways (blue) (composite Google Earth, 2008; National Institute of Water and Atmospheric Research, 2004; Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan, 2006).

2.2 Planning framework

The Regional Coastal Environment Plan for the Canterbury Region (Environment Canterbury, 2005a) predates both the Ministry for the Environment's *Coastal hazards and climate change: A guidance manual for local government in New Zealand* (Ramsay & Bell, 2008) and the NZCPS 2010. The Plan identifies coastal areas subject to erosion and saltwater inundation from storms and tides as hazard zones. Coastlines with stable or accreting[1] shorelines are designated Hazard Zone 1, that is, not subject to erosion for the next fifty years. The impacts of SLR are not factored into hazard zone maps (Environment Canterbury, 2005a and 2005b). This has in some instances led to a false sense of security and resulted in legal challenges as to the meaning of 'hazards zones' in the context of SLR (see for example Ramsay & Bell, 2008, Appendix 2: Relevant case law). Environment Canterbury (ECan) does not disregard SLR and climate change as potential hazards, rather, it has not yet assessed them. Consequently, in 2005, based on historical data the Park's beaches were assessed as prograding and ECan set Hazard Zone 1 near the storm berm ~2.5-3m above MSL (see Fig. 2 for an explanation of terms) (Environment Canterbury, 2005b).

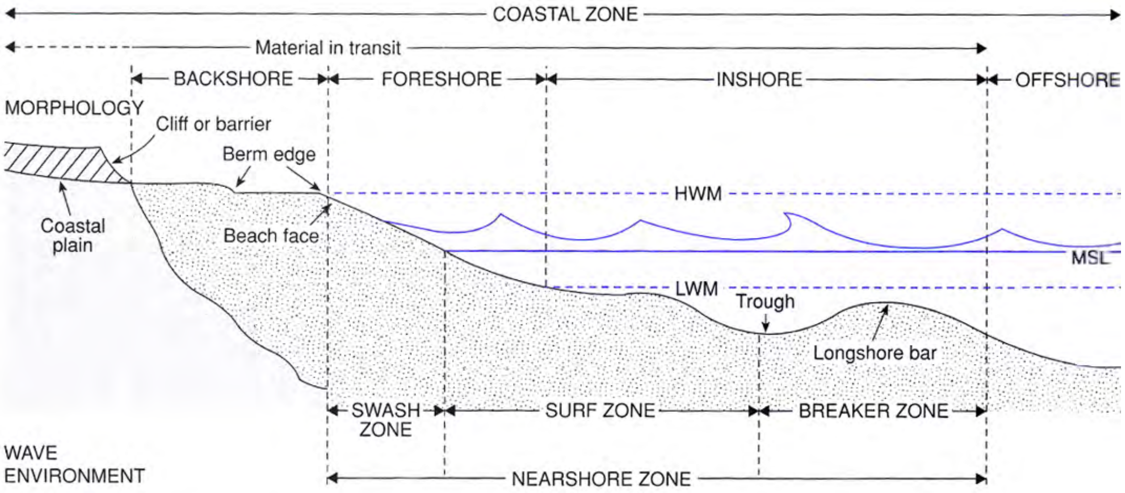

Fig. 2 Coastal zone and morphology including tide and wave environments, high water mark (HWM) and swash zone, mean sea-level (MSL), and low water mark (LWM) (Smithson *et al*., 2002:356).

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[1] Accreting means sediment is accumulating. It does not necessarily mean the coastline is extending seaward, which is described as prograding.

2.3 Summary of sea-level drivers

Multiple dynamic factors or 'drivers' cause ongoing changes in sea-levels relative to the land (Table 1). Drivers superimpose on one another globally, regionally, and locally, and over different time frames. Their relative impacts on the Park are discussed throughout this report.

Table 1 Sea-level drivers and time frames in no particular order of importance (derived from Goring & Bell, 2001; Church *et al*., 2010; Millie *et al*., 2010).

Driver		Sea-level	Timescale of effects
#1	Eustatic[2] – contribution from terrestrial cryosphere (ice caps and glaciers)	Global rise	Centuries to millennia
#2	Thermosteric[3] – thermal expansion of water due to global warming, horizontally constrained by landmasses, is forced to rise	Global rise	Centuries to millennia
#3	Steric – El Niño/La Niña-Southern Oscillation (ENSO)	Regional rise & fall	Months or longer
#4	Steric – Interdecadal Pacific Oscillation (IPO)	Regional Rise & fall	Decades
#5	Thermosteric – seasonal temperature changes	Regional Rise & fall	Seasonal
#6	Halosteric and thermosteric – regional freshwater from rivers, ice melt etc.	Local rise & fall	Hours to seasonal
#7	Chaotic interactions (seiche effect)	Local rise & fall	2 to 4 hours
#8	Wind set up of water (waves)	Regional rise & fall	Hours to days
#9	Atmospheric pressure	Regional rise & fall	Hours to days
#10	Tides	Regional rise & fall	24, 12, 8, 6, 3 hours
#11	Tsunami (tectonic, underwater landslides etc.)	Regional rise	Minutes to hours
#12	Tectonic – land subsidence or uplift relative to sea-levels	Local rise or fall	Millennia
#13	Sediment supply – excess causes coastlines to accrete and/or prograde relative to sea-level; conversely insufficient causes coastlines to erode	Regional/local rise or fall	Hours to millennia
#14	Isostatic rebound – post-Glacial land rising relative to sea-levels	Regional rise	Millennia
#15	Terrestrial water storage (non-cryospheric, ie rivers/dams/aquifers)	Global rise or fall	Centuries/ millennia

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[2] Global sea-levels due to the volume of water in oceanic basins (Nichols *et al*. 2010).

[3] Thermosteric (heat) and /or halosteric (salinity) changes are together referred to as steric changes. Where oceanic waters are warmer and/or saltier and thus are denser, sea-levels are higher relative to regions of cooler and/or less saline (less dense) waters (op. cit.).

Canterbury was not glaciated during the Quaternary (#14, Table 1) (Berryman & Hull, 2008). Milly *et al*. (2010) established that terrestrial water storage (#15, Table 1) has equalled terrestrial water loss and on balance has no impact on global sea-levels. Consequently neither of these drivers will be discussed further in this report. Tides (#10, Table 1) have the single greatest impact on sea-levels on a daily basis. However the coastline of the Park has evolved to accommodate tides, which are understood and readily forecast, and episodic drivers such as waves, ENSO, and IPO. The concern for the Park centres on how changes to these and other less predictable drivers might increase its vulnerability to erosion and /or inundation.

Because of the dynamic nature of sea-level drivers, other than tides it is often difficult to forecast or determine their contribution to the relative height of the sea to the land. Moreover, data averaged over long periods masks recent acceleration. For example the Ministry for the Environment states that during the last 100 years sea-levels around New Zealand rose ~160mm (Ramsay & Bell, 2008). Other sources state that global sea-levels rose 180mm during the twentieth century (Woodworth *et al*., 2010) and ~195mm between 1870-2004 (Glasser *et al*., 2011). The Port Lyttelton tide gauge inside Pegasus Bay shows that by 2004 SLR was 2.1mm/yr (Bryan *et al*., 2008). In 2010 SLR was 3.2mm/yr ±0.4mm (Cole, 2010). Globally, the Arctic Monitoring and Assessment Program (AMAP) (2011) determined SLR to be ~3.1mm/yr between 2003-2008. While this parallels figures from Port Lyttelton, as Cole (2010) points out the relative contribution of drivers around New Zealand is not entirely clear. It is clear, however, that global SLR is accelerating, while the episodic nature of regional and local drivers cause fluctuations around this upwards trend.

2.4 Overview of climate change

In 2007 the Intergovernmental Panel on Climate Change (IPCC) published its Fourth Assessment Report (AR4), an assessment of the published literature on the impacts of climate change (Solomon *et al*., 2007). The IPCC used various criteria to develop possible scenarios for a warming world. The worst-case scenario, A1F1, was considered to be least likely in part because of assumptions that governments would act jointly to reduce carbon emissions. AR4 projections of SLR for New Zealand were based partially on NIWA generated reports, including modelling for Pegasus Bay published six years earlier in 2001 (Fig. 3), which were based in part on previous 2001 IPCC projections (Bell *et al*., 2001).

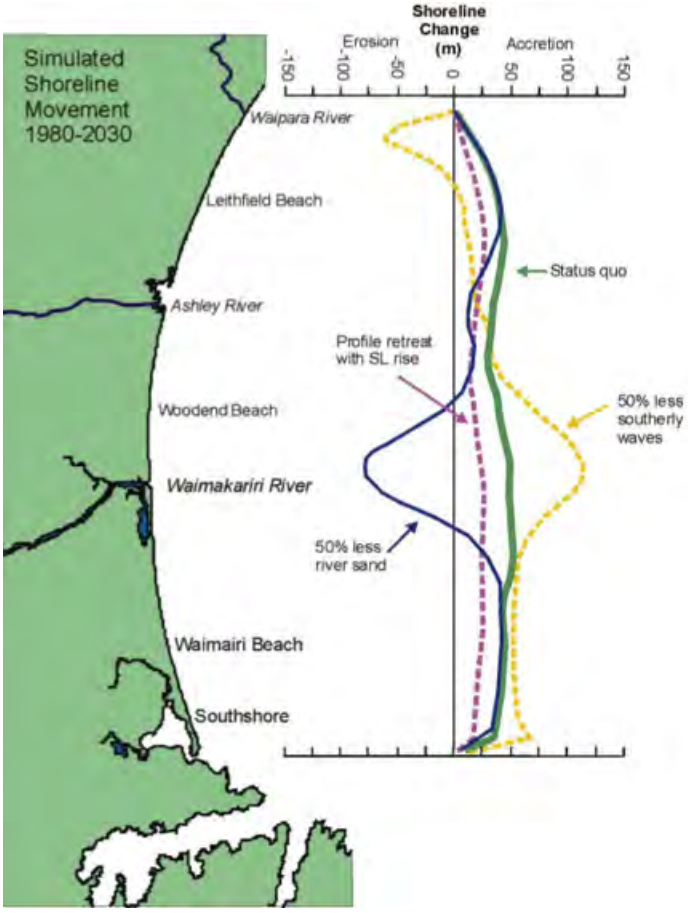

Fig. 3 Shorelines modelled for Pegasus Bay 1980-2030 using data available in 2001 for sea-level rise, sediment supply, and wave climate projections (Bell *et al.*, 2001:36).

The last time atmospheric CO_2 was at current levels some 15 million years ago, sea-levels were 23–36m higher than present (Tripati *et al.*, 2009). While the volume of ice in Greenland and Antarctica has the capacity to raise sea-levels by 60m (Woodworth *et al.*, 2010), the AR4 SLR projections largely excluded contributions from melting ice caps (#1, Table 1) because it stated that the physics of ice sheet dynamics was not sufficiently well understood (Solomon *et al.*, 2007; Nichols *et al.* 2010). Thermal expansion (#2, Table 1) was regarded as the primary driver for SLR during the twentieth and twenty-first centuries (op. cit.).

By 2009 work on the physics of ice sheet dynamics had grown substantially in peer-reviewed journals and it was evident the IPCC had underestimated the contribution from melting ice caps. At the Copenhagen Climate Congress in December that year unequivocal evidence was presented showing the AR4 worst-case (A1F1) scenarios for SLR were being met or exceeded (Fig. 4). The Conference concluded that unless governments act to reduce carbon emissions the planet is committed to temperature increases of 3–7˚C by 2100 (Fig.

5) and SLR of 0.8–2m (Allison *et al.*, 2010; Nichols *et al.*, 2010).

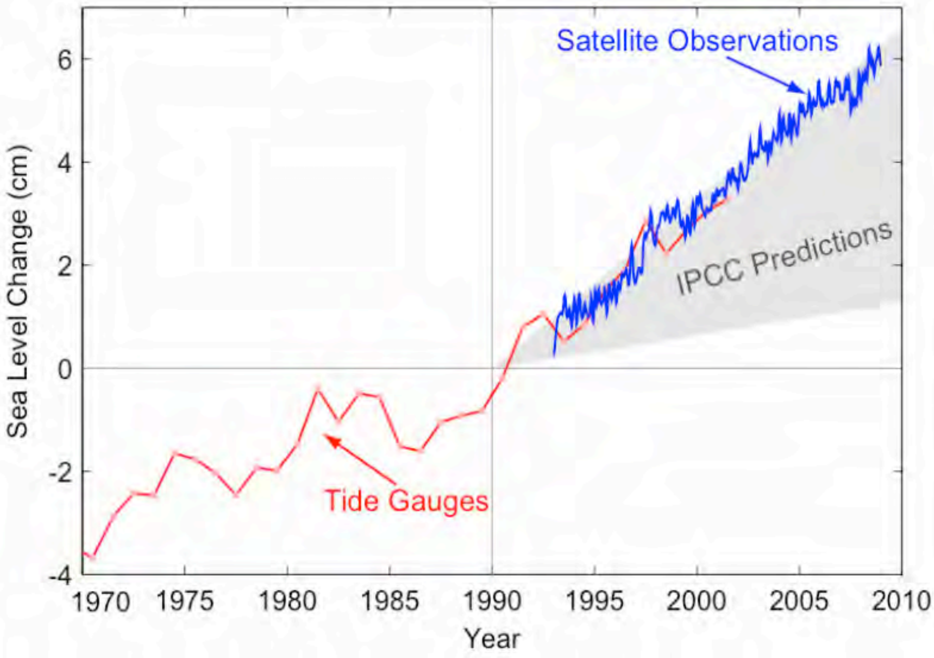

Fig. 4 Satellite observations of sea-level rise compared to IPCC projections. The top of the grey area is the A1F1 scenario (from Allison *et al.*, 2010:37).

