



Coastal tectonics and habitat squeeze: response of a tidal lagoon to co-seismic sea-level change

Shane Orchard^{1,2} · Kenneth F. D. Hughey^{3,4} · Richard Measures⁵ · David R. Schiel²

Received: 1 February 2020 / Accepted: 1 July 2020 / Published online: 11 July 2020
© Springer Nature B.V. 2020

Abstract

We investigated the response of a tidal lagoon system to a unique situation of relative sea-level change induced by powerful earthquakes (up to M_w 7.1) on the east coast of New Zealand in 2010–2011. Spatiotemporal impacts were quantified using airborne light detection and ranging (LiDAR) datasets complemented by hydrodynamic modelling and evaluation of anthropogenic influences. Ground-level changes included examples of uplift and extensive subsidence (ca. 0.5 m) associated with intertidal area reductions, particularly in supratidal zones. ‘Coastal squeeze’ effects occurred where incompatible infrastructure prevented upland ecosystem movement with relative sea-level rise. Despite large-scale managed retreat, legacy effects of land-filling have reduced the reversibility of human modifications, impairing system resiliency through poor land-use design. Elsewhere, available space in the intertidal range shows that natural environment movement could be readily assisted by simple engineering techniques though is challenged by competing land-use demands. Quantification of gains and losses showed that lagoon expansion into previously defended areas is indeed required to sustain critical habitats, highlighting the importance of a whole-system view. Identifiable coastal planning principles include the need to assess trade-offs between natural and built environments in the design of hazard management plans, requiring greater attention to the natural movement of ecosystems and areas involved. Treating these observations as a scenario illustrates the mechanisms by which coastal squeeze effects may develop under global sea-level rise, but our purpose is to help avoid them by identifying appropriate human responses. We highlight the need for an improved focus on whole-system resilience, and the importance of disaster recovery processes for adaptation to climate change.

Keywords Resilience · Risk management · Disaster recovery · Climate change adaptation · Socio-ecological systems · Tipping points

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11069-020-04147-w>) contains supplementary material, which is available to authorized users.

✉ Shane Orchard
s.orchard@waterlink.nz

Extended author information available on the last page of the article

1 Introduction

Coastal river mouths and estuaries are characteristic natural features supporting highly productive ecosystems, important biodiversity and a wealth of natural resources (Kennish 1986). Their benefits include food, coastal protection, recreational opportunities, water filtration and many other ecosystem services (Pendleton 2008; Thrush et al. 2013). Economic evaluations have shown their high value to society (Barbier et al. 2011; Costanza et al. 1998), underpinned by the popularity of coastal floodplains for human uses and settlement (Lichter et al. 2011; McGranahan et al. 2007). Unfortunately, the integrity of estuarine environments has also suffered from anthropogenic effects (Kennish 2002). Pervasive issues include hydrological and morphological changes associated with nearby land-uses and the cumulative effects of land reclamation within the intertidal zone (Duarte et al. 2015; Perkins et al. 2015). These aspects illustrate a need for conservation measures that address both local spatial planning and catchment-wide land-use trends.

The conservation of dynamic coastal environments is already difficult in heavily populated areas, and climate change introduces a further considerable threat (Martínez et al. 2007). Under sea-level rise, low-lying landscapes may be eliminated if the landward retreat of erodable shorelines becomes constrained by anthropogenic infrastructure (Berry et al. 2013; Chapman 2012; Robins et al. 2016). These ‘coastal squeeze’ threats to natural environments include the erosion of substrate-dependent ecosystems seaward of engineered defences, and the drowning of others with increased inundation. In both cases, constraints on natural system movement underpin ecosystem risk and are often anthropogenic in origin (Martínez et al. 2014; Schleupner 2008). However, solutions to these issues do exist in the form of ‘nature-based solutions’ (Cohen-Shacham et al. 2019; Kabisch et al. 2016), that embrace more holistic planning and infrastructure design (Macreadie et al. 2017). Such solutions include the concept of ecosystem-based adaptation, defined as “adaptation that integrates ecosystem services and biodiversity into a strategy to limit the adverse impacts of climate change” (Renaud et al. 2016; UNEP 2010). Challenges, however, include the need for strategies to accelerate the uptake of these new approaches, and the identification of options that are both effective in accommodating natural ecosystems and workable for the communities involved (Bardsley and Sweeney 2010; Füssel 2007).