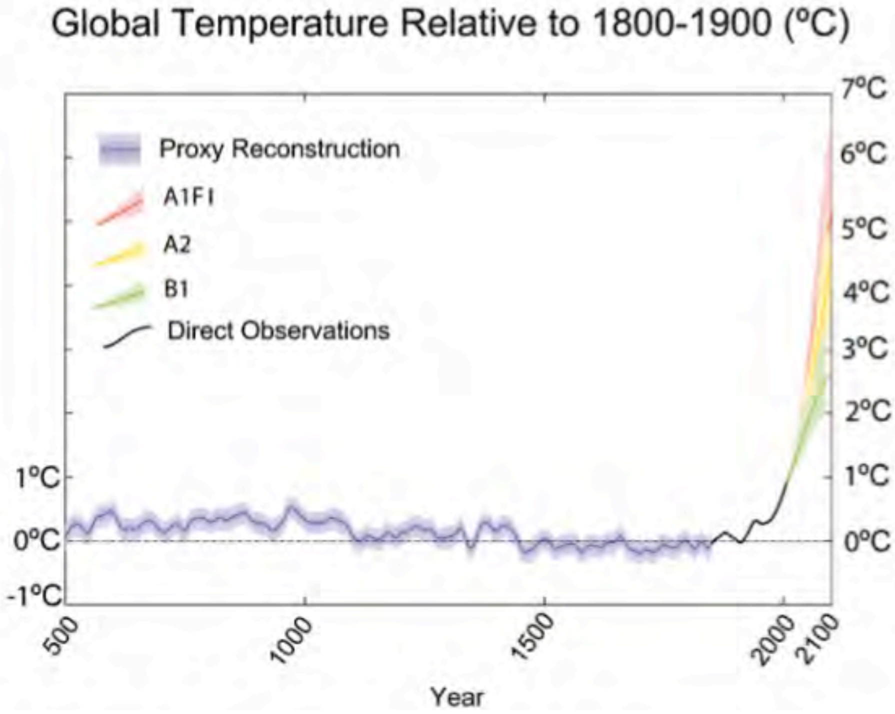

Fig. 5 If projected temperatures match the upper limit of A1F1 sea-level predictions, then by 2100 temperatures could be as much as 7˚C hotter than last century (from Allison *et al.* 2010:50).

It is currently understood that ice caps and glaciers contributed 15% to the observed SLR between 1993-2003 (Domingues *et al*., 2009; Millie *et al*., 2010), and 40% between 2003-2008 (Arctic Monitoring and Assessment Program, 2011). There is strong agreement in all models that temperatures in polar regions will continue to accelerate beyond global averages (Domingues *et al*; 2009; Allison *et al*., 2010; Steffen *et al*., 2010; Woodsworth *et al*., 2010; Arctic Monitoring and Assessment Program, 2011). At current acceleration rates, ice caps and glaciers (#1, Table 1) are likely to have the greatest single impact on SLR over the coming decades, with AMAP projecting a 0.9–2m rise by 2100 (Arctic Monitoring and Assessment Program, 2011).

The range of projections from 0.9–2m are subject to revision upwards but not downwards (Church *et al*., 2010). This upward revision depends upon the speed at which uncertain thresholds and dynamic feedbacks occur. These include but are not limited to the following:

- The stability of Greenland and Antarctic ice shelves where large system imbalances are being observed (Velicogna, 2009; Chen *et al*., 2009; Steffen *et al*., 2010; Yin *et al*., 2011; Rignot *et al*., 2011; Ding *et al*., 2011; Arctic Monitoring and Assessment Program, 2011; Siddall & Valdes, 2011). This is not limited to surface melt from rising atmospheric temperatures. Water temperatures under ice packs are 'increas[ing] basal melt rate…by a factor of approximately 6. By analogy with recent observations in Antarctica, the resulting ice-shelf loss and attendant [Hudson Bay Ice Stream] acceleration would produce a Heinrich event[4]' (Marcott *et al*., 2011). In light of research undertaken by Jacobs *et al*. (2011), which shows that a rapid increase in Antarctic water temperatures between 2009-2011 led to rapid basal melting of the Pine Island glacier, the trend is unmistakable. It is also irreversible even if CO_2 emissions are halted and/or geoengineering solutions are found to sequester CO_2 (Solomon *et al*., 2009; Gillette *et al*., 2011). This inevitable rise has been termed 'commitment to sea-level rise' (Nichols *et al*., 2010:21).
- New sources of ice loss contributing to SLR (see for example Shepherd *et al*., 2010).
- The volume of greenhouse gasses (GHGs) released from melting permafrost and tundra, absent from IPCC models, predicted by the National Snow and Ice Data Centre to shift from a CO_2 sink to source in the mid 2020s (Arctic Monitoring and

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[4] Abrupt collapse of ice sheets.

Assessment Program, 2011; Schaefer *et al*., 2011), and from submarine methane hydrates (also known as clathrates) elsewhere (Nisbet & Piper, 1998; Archer, 2007).

- GHGs released from forests that the IPCC calculated were carbon sinks but are becoming carbon sources, for example North American pine forests (Kurz *et al.*, 2008) and the Amazon rainforest (Lewis, 2011).

Moreover several assumptions used by the IPCC regarding the capacity of terrestrial and oceanic systems to absorb GHGs are being revised downwards as quantitative data emerges (see for example; McKinley *et al*., 2011; Van Groenigen *et al*., 2011; Rogers & Laffoley, 2011; and Sayer *et al*., 2011).

In terms of the rate at which SLR (and temperatures) will accelerate, a growing body of research challenges assumptions that acceleration will be linear once critical thresholds are reached and dynamic feedbacks amplify the effects of climate change (Severinghaus & Brook, 1999; Maslin *et al*., 2001; Lambeck *et al*., 2010; Nichols *et al*., 2010; Valdez, 2011; Inman, 2011). Palaeobotanic and palaeogeologic evidence suggests four and possibly five significant non-linear abrupt meltwater pulses (MWP) resulting from Heinrich events during the last 125,000 years. MWP-1A for example matches archaeological evidence of a rapid 14m SLR during the Holocene (Weiss, 2004). This is supported by palaeoclimate records of non-linear ice-sheet disintegration and subsequent SLR 'of the order of tens of millimetres per year' (Lambeck *et al*., 2010:66). Based on coral cutbacks in tectonically stable settings, Blanchon *et al.* (2009) established a SLR up to 1.8m within a 50-year time-span. While these pulses occurred when the rate of GHGs entering the atmosphere was 100 to 1000 times slower than the current rate, Maslin *et al.* (2001) suggest SLR will occur in an abrupt step once critical thresholds are reached (by inference, regardless of the speed at which these thresholds are reached). Hansen & Sato (2011) argue that SLR will be logarithmic, the rate doubling every 10-15 years, reaching up to 7m by 2100.

Rising temperatures in the Canterbury region are likely to alter SLR at Tuhaitara Coastal Park (forcings #3–#10,Table 2) (Ramsay & Bell, 2008; Allison *et al*., 2009; Woodworth *et al*., 2010). This will increase the Park's vulnerability to short-term SLR events such as storm surges, and inundation by eustatic SLR (#1, Table 1). Determining these vulnerabilities requires an understanding of the geomorphological processes that shaped and continue to act upon the Park.

2.5 Geomorphology and coastal processes of Pegasus Bay

Considerable research has been undertaken on the geomorphology and coastal processes at work in Pegasus Bay. This section is an overview.

Recent Quaternary evolution

The alluvial megafans that coalesced into the Canterbury Plains during the Quaternary are a result of tectonic uplift of the Southern Alps and high rates of erosion caused by high levels of precipitation from moisture-laden westerly winds. The sediments in the coastal zone are a mix of fluvial silt, sand, and gravel reworked and redistributed during late Pleistocene by dynamic beach processes and glacio-eustatic sea-level changes (Lecke, 2003; Hilton & Nicol, 2008).

Pegasus Bay is the northernmost coastal environment of the Canterbury Plains. Following the end of the Otira glaciation 18-20,000 years ago the coastline retreated some 50-70km as sea-levels rose. By 9,500 B.P. the coastline had largely retreated behind the Banks Peninsula, a Tertiary volcanic complex, which protected it from the predominant southerly and south-easterly swells (Lecke, 2003; Gabites, 2005). Around 6,000 B.P. Holocene sea-levels peaked ~0.5m above their current height before stabilising near their present height ~4,500 B.P. (Campbell, 1974). Between ~4,500 B.P. and present the dunes, spits, and wetlands characteristic of wave-dominated prograding deltas extended seaward up to 11km at the southern end of the Bay tapering to 4.8km around the Waimakariri River plain (Fig. 6) (Blake, 1964; Campbell, 1974; Pescini, 2002).

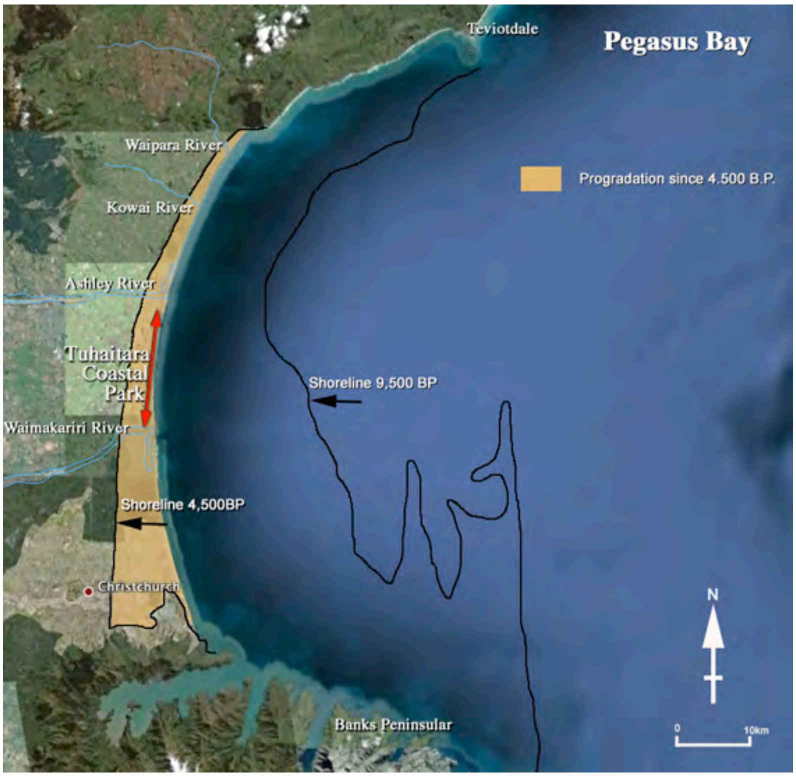

Fig. 6 The shoreline ~9,500 B.P., ~4,500 B.P., and progradation (tan section) ~4,500 B.P to present (composite from Campbell, 1974; Pescini, 2002; Google Earth, 2008).

This equates to an annual accretion rate of ~1m along the Park's coastline, consistent with Bell *et al*., 2001's projected 'status quo' modelling 1980-2030 in the absence of SLR (Fig. 3). Net progradation was characterized by cycles of intense rapid erosion and slow rebuilding (Shulmeister & Kirk, 1993; Stephenson & Schulmeister, 1999; Bryan *et al*., 2008). This illustrates that even under relatively stable climate conditions and sufficient sediment for beaches to prograde, the Pegasus Bay coastline is subject to constant readjustment in response to dynamic coastal and fluvial processes.

Centrally located in Pegasus Bay, Tuhaitara Coastal Park is a coastal barrier (as defined by Shepherd & Hesp, 2008). At its widest point it extends less than 1.5km inland, inferring it began forming <2000 B.P. as a result of the prograding Waimakariri River delta and moderate to high-energy wave climate. It evolved into a coastal barrier composed of transverse dunelands and a once extensive deltaic wetland system (Hilton *et al*., 2000).

Contemporary morphology

Transverse dunelands are the first defence against SLR (Bell *et al*., 2001) while tectonic activity (#11 and #12, Table 1) can alter the relative height of sea-levels and/or generate tsunamis (Berryman & Hull, 2008). The Park's dunes and the effect of earthquakes and tsunamis are discussed in this section.

Dunelands

Transverse dunelands are created through a combination of well-understood physical processes. Their features are governed by the amount and type of sand available, the wind regime, and the substrate that can in some areas can be below the water table. Key to understanding their morphology is the role of sand-binding vegetation in creating topographic profiles (Partridge, 1992; Hesp, 2002; Hilton, 2006).

Native species such as salt-tolerant spinifex (*Spinifex sericeus*) grow closer to the waterline than the non-native marram (*Ammophila arenaria*) (Harrison, 2006; Hilton, 2006). Fast growing with extensive rhizomes and wide spreading leaves, spinifex creates dunes up to 6m high with profiles 14-16° from the horizontal. This tempers the wind, which drops more sand than it otherwise would on un-vegetated surfaces, stabilising the dunes so they act as a buffer against SLR, and making them resistant to undercutting and erosion from storm surges (Partridge, 1992; Bell *et al*., 2000; Hesp, 2002; Hilton, 2006).

As with many coastal dunes around New Zealand, the Park's dunes have been thoroughly remodelled by non-native tree lupin (*Lupinus arboreus*), marrum grass, and plantation radiata pine (*Pinus radiata)* (Hilton *et al*., 2000; Hilton, 2006) (Appendix 1, plates 1-10 and 13). The Park's wetlands have been almost completely drained for recreational, farming and other commercial purposes (Wood, 2003; Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan, 2006).

The clumping marram grass is less salt-tolerant and consequently grows further back from the waterline. Marram is known to create dunes up to 8m high with an average profile of 24-28°, making them less stable and more susceptible to blowouts and undercutting during storm surges (Barr & McKenzie, 1975; Esler, 1978; Hesp, 2002; Hilton, 2006). Tree lupin, also abundant on the Park's dunes, fixes nitrogen in the sand, changing the chemistry and rendering it less suitable for natives adapted to lower nitrate levels. Radiata pine also changes the chemistry and shades-out sand stabilising plants (Sprent & Silvester, 1973). Radiata pine is cultivated as a commercial crop at the Park (Tuhaitara Coastal Reserve and Waikuku Beach Reserves Management Plan, 2006).

Bell *et al.*, (2001) point out that as sea levels rise, accreting coastlines will continue to accrete conditional on them receiving a continuing supply of sediment. If coastlines are in equilibrium or begin to erode then dunes will respond by increasing in height and steepness while migrating inland, effectively causing the coastline to retreat (Fig. 7).

How the Park's coastline, which has historically prograded ~1m/yr, responds to SLR depends on the stability of the dunes and an ongoing supply of sand (#13, Table 1).