In this study, we investigated these issues in relation to a unique situation of sea-level change that was generated by a major earthquake event. A defining feature of this case involved large areas of subsidence with an accompanying sea-level rise (ca. 0.5 m) that affected coastal communities and generated long-term environmental change. The context provided a novel opportunity for the empirical assessment of impacts and evaluation of contributing factors in a low-lying socio-ecological system typical of many facing the global challenge of sea-level rise.

1.1 Tectonic displacement context

The Canterbury Earthquake Sequence (CES), involved a series of strong earthquakes (up to M_w 7.1) beginning 2010 on the east coast of New Zealand’s South Island. The most serious earthquake occurred on 22 February 2011 beneath the city of Christchurch (Fig. 1). As one of New Zealand’s worst natural disasters, it caused 185 fatalities and capital costs estimated at NZ\$40 billion, or approximately 20% of the Gross Domestic Product (Kaiser et al. 2012; Potter et al. 2015). Three other earthquakes exceeded M_w

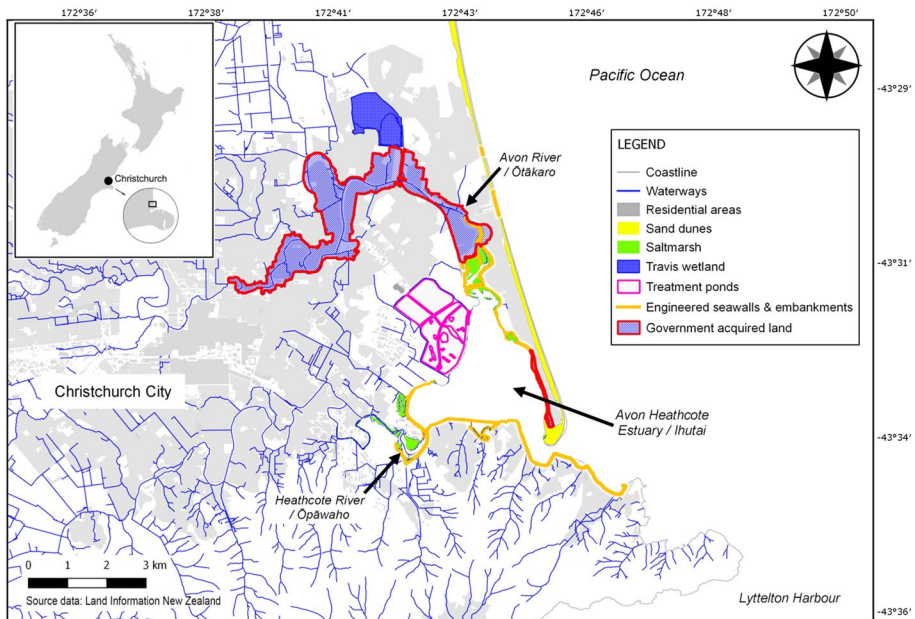


Fig. 1 Configuration of the Avon-Heathcote Estuary Ihtai and surrounding area in Christchurch, New Zealand, showing the position of key natural features, coastal defences, and earthquake-impacted land that was acquired by the New Zealand government after the Canterbury earthquakes of 2010–2011

6.0, all on previously unrecognised fault lines (Beavan et al. 2012; Bradley et al. 2014). Along with catastrophic effects on built infrastructure the CES caused severe impacts on the natural environment. Many of these were associated with surface deformation phenomena including liquefaction, lateral spread, subsidence and landslides (Quigley et al. 2016; Robinson et al. 2012; Zeldis et al. 2011). Many residential areas were affected by increased flood risk associated with subsidence and coastal defence breaches, particularly in the east of the city (Hughes et al. 2015). Societal responses included central government acquisition of thousands of residential properties along the estuary shoreline and lower river corridors creating a rare opportunity for reconfiguring the relationship between people and the aquatic environment (Orchard 2017).

This study investigates disturbance and resilience aspects of the earthquake-induced change. Our particular focus was the identification of long-term effects on the aquatic margins and footprint of the Avon Heathcote Estuary Ihtai, a tidal lagoon typical of many worldwide (Hume et al. 2007). Complications for gaining a comprehensive picture arise from the lag times of responses and the potential for further time-varying effects associated with physical change. Initially, the latter was significant due to the high frequency of aftershocks and associated further land movements and erosion effects (Beavan et al. 2012; Quigley et al. 2013). To address this, we collected data over a considerable period as conditions stabilised. The magnitude and frequency of aftershocks have generally reduced since 2011, with the exception of a 5.7 M_w earthquake on 14 February 2016.