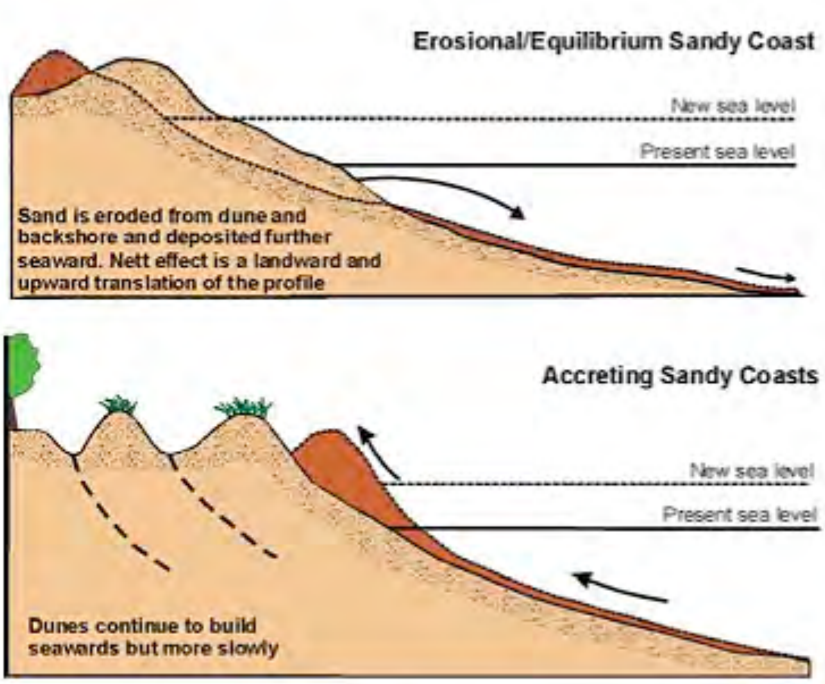

Fig. 7. Morphology of erosional, equilibrium, and accreting sandy dunelands subject to SLR (Bell *et al.*, 2001:46).

Tectonic movements

Quantifying the risk of a short term SLR event, a tsunami (#11, Table 1), to the coastline is beyond the scope of this report. However Hart & Knight (2009) established the impact of a tsunami (originating outside Pegasus Bay) on the Pegasus Bay coastline is likely to be an order of magnitude less than at Lyttleton Harbour (largely because the shape and bathymetry of the Bay causes waves to refract and dissipate. See Fig. 8). They also established that dunes which are well vegetated offer Christchurch protection against tsunamis up to 6m AMSL run-up (see also Goring, 2001). NIWA is currently undertaking a bottom survey of Pegasus Bay to, amongst other things, determine the presence of faults subsequent to the 2010 and 2011 Christchurch earthquakes (National Institute of Water and Atmospheric Research, 2011a).

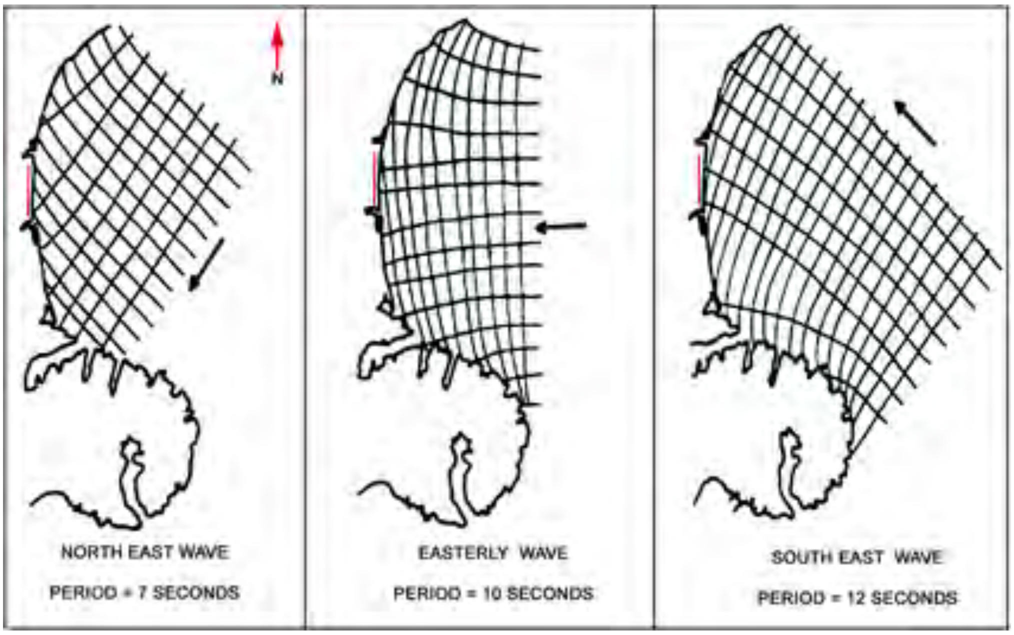

Fig. 8 Refraction of waves entering Pegasus Bay (Brown, 1976).

In 2001 tectonic movements (#12, Table 1) were not considered to be a significant driver in determining relative long term SLR around New Zealand (Bell *et al.*, 2001). Surveys north of the Pegasus Bay fault (Fig. 9) show the coastline has undergone minor uplifting (Forsyth *et al.*, 2008). South of the fault the coastline has subsided. While this movement is ~10cm/thousand years, it can be sudden. 'The most important tectonic mechanism shaping New Zealand shorelines is clearly large earthquake occurrence' (Berryman & Hull, 2008:50). Reyners (2011) notes around 5% of the movement beneath the Canterbury Plains still has not been accounted for, implying the existence of further as yet to be identified faults.

Fig. 9 Pegasus Bay fault (Forsyth *et al.*, 2008). Green area is Tuhaitara Coastal Park. Red areas are residential areas 'red-zones', that is, uninhabitable subsequent to the 2010 and 2011 Canterbury earthquakes (Canterbury Earthquake Recovery Authority, 2011).

Tuhaitara Coastal Park was known to be at a high risk of liquefaction (Christensen, 2001), which damaged some 3.5km of walkways and brought down trees during the 2010 earthquake (Orense, 2011). LiDR surveys taken March 2011 show southern sections of the Park have dropped up to 1.5m (Appendix 2, Map A) (Tonkin and Taylor, 2011). It is highly likely that reclaimed wetlands and areas adjoining river channels will subside further (Orense, 2011).

Wind and wave climate

Sea-levels constantly change due to wave action (#8, Table 2). The New Zealand land mass protects the east coast from the west to south-westerly swell waves. Consequently 53%-76% of the waves reaching the Canterbury coastline are from the south-south-east to the south-west (160- 225°), with the majority of high energy waves originating from 180-225° (Walsh, 2011a & b). Because the Banks Peninsula shelters and refracts waves from this direction, the southern end of Pegasus Bay experiences a lower energy wave climate than the northern end for much of the year (op. cit). The net result is an average wave height > 2.4m 95% of the time (Walsh 2011b), with the majority of waves >2m most of the time. Long-term wind records for the area show that the dominant winds are onshore from the east and northeast (Senior, 2002). This is typical of the wind and wave energy climate conducive to constructing barrier coastlines that have a high sediment input (Shepherd & Hesp, 2008).

There is also a significant east to north-easterly component to the waves, often associated with destructive storms. Waves from this direction are neither impeded nor refracted by Banks Peninsula. Historically, storms from this direction have resulted in significant erosion (Appendix 1, plates 8 and 9), particularly towards the southern end of the Bay where modal beach morphologies have adjusted to a lower energy regime (Bryan *et al*., 2008). North-easterly waves occur under three conditions: local sea-breezes, trough conditions developing off the lee (eastern) side of the South Island, and subtropical depressions (Stephenson & Schulmeister, 1998; Walsh, 2011a; Walsh, 2011b). However any association between north-easterly storms and large scale atmospheric and oceanic conditions is unpredictable, and best summed up by Miller *et al*. (2004):

> There is no strong seasonality of storm wave systems reaching the Christchurch coast. They may occur at any time and may occur in some years and not in others. Consequently there can also be runs of stormy years such as experienced in 1977 to 1979. There may be a link to the Southern Oscillation Index (SOI) or to Inter-decadal Pacific Oscillations (IPO), but there is no certainty to when storms might occur' (p6-14).

Thermodynamics assures increasing global temperatures will result in more energy in the atmosphere and oceans, increasing the number and intensity of storms (Bell *et al*., 2001; Solomon *et al*., 2007; Renowden, 2007). How this might impact the duration or height of erosional north-easterly waves striking the Park's beaches is unknown[5] (op. cit.; Miller *et al*., 2004). Nevertheless as a result of global SLR even if the present wave regime remains unchanged, the Park's beaches will be affected by the compound effect of drivers.

Storm surges

Storm surges are short SLR events resulting from reduced atmospheric pressure[6] (#9, Table 2). They generally are associated with storm winds (#8, Table 2), resulting in a cumulative effect that results in higher wave run-up than normal (Fig. 10; Appendix 1, plates 8 and 9).

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[5] A PhD research project on the Canterbury wave climate is currently being undertaken by A.E. Moghaddam through Canterbury University.

[6] Falling atmospheric pressure raises waters level ~1cm per hPa of fall in pressure, referred to as the inverse barometer effect (Commonwealth Industrial and Research Organisation (CSIRO), n.d.)

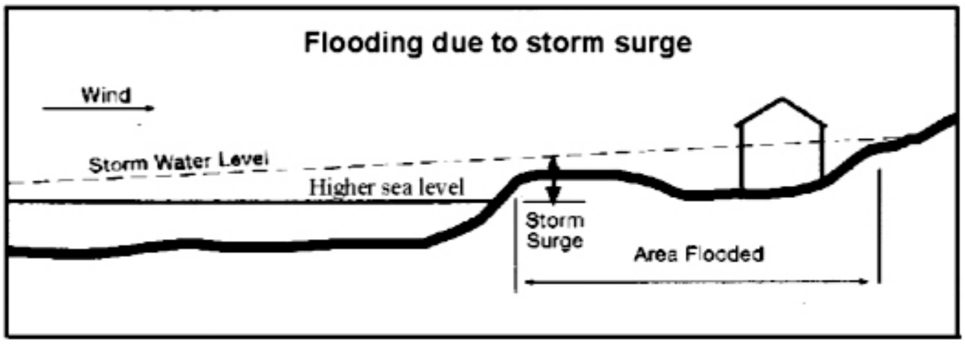


Fig. 10 Cumulative impact of storm winds + low barometric pressure (Bell *et al*., 2001:41).

The risk of storm surges is directly related to the number and magnitude of low-pressure storms and the morphology and gradient of the impact area, while their height is compounded by tides (#10, Table 2) (Hubbert & McInnes 1999; von Storch & Woth 2008; Webster & Stiff, 2008). In New Zealand storm surges appear to have a 1m upper limit (in addition to normal wave set-up and run-up), with an average height 0.5 – 0.7m (Bell *et al.,* 2001).

Tides

Around 95% of the changes in sea-levels along the New Zealand Coast are caused by tides (National Institute of Water and Atmospheric Research, n.d.). The largest variation occurs during perigean-spring tides, where the gravitational pull of the moon and sun combine, causing the largest sea-level rise. The mean tidal range in Pegasus Bay is 2m, with up to 2.5m (i.e., 1.25m above MSL) during perigean-spring tides (Fig 11; Appendix 1 plates 8, 9, and 11).

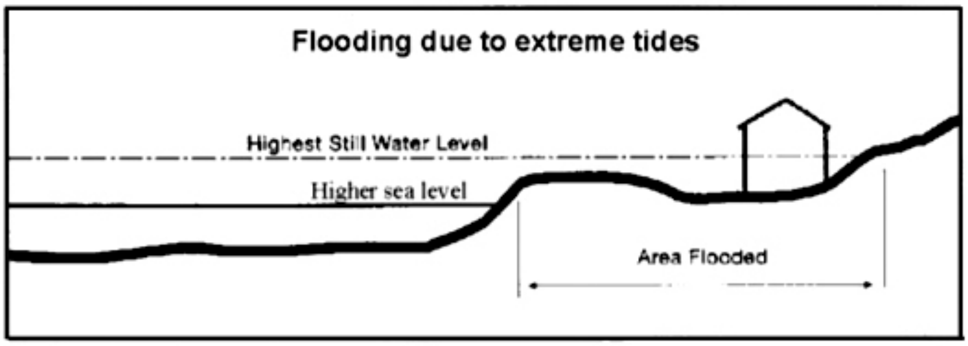


Fig. 11 Effect of extreme tides (Bell *et al*., 2001:41).

A storm surge during a spring high tide results in a cumulative effect of drivers. While storm surges are not always predictable until a few hours ahead, NIWA publishes 'red alert' perigean-spring tides dates (National Institute of Water and Atmospherics, 2011b.) For the same reasons tsunamis have a lesser impact on Pegasus Bay (Fig. 8), even when entering the Bay directly from the east, the effect of storm waves on the Park is less than on exposed coastlines.

Short-term sea-level heights measured at the Sumner Head available from NIWA and ECan (2011c) show the storm surge and inverse barometer effect at the southern end of Pegasus Bay (Fig. 12).

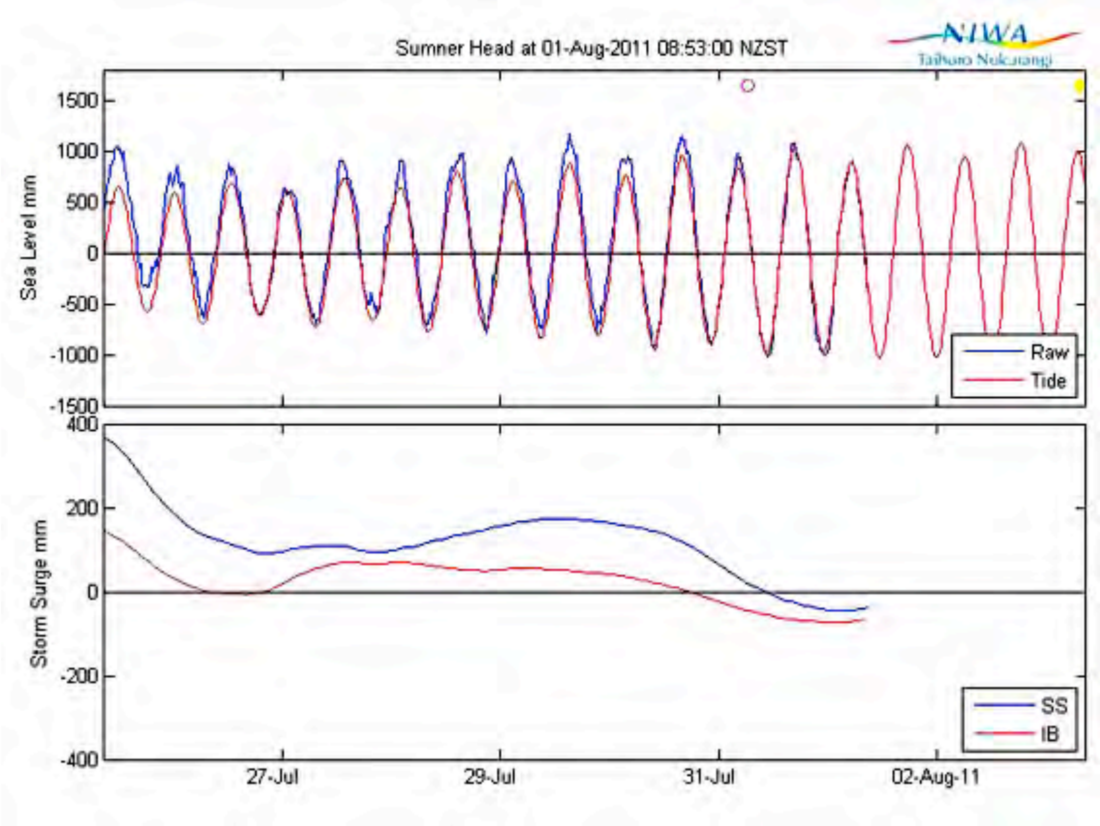


Fig. 12 The upper graph shows forecast tide (red) and raw data (blue). Raw data above or below forecast tides shows positive or negative storm surge. The lower graph shows the comparative components of storm surge (SS) (blue) and inverted barometer effect (IB) (red). Both data sets were for the period July 25 – August 04, 2011 (National Institute of Water and Atmospherics, 2011c).

Even a slight increase in eustatic sea-levels will amplify the effect of storm surges and tides as the backshore, which is unaccustomed to wave action, becomes inundated and vulnerable dunes are undercut (Appendix 1, plates 8 and 9) (Bell *et al*., 2001; Woodworth *et al*., 2010). Where inundation occurs through dune overtopping drainage from low lying areas can be can impeded by the dunes once the storm/tide recedes.

Analysis of coastal flooding in San Francisco (Woodworth *et al*., 2010) found that 100-year SLR events in the first half of the twentieth century had become 10-year events by the second half. In Australia, The Antarctic Climate and Ecosystems Coastal Research Centre has developed a risk assessment model for estimating the probability that a given sea-level will be exceeded during any prescribed period under eustatic SLR. Based on data from Australian tide gauges, 'the frequency of sea-level extremes of a given height has already increased by a factor of about three during the 20th century' (Hunter, 2008:1). Hunter estimates that for every 20cm of eustatic SLR, the frequency of extreme high tide of a given sea-level height increases by a factor of ten. Crucially, these extremes are not due to storm surges; rather they are a direct function of eustatic SLR. In the event of an SLR of 50cm, for example, 'High sea-level events which now only occur every 100 years will happen several times per year' (op. cit.).

Sediment source and movement

From 2.5.2.1 it is evident that the Park will need to maintain a positive sand budget to stay abreast of rising sea-levels. Wright *et al*., (1979) found that sediment carried by currents and destructive storm waves to depths below 20-30 metres becomes inaccessible to constructive swell waves, and is permanently removed from the sand budget. Rising sea-levels have the same effect by deepening the water.

In 1979, referring to the historic trend of the coastline to prograde, Kirk (in Pescini, 2000) described Pegasus Bay as an 'enormous sediment trap' (p51). Multiple studies of the historic and current source of sediment have been undertaken, for example Herzer (1981), Stephenson & Schulmeister (1999), Pescini (2000), Miller *et al*. (2004), Gabites (2005), Hilton & Nicol (2008). Attempts to calculate the Bay's sediment budget have produced variable results (Gibb & Adams, 1982; Duns, 1995; Hicks, 1998). Bryan *et al*. (2005) estimate that currently only 5% of sediment comes from offshore, however this percentage is declining as sea-levels rise, while 95% of sediment is derived from rivers: ~18% from the Ashley and Waipara Rivers and ~77% from the Waimakariri River (Table 2). Sand and gravel is deposited closer to beaches, the percentages declining proportional to mud (silt), which is carried further offshore. The relationship between bathymetry, river outputs and where sediment is transported can be seen in Figs. 13, 14, and 15.

Table 2 Characteristics of rivers supplying sediment to Pegasus Bay. The size and quantity is a function of river catchments and gradients.

	Waimakariri	Ashley	Waipara
Source (Pescini, 2000)	Main divide	Lowland	Lowland
Catchment (Pescini, 2000)	24,000km^2	1,340km^2	459km^2
Gradient (Bryan *et al*., 2005)	0.0018m m^{-1}	0.0034m m^{-1}	0.0054m m^{-1}
Estimate suspended sediment (Pescini, 2000)	5.35 x 10^6 t. y^{-1}	1.16 x 10^6 t. y^{-1}	0.46 x 10^6 t. y^{-1}
Sediment type (Bryan *et al*., 2005)	Silt and sand	Sand (modal) Gravel (flood)	Gravel

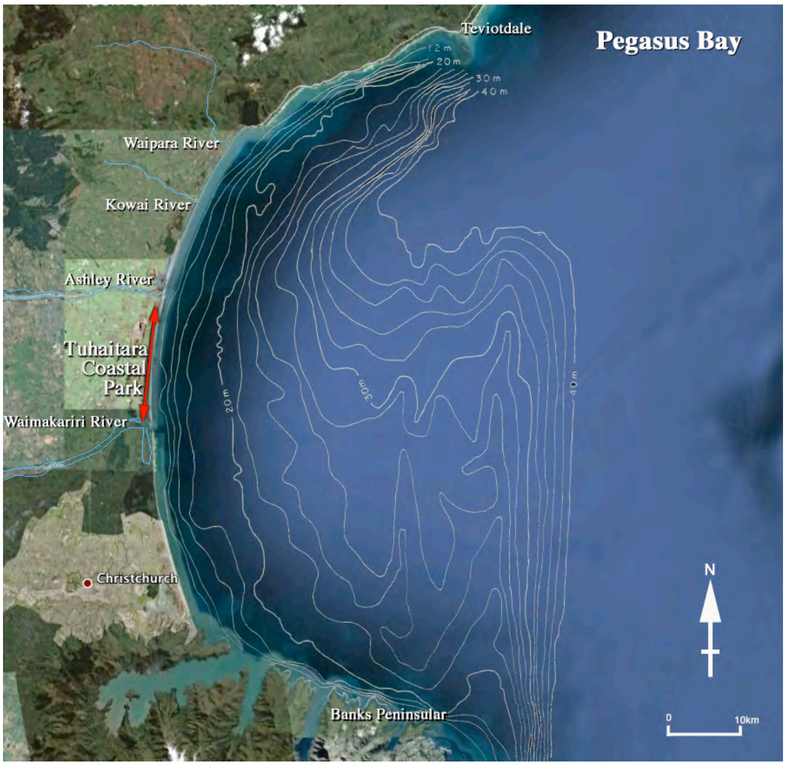


Fig. 13 Bathymetry of Pegasus Bay (composite Brown, 1976, and Google Earth, 2008).

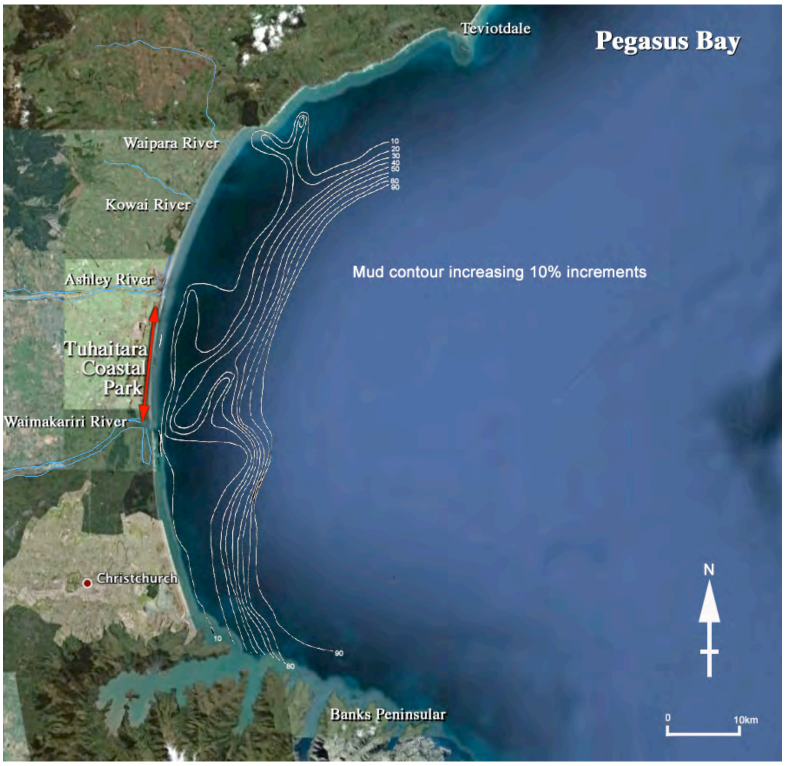


Fig. 14 Percentage of mud deposited offshore in proportion to sand (composite Brown, 1976, and Google Earth, 2008).

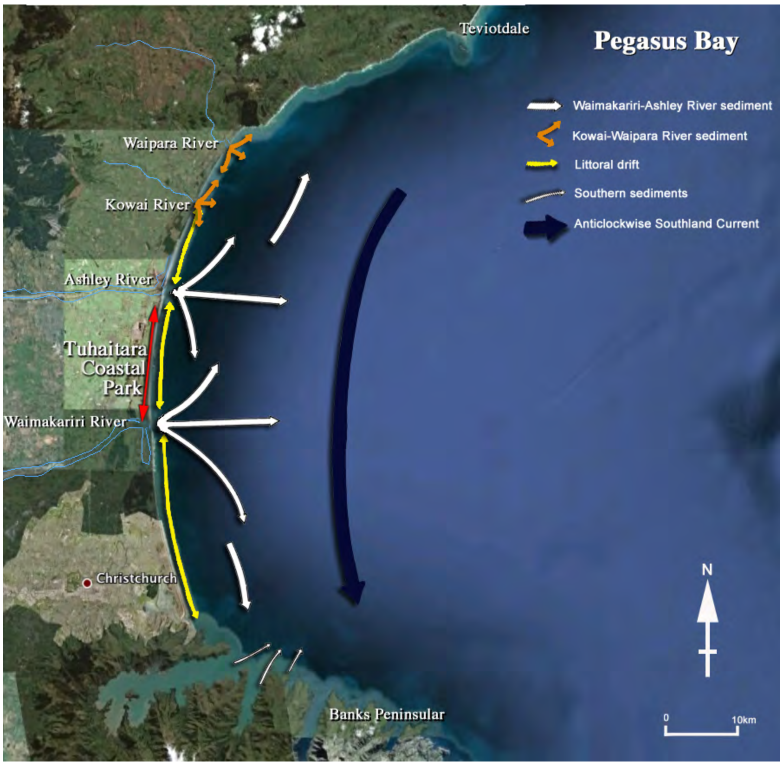


Fig. 15 Sources and movement of sediment throughout Pegasus Bay (composite Brown, 1976, and Google Earth, 2008).

The mean diameter of sediment grains increases northward from Sumner to the Ashley River. North of the Ashley River beaches are defined as composite sand and gravel (Shulmeister & Kirk, 1993; Pescini, 2000; Gabites, 2005). Large sediment size is associated with higher wave energy, particularly where rip and longshore currents redistribute the sediments according to beach type (Wright *et al.*, 1979; Wright & Short, 1984). However in Pegasus Bay, where the increasingly steeper gradients of the northern rivers deliver gravel (Table 2), sediment transport is complicated by a wave climate strongly influenced by the Banks Peninsula. Moreover several studies reveal a complex interplay of wind, waves, tides, and offshore currents (Blake, 1964; Campbell, 1974; Brown, 1976; Allan *et al.*, 1999; Stephenson & Schulmeister, 1999and de Lange, *et al.* 2008). Reynolds-Fleming & Fleming (2005) found that the M2 tide is responsible for 90% of the flow variance inside the southern end of the Bay, differential heating (#6, Table 1) which produces surface and baroclinic currents, and a small seiche effect (#7, Table 1) with a period of 3.4 hrs. These forcings combined with an average 2m tide, a portion of the northwards moving Southland Current breaking away and moving southwards inside the Bay (Fig. 15), winds, and freshwater input from the rivers generates a complex movement of water both horizontally and vertically through the Bay's waters. The net result is that ~50% of the sediment from the Waimakariri River is carried south while the remainder moves north, much of it accumulating on the Park's beaches (op. cit.). Based on measurements undertaken as part of the Christchurch City Wastewater Study (Miller *et al.*, 2004) and Waimakariri District Ocean Outfall Option (Senior *et al.*, 2001), longshore currents driven by the predominant southerly swells carries sand from the Park past the Ashley River in a northwards direction. The morphology of the northern Canterbury beaches, higher wave energy, and generally steeper offshore gradient suggests that a large proportion of that sand is then carried permanently from the sediment budget, either northwards out of the Bay, or to deeper waters. Contrary to studies by Ranasinghe *et al.*, (2004) this movement does not appear to be affected by ENSO or IPO.

By 1995 doubt was growing that the Pegasus Bay coastline as a whole was still prograding (Duns 1995; Bryan *et al.,* 2008). While Pines and Woodend beaches fronting the southern half of the Park continued to prograde ~0.33m yr^{-1}, this was one-third the previous long-term rate of ~1.0m yr^{-1} (Fig. 2). North of the Ashley River beaches were showing a long-term tendency to erosion (Duns, 1995).

Fluvial processes

As Bell *et al*. (2001) point out and the abovementioned studies confirm, the ability of the Park to withstand SLR hinges on the capacity of the Waimakariri River to deliver sufficient beach and dune-building sediment. Rivers play a key role in coastal systems. The abstraction of water from other Canterbury rivers for irrigation has been proven to alter the rates of deposition and erosion along coastal margins (Hart & Knight, 2008). While the channels and embankments of the Waimakariri have been subject to 'man's unfortunate but necessary interference' (Griffiths, 1979:28) through flood mitigation trenching and confinement, Blake & Mosley (1987) opine this has in fact increased the sediment carrying capacity of the river during floods. However modelling by Bell *et al*. (2001), which assumes a lower SLR than the latest data suggests, shows that abstraction of water could lead to 50% less sand. This would lead to the shoreline along the southern end of the Park retreating >75m (Fig. 2).