In this paper we provide a comprehensive overview of relative sea-level changes, shoreline movements, and impacts on the extent of intertidal areas associated with tectonic displacement. We draw conclusions for the management of sea-level rise derived from direct

empirical analysis, and discuss natural disaster recovery and climate change adaptation (CCA) principles that may be identified from this case.

2 Methods

2.1 Study area

The study area is within the city of Christchurch on the east coast of New Zealand's South Island (Fig. 1). The estuarine system includes two river mouth environments (Avon Ōtākaro and Heathcote Ōpāwaho) and several smaller tributaries connected to a tidal basin of ca. 8 km². The lagoon is a barrier-built system enclosed by a 10 km long beach and sand-spit formation. In recent history it has been permanently open to the Pacific Ocean via an entrance channel located in the southern corner of Pegasus Bay, a shallow embayment 54 km long extending north from Banks Peninsula (Hicks 1998; Kirk 1979). The estuary supports a wide variety of native birds, fish and invertebrate species, and indigenous plant communities including seagrass meadows, saltmarsh and other coastal wetland types (Jones and Marsden 2007). It is an important site for shorebirds and migratory waders, supporting aggregations of at least 13 species exceeding the 1% international importance threshold defined by Wetlands International (Crossland 2013; Delaney and Scott 2006). The estuary is of high significance to Māori for mahinga kai (food gathering), and other traditional practices (Jolly and Ngā Papatipu Rūnanga Working Group 2013; Tau et al. 1990), hence our adoption of bilingual naming for major aquatic features. However, residential and industrial development has had adverse impacts on cultural values, especially those dependant on the maintenance of natural ecosystems and traditional resources (Lang et al. 2012; Pauling et al. 2007). A large proportion of the estuarine shoreline has been modified by seawalls and stopbanks, some of which are associated with a sewage treatment facility on the western shore (Fig. 1).

2.2 LiDAR data and digital elevation models

Shoreline change was investigated using geographic information system (GIS) analyses of digital elevation models (DEM) derived from LiDAR datasets. Four datasets were available with complete coverage of the study area. These include a pre-quake (2003) dataset and others captured after key events in the CES (Table 1). Bare earth DEMs representing averaged ground-return elevations were included in the LiDAR products at 1 × 1 m resolution for the 2015 survey, and 5 × 5 m resolution for all others (Canterbury Geotechnical Database 2014; LINZ 2017). Identical DEM configurations were developed by reprocessing the 2015 DEM to 5 m resolution. Elevation errors have at least three components that include locality-dependent interpolation errors, potential geoid errors, and measurement errors in the underlying LiDAR point cloud. However, the 5 m DEMs have relatively high accuracy due to the quantity and geographic spread of point elevations captured in the source data. Tables 1, 2 show the estimated horizontal and vertical accuracy for each dataset excluding GPS network error and approximations within the New Zealand Quasigeoid 2009 reference surface which have a vertical accuracy of ±0.06 m (Canterbury Geotechnical Database 2014).

To investigate inundation patterns in the lower intertidal zone we used DEMs developed from echosounder surveys covering areas of the estuary and river channels that were

Table 1 Data sources: LiDAR datasets and specifications

Timing in earthquake sequence	Major earthquake events in period ^a	LiDAR acquisition dates	Supplier	Commissioning agencies	Accuracy specification (m)	
					Vertical	Horizontal
Pre-earthquake	N/a	6–9 Jul 2003	AAM Brisbane	Christchurch City Council	±0.15	±0.55
Post-February 2011	Darfield 7.1 M_w , Christchurch 6.4 M_w	20–30 May 2011	AAM Brisbane	Christchurch City Council	±0.07	±0.55
Post-June 2011	Christchurch 6.2 M_w	2–3 Sep 2011	New Zealand Aerial Mapping	Earthquake Commission	±0.07	±0.55
Post-December 2011	Christchurch 6.1 M_w	5 Oct–7 Nov 2015	AAM Brisbane	Canterbury Regional Council	±0.20	±1.00

^aBeavan et al. (2012). December 2011 magnitude represents combined moments of the two largest tremors

Table 2 Data sources: Comparison of tidal and benchmark heights at the Standard Port of Lyttelton (Lat. 43° 36' S., Long. 172° 43' E) against chart datum and two vertical datums in current use

Tidal level or feature	Height above chart Datum ^a (m)	Orthographic heights (m)	
		LVD37	NZVD2016
HAT	2.72	1.479	1.072
MHWS	2.49	1.249	0.842
B40V geodetic reference mark	4.478	3.237	2.83

LVD37 Lyttelton Vertical Datum 1937, NZVD New Zealand Vertical Datum 2016

^aLINZ (2018a, b)

submerged during the LiDAR surveys and therefore not captured. Although only two such DEMs were available due to the limited collection of bathymetric data over the CES, they are representative of pre- and post-earthquake conditions. Each DEM was generated using triangular irregular network (TIN) interpolation constrained with manually digitised break-lines following the main estuary channels to preserve channel connectivity and minimise interpolation artefacts (Measures and Bind 2013). Data sources are provided in Supplementary Material (Table S1).

2.3 Shoreline change

Shoreline sampling transects were developed using the AMBUR package (“Analyzing Moving Boundaries Using R”) for detecting movement and trend changes relative to a baseline position (Jackson et al. 2012). A baseline was developed from the Land Information New Zealand (LINZ) 1:50,000 coastline polyline and smoothing to improve fit with 0.075 m aerial imagery (LINZ 2016). A set of perpendicular transects ($n = 1428$) were cast at 10 m spacing from a start point at the southern estuary entrance (Lat. 43° 56' S, Long. 172° 75' E). Transect lengths were adjusted to cover all areas of potential tidal inundation (Fig. 2a). At river mouths, the sampling area was confined to the confluence with the main tidal lagoon basin. This breakpoint approximates the Coastal Marine Area boundary, an important jurisdictional division within environmental legislation (Orchard 2011). Ground level changes were assessed by point sampling of DEMs at 1 m spacing on the sampling transects followed by differencing. Spatial variation was investigated by grouping transects within five contiguous zones (Southshore, South Brighton, Bromley, Ferrymead and Redcliffs) reflecting changes in shoreline aspect and proximity to river mouths (Fig. 2a).

Shoreline position changes were calculated for two tidal heights of particular interest: Highest Astronomical Tide (HAT) and Mean High Water Springs (MHWS). These were delineated as orthographic heights (Table 3) obtained from the average predicted values over a full 18.6 year tidal cycle (2000–2018) at Port Lyttelton (LINZ 2018a). For MHWS the yearly variation is 0.1–0.15 m using current predictions (1 July 2018–30 June 2019). The current MHWS height is 2.6 m above chart datum, or 0.11 m above the mean value for the full tidal cycle (LINZ 2018b). These considerations do not affect HAT which is based on the full cycle. Shoreline position changes were quantified by extraction of the MHWS and HAT heights from each DEM followed by contour and intersection analysis on the sampling transects. Changes were measured as seaward or landward movement relative to the baseline.