Controlling the flow of the Waimakariri River also prevents floodwaters from depositing sediment landward of the dunes west and north of Kairaki, disabling any natural capacity the area, which was previously swampland, has to keep pace with rising sea-levels (Fig. 16).

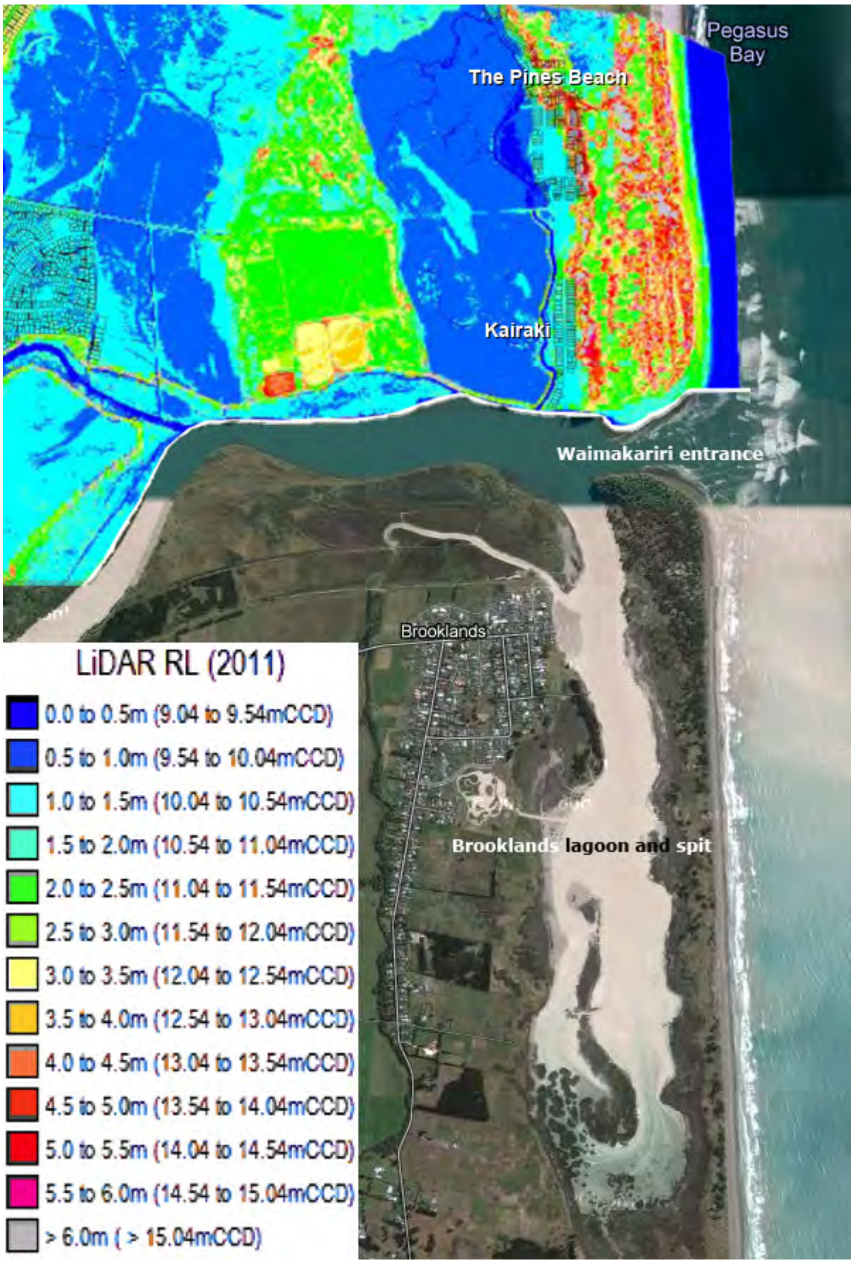


Fig. 16 Medium dark blue areas west and north of Kairaki were <1m above MSL prior to the June 2011 earthquake. Historically subject to inundation, this area presents a major vulnerability to the Park (Google Earth image 2009; LiDR map from Tonkin & Taylor, March 2011, see Appendix 2 Map B for full area map).

As 50% of the sand from the Waimakariri is transported south (Fig. 16) the Brooklands lagoon spit on the southern side of the Waimkariri River mouth is equally dependent on river sand to maintain its integrity against SLR. If this low-lying spit is inundated and the river mouth retreats to Brooklands (Fig. 17), then the southern end of Park where the Waimakari River currently exits will be directly exposed to dynamic beach processes from the predominant south-easterly swells. Moreover, the topographic survey reveals the Park will be inundated through the low-lying swales behind the dunes, which are presently protected only by a highly mobile sand spit on the northern side of the River's entrance.

Fig. 17 North side of the Waimakariri River entrance at Kairaki, facing south to Brookland's spit and lagoon (*S. Whitelaw, 2011*).

The most recent research by Zammit & Woods (2011) on the current and projected flows of the Waimakariri use the AR4 A1B scenario, which projects a conservative ~2.8ºC increase by 2100. The study is dependent on a large degree of uncertainty pertaining to changes in precipitation, and the authors recommend further modelling be undertaken using the A1F1 scenario (Fig. 5, or 'worst case' scenario) to provide a 'fuller picture' (p.5).

In sum, the capability of the Waimakariri to deliver sufficient sand in the face of climate change and increasing demands for human use is difficult to determine. Increasing westerly winds brought by El Niños are expected to result in a drier climate for Canterbury and hence more demand on irrigation from the Waimakariri and the surrounding groundwater. Equally, an increase in westerly flows may cause more precipitation in the Waimakariri headwaters and result in an increased flow. As yet there is little understanding how this complex dynamic will play out in the coming years.

Steric drivers

If the volume of freshwater delivered into Pegasus Bay by the Waimakariri is altered then a change in local steric effects (#6, Table 1) may have a slight impact on local sea-levels. These are probably not of great significance, however seasonal temperature variations (#5,

Table 2) are known to cause sea-levels to rise a few centimetres during warmer months and fall during cooler months (Bell *et al*., 2001).

La Niña/El Niño Southern Oscillation or ENSO is a Pacific and Indian Ocean east-west variation in temperatures and sea-levels that governs year-to-year climate variability (#3, Table 2). Measured by the Southern Oscillation Index or SOI, sea-levels are lower during cooler La Niñas and higher during warmer El Niños, varying up to 15cm. A similar but longer (20-30 year) cycle, the Interdecadal Pacific Oscillation or IPO (#4, Table 2), can raise and lower sea-levels by as much as 5cm. Where both SOI and IPO are high the cumulative effect is as much as 20cm (Bell *et al*., 2001). The past few decades have experienced an increase in the number and intensity of El Niños (Fig. 18).

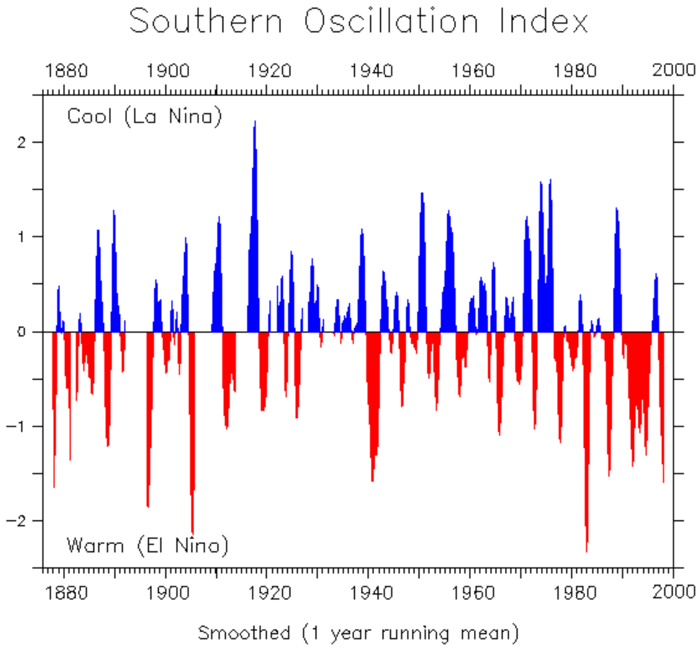


Fig. 18 Southern Oscillation Index (SOI) 1878-2000 (National Oceanic and Atmospheric Association, n.d.)

Closer inspection of recent data shows that La Niña conditions can dominate over shorter time frames (Fig. 19). The most recent La Niña (2010-2011) was so intense it caused sea levels to drop 6mm, in part because water evaporated from the oceans fell as record-breaking floods on landmasses such as Australia (Buis, 2011). This apparent reversal in SLR has led to confusion amongst some observers (see for example de Lange, 2010), however as NASA (Buis, 2011) points out this is a cyclic variation against a broader and irreversible trend to rising sea levels. The frequency and intensity of El Niño events is expected to increase as global temperatures continue to rise (Solomon *et al.*, 2007; Renowden, 2007).

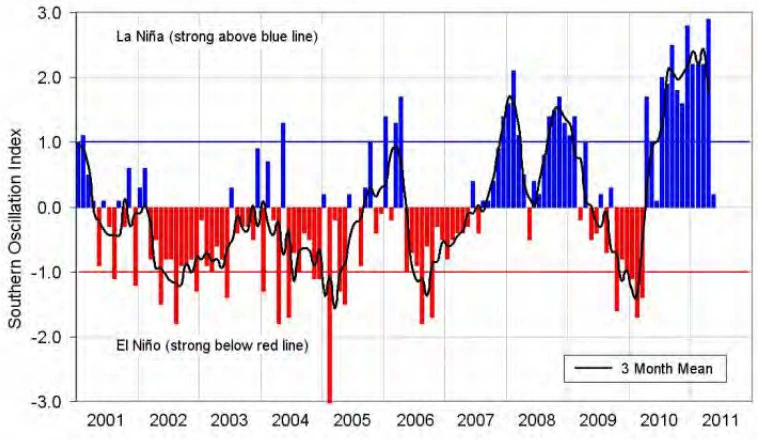


Fig. 19 SOI 2001-2011 (National Institute of Water and Atmospheric Research, 2011d)

In sum, while the rate which SLR is occurring has not been determined, multiple drivers influencing sea-levels in Pegasus Bay appear to make Tuhaitara Coastal Park vulnerable to SLR in five ways:

- The Waimakariri River as a source of sediment
- The capability of the Park's coastal barrier, its dunes, to defend against SLR
- Inundation from the south and west through the dune slacks and reclaimed wetlands, which may be exacerbated by—
- The response of Brookland's Lagoon spit to SLR
- The response of the Waimkariri River mouth to SLR

This thesis is tested through an analysis of data from LiDR maps and field trips outlined in the following sections.

Methods

Comparisons were made between cross sections from annual beach surveys 1991–2010 at six locations between the Waimakariri and Ashley Rivers (Cope, 2011), LiDR survey maps July 21, 2005 (courtesy Waimakariri Council), and Google Earth maps 11 November, 2009 (north of Reid Memorial Avenue) and 16 June, 2009 (Reid Memorial Avenue to the Waimakariri River). The 2005 LiDR maps covered the seaward margins of the Park.

Changes in elevation, beach width, the angle and heights of dunes, and the type and extend of vegetation were assessed. The 0m contour line on both LiDR maps is MSL. Examination of 2005, 2008/09, and 2011 aerial photos and field trips 20 March, 18 April, 16 May, 20 June, and 19 July established that the average impact of high tide (2m range) + average wave height (2m crest to trough) + run-up (0.25-5m) has a cumulative impact ~2.5m above MLS (Fig. 20). That is, during modal beach conditions the effective high water mark is 2.5m above MSL. For purposes of this report the 2.5m contour line is referred to as the effective sea-level.

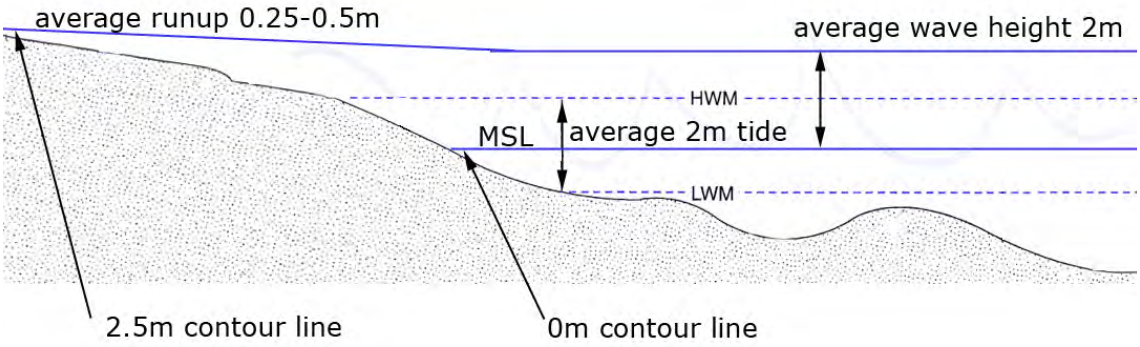


Fig. 20 At Tuhaitara Coastal Park, the cumulative effect of average high tide (1m above MSL) + average wave height (2m wave height) + runup (0.25-0.5m) = effective high water mark of 2.5m above MSL during modal sea conditions.

One field trip was undertaken 30 August 2011 during the maximum perigean-spring high tide of 2.38m (i.e., 1.19m above MSL). Average wave height at the time was ~1.5m, resulting in a net run up of approximately 3.8m. This followed a period of several days where a storm generated easterly waves up to 4m, causing undercutting of the dunes at the northern end of the Park near Kairaki (Appendix 1, plates 8 and 9), and creating a storm berm at Pines Beach, which was washed away during the perigean-high tide (Appendix 1, plate 11). It is possible under these circumstances that a combination of perigean-spring tides and storm waves could result in waves reaching beyond the 4m contour.

2005 LiDR data

Data from these maps was used to generate high-resolution 0m, 1.0m, and 2m SLR inundation maps for the length of the park's coastline. Additional 0.5 and 1.5m SLR inundation maps were generated for low-lying areas around Pines Beach and the entrance to the Waimakariri (approx 2.4km of coastline).

All maps have been included as high resolution layered *.tiffs in the accompanying DVD (see Appendix 3 for details).

Determining dune angles and Pines Beach profile

1. Using the 2005 LiDR maps, dune heights and angles were obtained from 0.5m topographic lines using a horizontal scale of 1.0m increments (Fig 21).