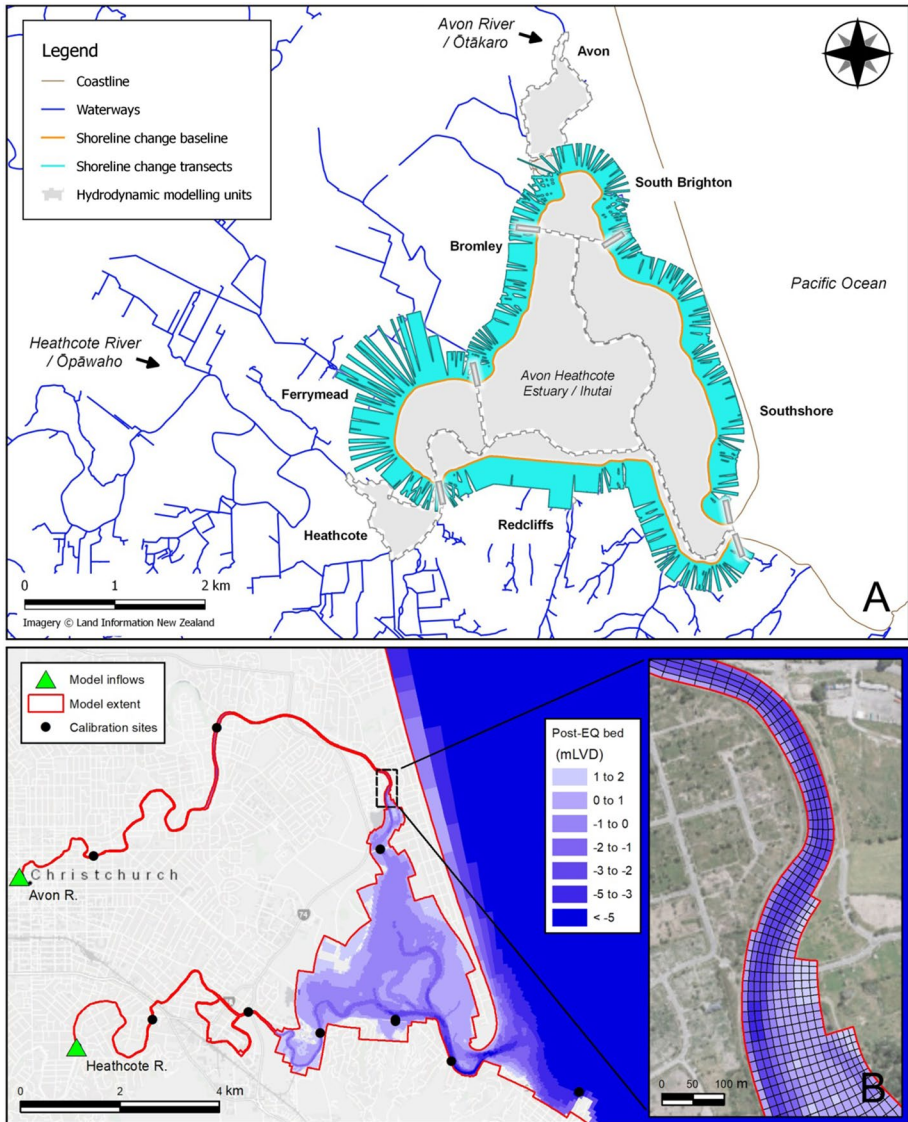


Fig. 2 Sampling design. **a** configuration of sampling transects for shoreline change analysis and estuarine localities used for spatial comparisons including boundaries of hydrodynamic modelling units. **b** Hydrodynamic model extent and example of model cell fit in relation to the estuary shoreline

2.4 Tidal inundation

Supratidal area changes were assessed for the four DEMs using the elevation band bounded by MHS and HAT (Table 2). Upstream freshwater regions were removed from the analysis by clipping at the limit of salt water intrusion as measured in field surveys on spring high tides. All DEM analyses assume full connectivity between adjacent hydrological basins, regardless of engineered modifications such as tidal gates and seawalls. Due

Table 3 Summary of key changes in the areal extent of the Avon Heathcote Estuary Ihutai over the period 2003–2015

Estuarine areas	Areal extent (ha) ^a			
	July 2003	May 2011	Sep 2011	Oct 2015
Area below HAT	1190.5	1146.0	1329.5	1135.8
Area below MHWS	1032.3	1009.7	1154.4	998.9
Supratidal area bounded by HAT and MHWS	158.2	136.3	175.2	136.9

The three later dates mark important time periods in the Canterbury Earthquake Sequence whilst the 2003 baseline is representative of pre-earthquake conditions

^aCalculations assume full hydrological connectivity between adjacent basins within the elevation range of interest

HAT Highest Astronomical Tide, *MHWS* Mean High Water Springs

to extensive earthquake damage to such infrastructure, this assumption approximates the actual post-disaster context and provides an assessment of potential inundation through connectivity improvements.

For mid-lower intertidal ranges where water surface slope and hydrological connectivity can strongly influence the inundation regime we used a calibrated Delft3D hydrodynamic model based on the bathymetric DEMs (Measures and Bind 2013). The model extends 15 km into the open ocean and has a curvilinear grid with horizontal resolution of ca. 20 m within the rivers and estuary basin (Fig. 2). Each grid cell is split into five vertical layers, with layer thickness proportional to water depth. Pre- and post-earthquake versions are identical apart from the DEM used to assign the bed level within each cell (Measures and Bind 2013). Month long simulations were computed using the pre- and post-earthquake models to quantify changes in inundation. Both simulations modelled identical astronomic tidal conditions and median river flows (Avon Ōtākaro = 1.65 m³/s, Heathcote Ōpāwaho = 0.77 m³/s). It is important to note that the model extent does not include all of the floodable intertidal areas in the estuary catchment. This results in an underestimation of potential inundation in the upper intertidal range, particularly above MHWS. The static DEM analyses are therefore more reliable for the investigation of changes at these higher elevations.