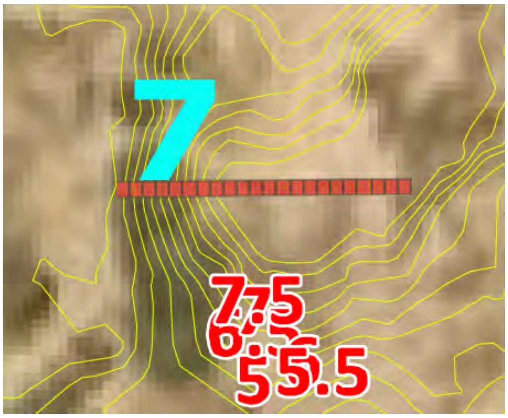


Fig. 21 Extract from Map 1 at location 7. Dune angles were determined from 0.5m contour lines and scale in 1.0m increments (red). In this example the contours were 2.5m to 7.5m (5.0m rise) over a distance of 7m = 35.5°.

2. Using the same maps, the height and width data on three dunes was entered into Excel to generate profiles, from which angles were calculated. As this resulted in the same angles as (1), it was deemed unnecessary to repeat this procedure with all dunes.

This method was also used to generate a 422m wide profile of the Pines Beach area (Fig 24).

3. Using a Sony satnav to verify locations, dune heights and angles were measured at locations 6 to 10 (Table 3) using an Electron Ultrasonic distance meter. The results confirmed the angles were within 5º. This was not a particularly accurate method for determining heights and angles, however it was useful to confirm the LiDR data on the ground.

Results

Elevation of Tuhaitara Coastal Park

The 2005 LiDR survey of the coastline (Fig. 23) revealed two vulnerabilities:

1. A 2m SLR would overtop dunes at Pines Beach at two locations: 43° 22' 41.39" S 172° 42' 36.11"E , and 43° 22' 24.56" S 172° 42' 33.47"E (circled in red Fig. 22). A cross section at Pines Beach shows an area of deflation (Appendix 1, plate 13) is below the current sea-level, while swales are below the effective sea-level (Fig. 23). A 422m cross-section of Pines Beach from LiDAR survey July 21, 2005 (Fig. 24) shows the effective high water mark under modal sea conditions, 1.0m, and 2.0m SLR.

2. A permanent SLR of 1m would begin to inundate the park from the south (Figs. 22 & 23). From the available LiDR data it is not possible to determine how far this inundation might extend. A permanent SLR of 2m would result in much of the Park being permanently inundated.

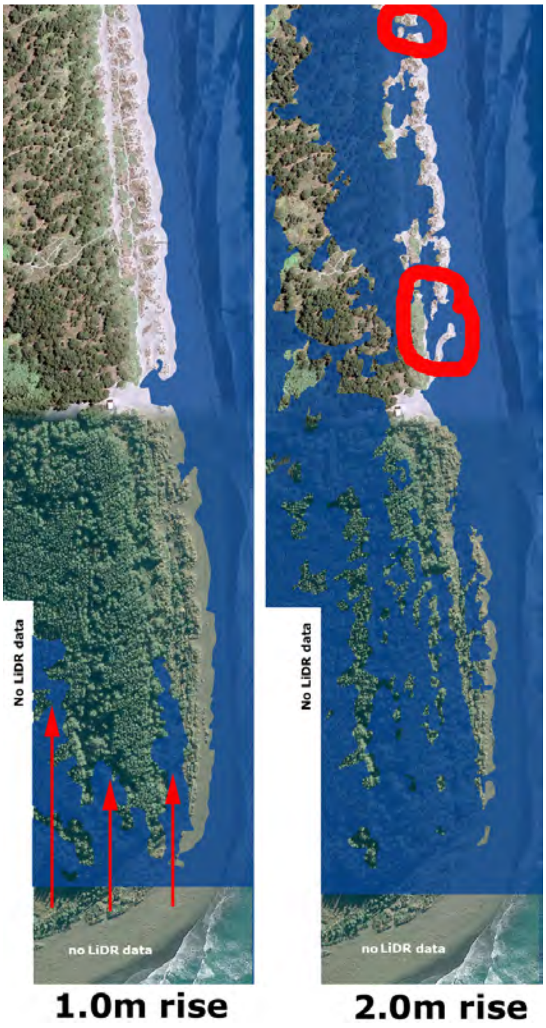
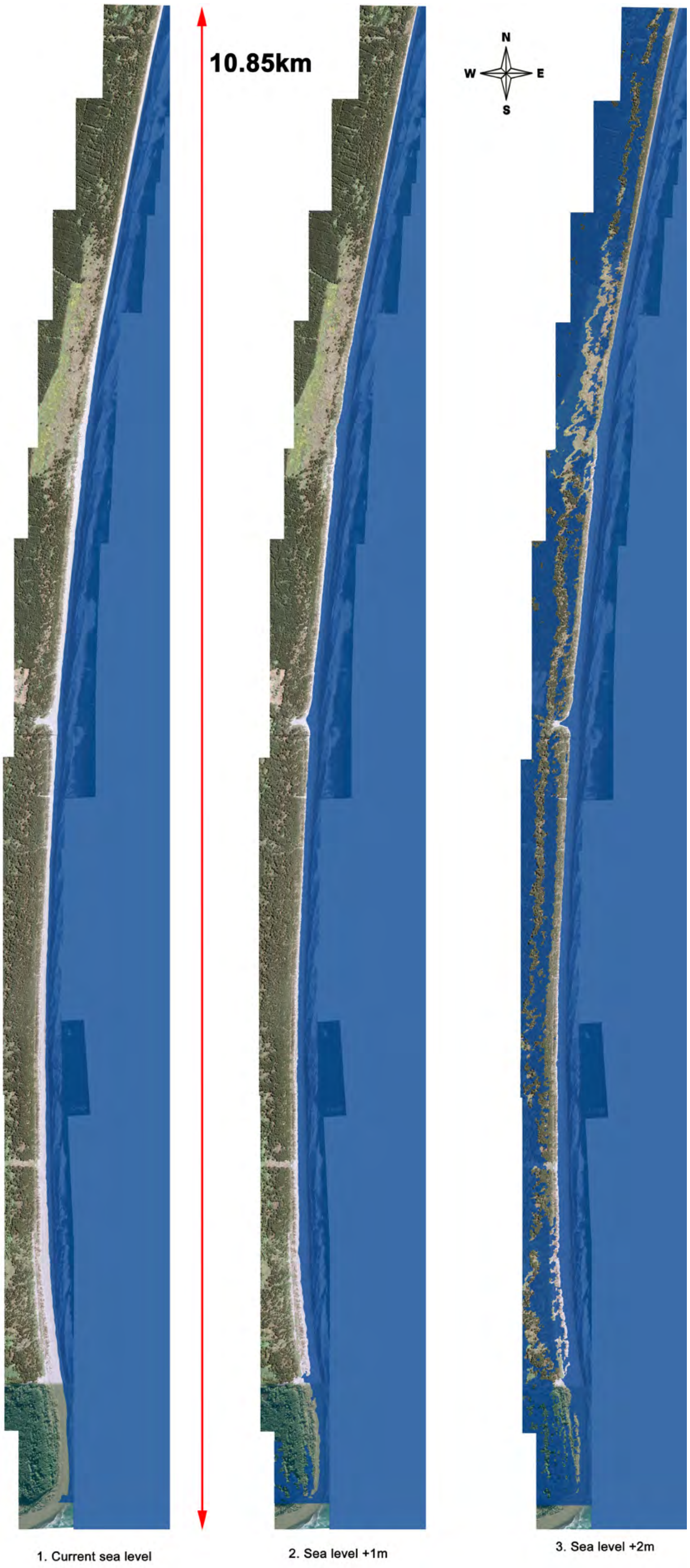


Fig. 22 1.0m and 2.0m flood maps (enlarged from Fig. 23). Areas flooded during a 1.0m SLR may exceed this if areas outside the available LiDR data were also flooded.



1. Current sea level
2. Sea level +1m
3. Sea level +2m

Fig. 23 Composite 2005 LiDR contour map and 2009 Google Earth images). Higher resolution maps are in the accompanying DVD.

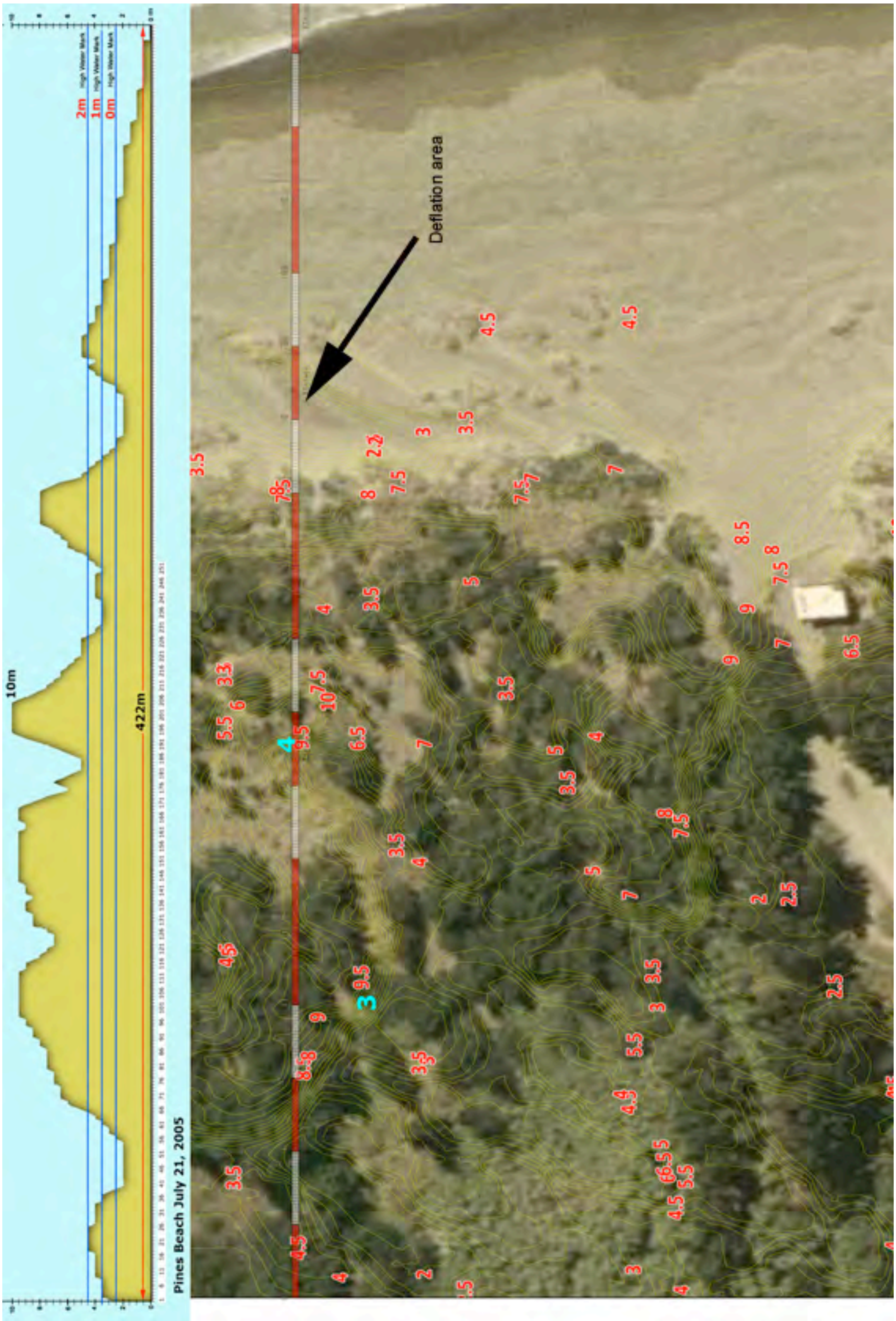


Fig. 24 422m cross-section of Pines Beach from LiDAR survey July 21, 2005. The deflation area below sea level can be seen in Appendix 1, plate 13. Horizontal blue lines on the graph at left represent the effective high water mark under modal sea conditions (2.5m contour line), and an SLR of 1.0m and 2.0m (3.5m and 4.5m contour lines respectively)(high resolution image in DVD).

Progradation

There appears to have been no discernable progradation of the coastline between 1991-2011 (see all maps in the DVD).

Angles and relative heights of dunes.

The LiDR data is reproduced in Table 3 and 4.

Table 3. LiDR data from 2005. Height is from base to summit not height above sea-level Locations are marked 1 to 10 on Map1.tiff (DVD). Location 7 is Plates 2 and 3 in Appendix 1.

	Latitude (S)	Longitude	Height > MSL 2005	Angle 2005
1	43º 23’ 13.88”	172º 42’ 50.83”	6.5m	24.8º
2	43º 22’ 58.26”	172º 42’ 30.17”	8m	30º
3	43º 22’ 43.67”	172º 42’ 26.60”	9.5m	33º
4	43º 22’ 42.86”	172º 42’ 30.18”	10m	33.7º
5	43º 22’ 36.22”	172º 42’ 33.83”	9m	31º
6	43º 22’ 26.14”	172º 42’ 33.81”	6.5m	32º
7	43º 22’ 12.35”	172º 42’ 30.21”	7.5m	35.5º
8	43º 21’ 58.19”	172º 42’ 32.33”	7.5m	7.5º
9	43º 21’ 49.14”	172º 42’ 31.19”	8m	45º
10	43º 21’ 43.81”	172º 42’ 27.17”	8.5m	38.7º

Table 4. LiDR data from 2005. Height is from base to summit not height above sea-level. Locations are marked 11 to 20 on Map3.tiff (DVD).

	Latitude (S)	**Longitude**	**Height >MSL 2005**	**Angle 2005**
11	43º 20' 22.25"	172º 42' 29.27"	11m	23.2º
12	43º 20' 17.14"	172º 42' 29.02"	12m	25º
13	43º 20' 14.99"	172º 42' 31.20"	8.5m	33.7º
14	43º 20' 02.35"	172º 42' 31.84"	10m	22.3º
15	43º 19' 53.07"	172º 42' 35.05"	11.5m	26.6º
16	43º 19' 53.69"	172º 42' 34.70"	12m	26.6º
17	43º 19' 51.24"	172º 42' 32.79"	10m	25.2º
18	43º 19' 21.76"	172º 42' 43.48"	7.5m	42º
19	43º 19' 22.33"	172º 42' 42.44"	3m	53.1º
20	43º 19' 19.35"	172º 42' 35.26"	11m	34.9º

Vegetation

Dunes along the length of the park are heavily vegetated by marram grass, radiata pine, lupin, and patches of broom and rye amongst other exotic species (Appendix 1). Between July 2005 and February 2011 incipient foredunes and foredunes became significantly more vegetated along the length of the park. Site visits revealed this is largely marram grass, lupin and in some areas radiata pine saplings. See for example Fig. 25 (from Map 2: 2005, 2009, and 2011 layers in the DVD).

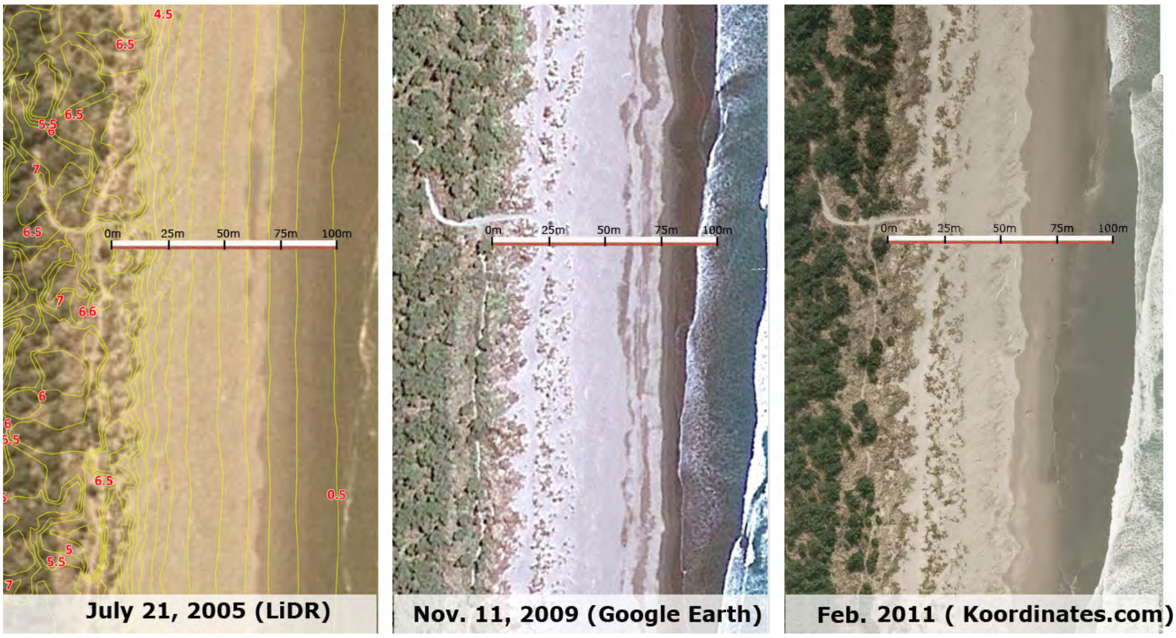


Fig. 25 Sample from Map 2 (DVD) showing changes in vegetation 2005 to 2011.

3. Discussion

The purpose of this research project was to determine Tuhaitara Coastal Park's vulnerability to rising sea-levels. In spite of a growing body of research too little is known to quantify the relative contribution of drivers to predict how high sea-levels will rise and over what time frames. Nevertheless it can be stated with certainty that the Pegasus Bay shoreline along the Waimakariri plain prograded ~1m/yr for over 4,500 years. This net progradation was marked by periods of cutbacks caused by storms and changes in the mouth of the Waimakariri, followed by long periods of accretion.

In 2001, modelling by Bell *et al.*, suggested that if sea-levels began to rise and the amount of sediment delivered by the Waimakariri remained the same, then by 2030 the shoreline along the Park would continue to prograde, but only 0.5m/yr, that is, around half the rate at which it prograded while sea levels were steady.

In 1995 surveys indicated that at Pines Beach and Woodend the coastline was prograding less than this, at 0.33m/yr. Retrospective analysis of surveys between 1991-2010 and comparison of aerial photos 2005-2011 indicate the Park's coastline has not noticeably prograded since 1991. While the 2010/2011 earthquakes caused areas of land to subside, the Park's dunes are increasing in height and the beach is accreting. This indicates that while the Waimakariri River is still supplying sediment to the Park's beaches (and dunes), the rate of sea-level rise is matching the rate of progradation.

While the rate which SLR is occurring has not been determined, understanding the drivers that influence sea-levels affecting the Park and surveys of the beaches and dunes have together revealed five key areas in which it is vulnerable:

- The Waimakariri River as a source of sediment
- The capability of the Park's coastal barrier, its dunes, to defend against SLR
- Inundation from the south and west through the dune slacks and reclaimed wetlands, which may be exacerbated by—
- The response of Brookland's Lagoon spit to SLR
- The response of the Waimkariri River mouth to SLR

Waimakariri River as a source of sediment

Trenching and confinement of the Waimakariri River has prevented it from delivering sediment to low lying areas behind the Park, disabling any capacity the area might have had to keep pace with rising sea-levels. It is not possible to determine if the Waimakariri is or will in the future deliver sufficient volume of sand to the Park's beaches to keep pace with rising sea-levels.

The capability of the coastal barrier to defend against SLR

Where coastlines are no longer accreting or are eroding, dunes are likely to respond to rising sea-levels by increasing in height and migrating inland (Fig. 7). The Park's shoreline does not appear to have migrated inland and sand has accreted on dunes between 2003-2011. However, the coastline appears to have ceased prograding. It is too early to determine if this is temporary or the beginning of a retreat in the face of SLR. However perversely, the manner in which sand has accreted on the dunes has exacerbated the Park's vulnerability to rising sea-levels.

While the sheer size of the dunes and their coverage in grass and mature pines gives them the appearance of stability, this is a dangerous illusion. Marram grass creates dunes up to 8m high with an average profile of 24-28°. Dunes at the Park commonly exceed these heights and angles while the profiles of incipient foredunes, the area of the coastline most vulnerable to erosion, can exceed 50°. The close-growing radiata pines shade-out large areas, inhibiting the growth of dune stabilising ground cover (Appendix 1 Plates 2, 3, and 7). Moreover radiata pine does not tolerate high summer temperatures, something to be considered as global temperatures rise. The dunes are preternaturally vulnerable to unpredictable high-energy destructive waves, particularly those generated by storms originating to the east and north-east. The dunes have become, in effect, exceptionally large and unstable sandcastles. If the dunes are undercut, once the sand that should have served as a barrier against SLR is eroded, studies of sediment movement in the Bay indicate it is likely to be permanently removed from the sand budget. If the dunes become mobilised and migrate inland (Fig. 7) then they will over-run the wetlands.

Inundation

Inundation could occur through low points in the dunes at Pines Beach if SLR reaches 2.0m, or through rapid erosion of excessively steep foredunes towards the northern end of the park around Waikuku, particularly following storms. Inundation is likely to occur via the dune swales and reclaimed wetlands near the Waimiakariri River mouth. Recent earthquakes have caused some areas to subside by as much as 1.5m. If the spit on the northern embankment of the Waimakariri River is eroded then the swales will become conduits, channelling water to low-lying sections of the park. As sea-levels continue to rise most of the Park will become submerged. As the base of dunes is exposed to tides and waves, dunes will be undercut and become mobilised.

Brookland’s Lagoon spit

In the event the Brookland’s Lagoon spit is breached and/or the river mouth retreats in response to rising sea-levels, the swales and land west of Kairaki would be regularly inundated by tides and directly subject to wave action. In this scenario, low-lying areas including Tutaepatu Lagoon would eventually become an estuary, slowly infilling with sand diverted from the Waimakariri. It is not possible to determine if the rate of sedimentation would keep pace with rising sea-levels. Elevated land along the coastline, that is, unstable dunes starved of sand, would become barrier islands until beach processes wash them away.

Waimakariri River Mouth

The Waimakariri River mouth is likely to retreat inland in response to SLR. This will alter the dynamics discussed in all of the above points, exacerbating their effects.

4. Conclusions

Sea-level rise is commonly viewed as a long-term problem, or not considered where coastal areas have historically prograded. This is a flawed assumption. Evidence presented in this report shows that Tuhaitara Coastal Park is vulnerable to sea-level on five broad fronts: the ability of the Waimkariri River to deliver sufficient sand to keep pace with rising sea-levels; the exposure of low-lying swales and reclaimed wetlands on the southern and western margins of the Park; through exotic vegetation which may have contributed to the lack of shoreline progradation by building overlarge and over-steep dunes preternaturally vulnerable to blowouts and storm damage; and through the response of the Waimakariri River Mouth and the Brookland's Spit to rising sea levels.

Recommendations

Tuhaitara Coastal Park's Management Plan policy provision 7.3.1 states that dune plant communities should be managed to 'reduce risks of dune blow-out and storm damage while enhancing and preserving the dune area as habitat for native plants and animals' (op. cit.:30). If the Park is to be preserved for future generations it is strongly advised that:

- A three-dimensional topographic profile of the Park and surrounding areas including Brookland's Lagoon spit be generated from the most recent LiDR data.
- Research be undertaken to determine the most suitable sand-stabilising native plants given the projected rise in temperatures and increasing exposure to salt water.
- Priority be diverted from restoring native vegetation in low lying areas likely to be permanently inundated within the 200-year time frame of the Draft Restoration Plan, to restoring native vegetation on upper beach faces and dunes. Urgent priority should be given to areas most vulnerable to inundation and erosion, identified in this report and confirmed by a 3D topographic profile.

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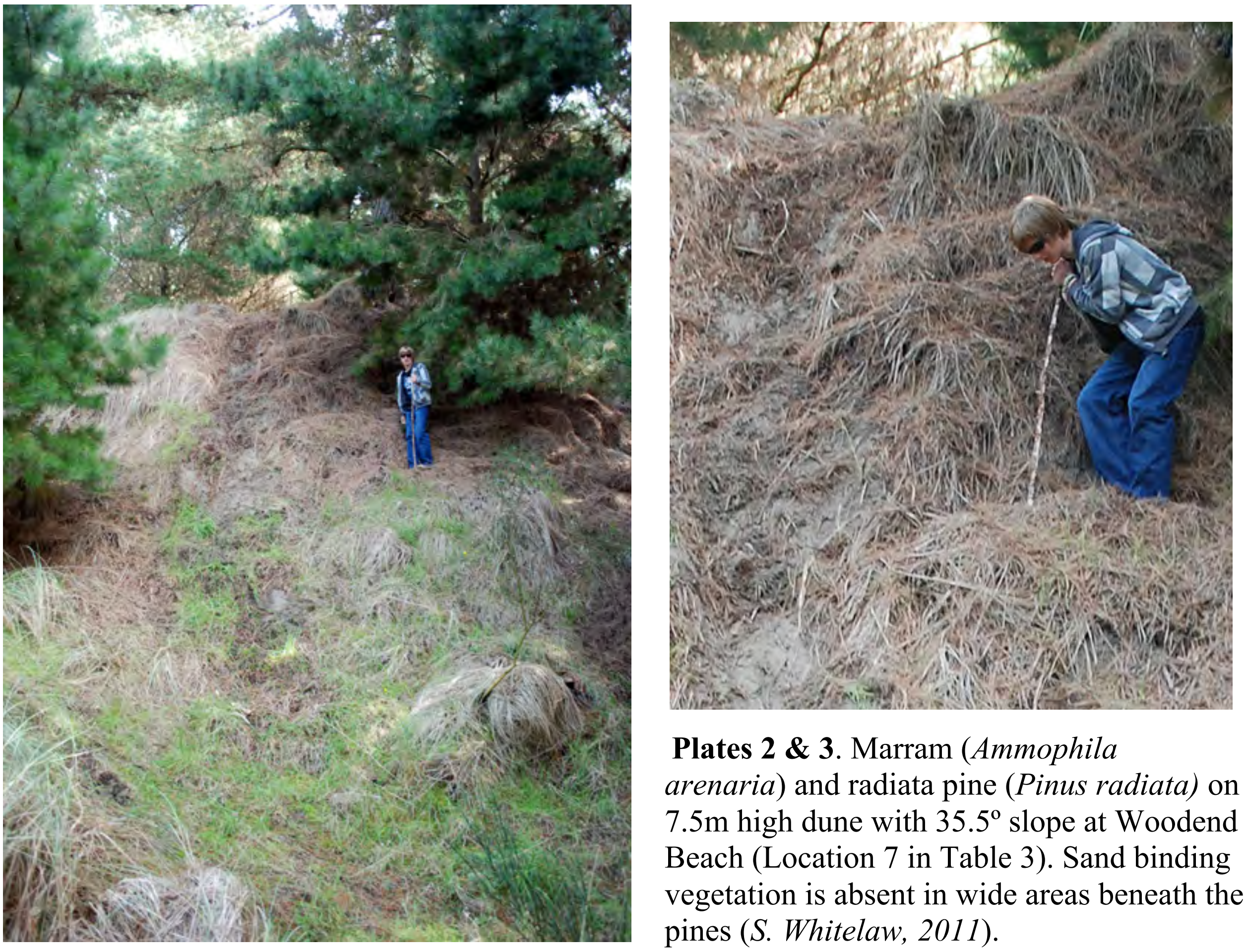
Appendix 1. Photographs of Tuhaitara Coastal Park

Plate 1. Exotic marram grass (*Ammophila arenaria*), tree lupin (*Lupinus arboreus*), and radiata pine (*Pinus radiata),* dominate the active dunes along the entire length of Tuhaitara Coastal Park. (*S. Whitelaw, 2011*).



Plates 2 & 3. Marram (*Ammophila arenaria*) and radiata pine (*Pinus radiata)* on 7.5m high dune with 35.5º slope at Woodend Beach (Location 7 in Table 3). Sand binding vegetation is absent in wide areas beneath the pines (*S. Whitelaw, 2011*).

Plate 4. Marram (*Ammophila arenaria*) forming steep incipient foredune (40º) at Woodend Beach (*S. Whitelaw, 2011*).

Plate 5. Unvegetated path bisecting dunes at Woodend Beach. (*S. Whitelaw, 2011*).

Plate 6. Exotic ice plant (*Carpobrotus edulis*), colonising the backdunes at Woodend Beach. (*S. Whitelaw, 2011*).

Plate 7. Needles from radiata pine on swales and back dunes at Waikuku Beach hinders growth of sand binding vegetation (*S. Whitelaw 2011*).

Plate 8. Undercutting of marram vegetated foredune near Waikuku Beach facing north, following 5m easterly storm-swell 17-18 August and perigean-spring tide 30 August (*S. Whitelaw, August 30, 2011*).