2.5 Data analyses

Raster analysis was used to quantify spatiotemporal changes in the elevation bands of interest with differencing between rasters to quantify ground level changes over time. Summary statistics were calculated for shoreline position changes on the sampling transects. Differences were identified using Kruskal–Wallis rank sum tests for independent variables of time and locality followed by post hoc pairwise tests where there was a significant movement relative to the pre-earthquake (2003) baseline. Hydrodynamic modelling outputs were post-processed to calculate the bed area inundated for different proportions of time under pre- and post-earthquake conditions, and summarised for the five main basin localities and additional upstream portions of the two major river catchments (Fig. 2a). Geospatial analyses were conducted in NZTM 2000: ESPG 2193 projection using QGIS v 2.18 (QGIS Development Team 2019). Statistical analyses were conducted in R v3.3.3 (R Core

Team 2017). Model post-processing was conducted in MATLAB using functions from the OpenEarthTools repository (<https://publicwiki.deltares.nl/display/OET/Tools>).

3 Results

Relative to pre-quake (2003) conditions, results from individual sampling points ($n=475,000$) showed more uplift than subsidence and marked differences between localities (Fig. 3). Subsidence occurred in the South Brighton area near the Avon Ōtākaro river mouth throughout 2011 though this had reduced by 2015. Here, and in other areas, the results also illustrate the ongoing nature of change in relation to key time periods in the CES, highlighting the difficulty in drawing conclusions from singular before-after comparisons. Large variations in the measured changes were seen in some areas, particularly in Redcliffs which is located at the foot of prominent hill-slopes (Fig. 3). This reflects the elevation signature of horizontal displacements on sloping ground that cannot be separated from the assessment of vertical movement at point coordinates. However, these effects are unlikely to affect shoreline change analyses due to the relatively flat topography of intertidal areas.

3.1 Shoreline movement

Large movements were detected in the position of post-quake versus pre-quake shorelines. Changes of over 500 m seaward were recorded for MHWS and HAT on individual transects. Landward shifts were also recorded to a maximum of 269 m for MHWS and 182 m for HAT (Fig. 4a). Shoreline change was significantly different between localities for both MHWS (Kruskal–Wallis $\chi^2=107.86$, $df=2$, $p<2.2e-16$) and HAT (Kruskal–Wallis $\chi^2=88.67$, $df=2$, $p<2.2e-16$), with several pronounced trends being

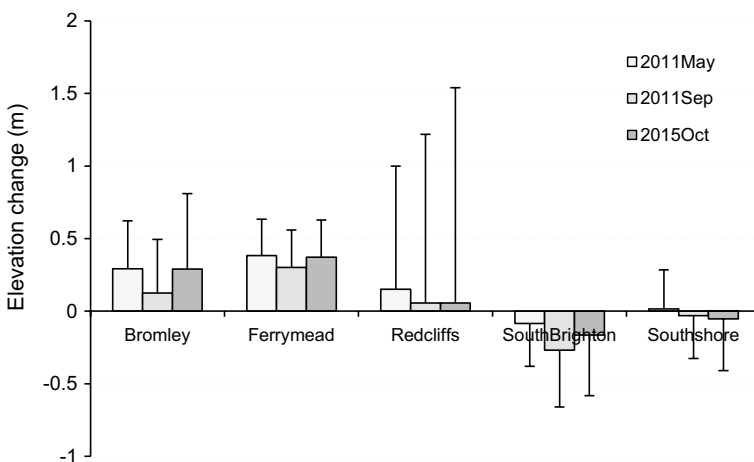


Fig. 3 Mean ground surface elevation changes relative to 2003 in the Avon Heathcote Estuary Ihutai for five contiguous localities on the shoreline of the tidal lagoon basin. Error bars represent one standard deviation. These results were obtained by differencing of individual sampling points ($n=475,000$) located on shore-perpendicular transect lines around the estuary perimeter