Plate 9. Undercutting of marram vegetated foredune near Waikuku Beach facing south, 5m easterly storm-swell 17-18 August and perigean-spring tide 30 August (*S. Whitelaw, August 30, 2011*).

Plate 10. Foredune near Waikuku Beach facing south, vegetated by marram grass (*S. Whitelaw, August 30, 2011*).

Plate 11. Pines Beach facing south during perigean-spring tide 30 August, scouring and eroding the beach face beyond the berm (bottom right) that was cut during the 5m easterly storm swell 17-18 August (*S. Whitelaw, August 30, 2011*).

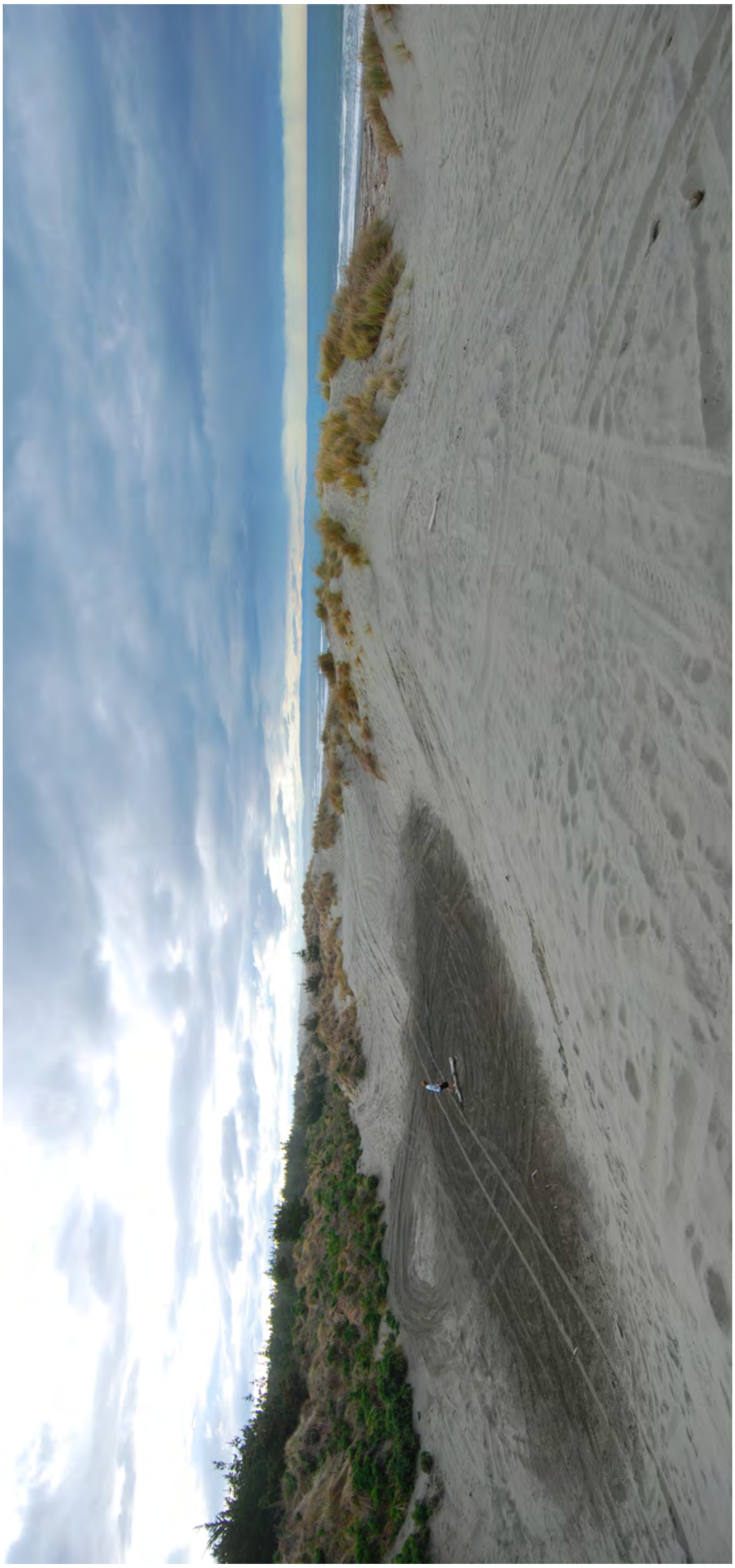
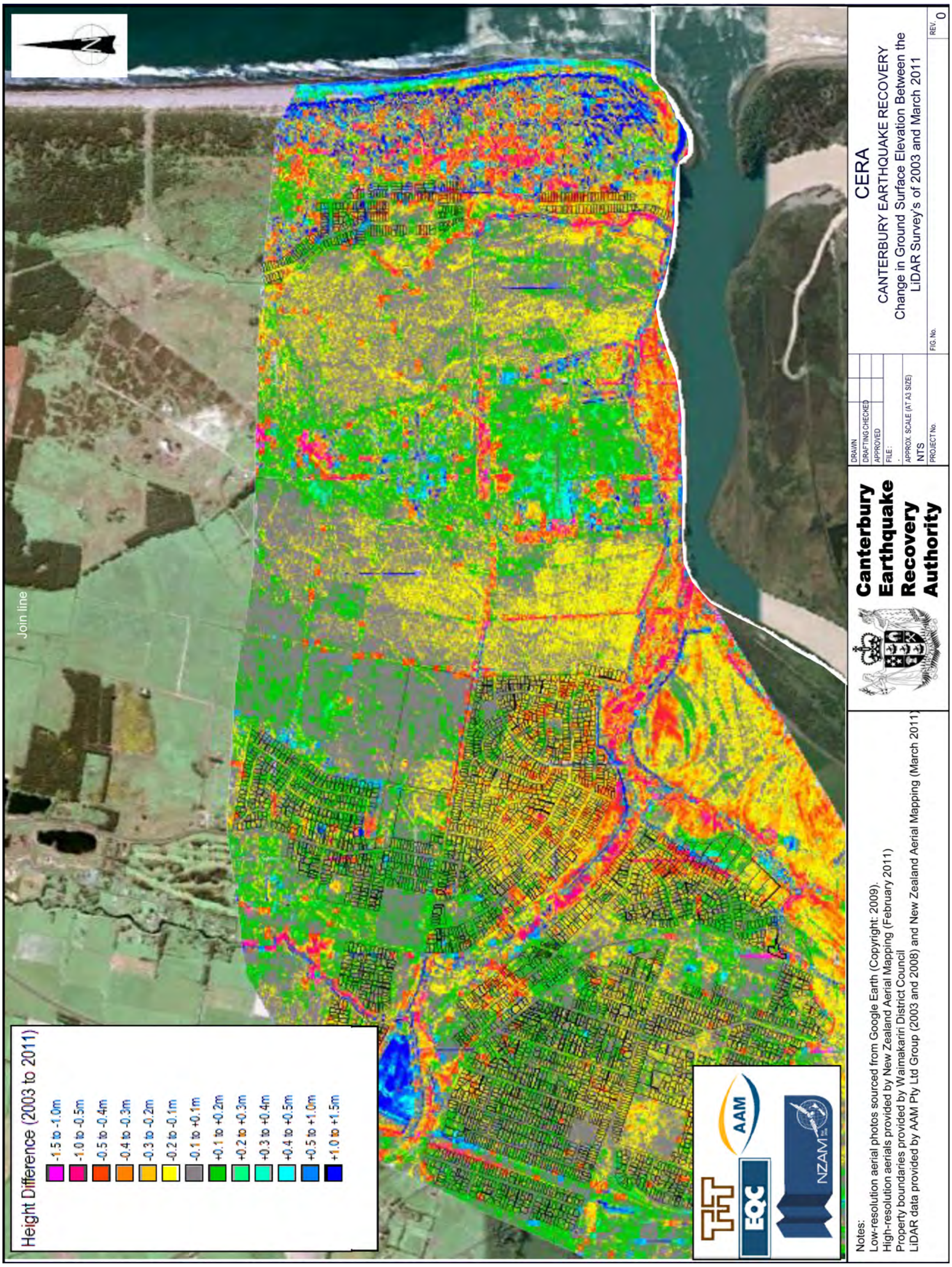


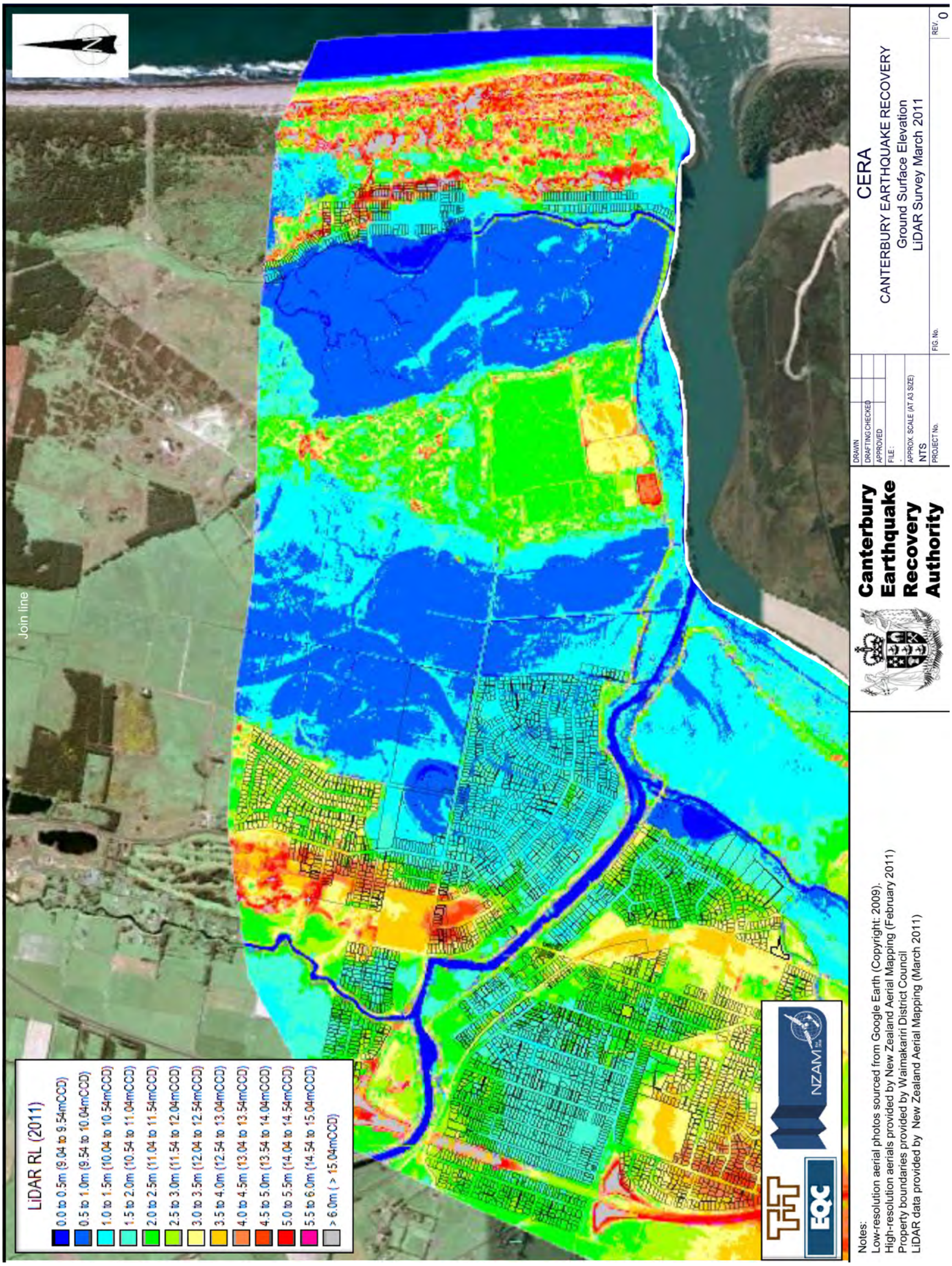
Plate 13. Deflation area at Pines Beach and gaps in the foredunes (right and centre) (*S. Whitelaw, August 30, 2011*).

Appendix 2. Elevation maps

Map A: Elevation changes between 2003 and March 2011 show sections of Tuhaitara Coastal Park have dropped up to 1.5m (pink). Raised coastal areas (dark blue) are largely a result of accreting foredunes, some backdunes south of Pines Beach near the Waimakariri River mouth, and short-term changes to the active beach profile (light blue to dark blue).



Map B: Absolute elevation March 2011. No data is yet available subsequent to the June 2011 earthquake.



Appendix 3 – Key to map file names in 'Maps' folder in enclosed DVD.

Note: *.tiff maps are in layers and require image software capable of choosing different layers to view the full range of data. ***.pdf maps** are a selection of layers presented in 5-page documents, each page representing a 0.5m rise in sea levels.

MapABC.tiff. The cumulative impact of rising sea levels 0m, 1m, 2m: 2005 LiDR data merged with 2009 Google Earth images. Covers the entire Tuhaitara Coastal Park coastline.

High-resolution images of southern Tuhaitara Coastal Park coastline from the Waimakariri to 2.4km north, in ~800m increments (A, B, C). File names: **A.pdf; A.pdf; C.pdf.** These images are included as individual files**:**

Effective current SL	0.5m rise	1.0m rise	1.5m rise	2.0 m rise
A0.tif	**A05.tif**	**A1.tif**	**A15.tif**	**A2.tif**
B0.tif	**B05.tif**	**B1.tif**	**B15.tif**	**B2.tif**
C0.tif	**C05.tif**	**C1.tif**	**C15.tif**	**C2.tif**

Map1.tif : 3.1k from Waimakariri north. Includes 0.5m incremental increases in sea level (LiDR data 2005) + 10 location locations of dunes surveyed. Covers Pines Beach area.

Map2.tif: 2.35km. Includes 0.5m incremental increases in sea level (LiDR data 2005) + Google Earth 2009 layer to compare beach widths and vegetation changes.

Map3.tif: 2.19km. Includes 0.5m incremental increases in sea level (LiDR data 2005) + Google Earth 2009 layer to compare beach widths and vegetation changes + + 10 locations of dunes surveyed. Covers Woodend Beach and east of Tutaepatu Lagoon.

Map4.tif: 2.54km. Includes 0.5m incremental increases in sea level (LiDR data 2005) + Google Earth 2009 layer to compare beach widths and vegetation changes.

Map5.tif: 0.7km. Includes 0.5m incremental increases in sea level (LiDR data 2005 + Google Earth image 2009). Covers area to Waikuku Beach.