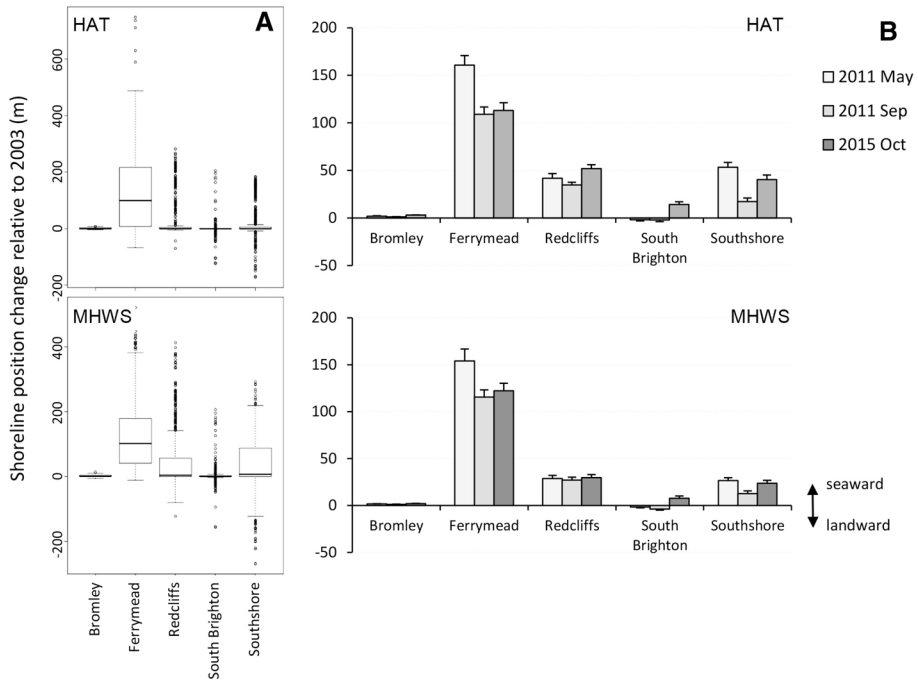
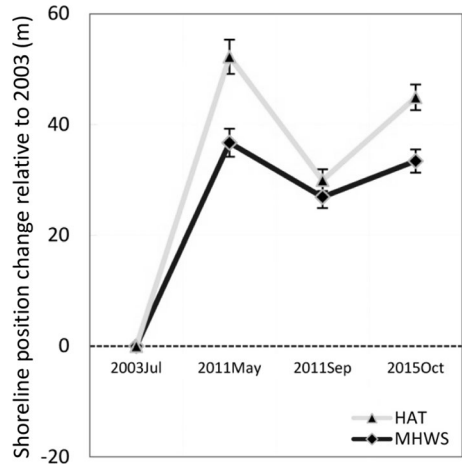


Fig. 4 Pattern of movement of two shorelines (HAT and MHWS) during the Canterbury Earthquake Sequence (CES) at the Avon Heathcote Estuary Ihtuai. **a** Box plots showing the total range of shoreline changes recorded at three post-quake time points for five estuarine localities relative to the July 2003 (pre-quake) position. Boxes show the median and interquartile range. **b** Mean shoreline position changes relative to July 2003 for each of the three points in time. Error bars are one standard error of the mean. See Table 1 for relationship to major tectonic events. Note different scales on the Y axis between **a** and **b**. *HAT* Highest Astronomical Tide. *MHWS* Mean High Water Springs

evident. At Ferrymead, large seaward shifts were recorded for MHWS and HAT (Fig. 4a), with the majority of movement having occurred by May 2011 as reflected by mean shifts of 161 m (HAT) and 154 m (MHWS) relative to 2003. At Southshore and Redcliffs the post-quake positions were consistently seaward of the 2003 shoreline but the movement was less than at Ferrymead (10–50 m). South Brighton and Bromley shorelines experienced little change on average relative to 2003. At South Brighton this was associated with large variances in the magnitude and direction of shifts on individual transect lines, whereas at Bromley little change was recorded on most transects due to the influence of shoreline armoring which is extensive in this area (Fig. 4a).

Mean shoreline change for the estuary as a whole was in a seaward direction for both MHWS and HAT shorelines. At all three post-quake time points, seaward movement in the HAT line was greater than for MHWS (Fig. 5). Shoreline position differences after the major earthquake of February 2011 (represented by May 2011 data) were significant for MHWS and HAT ($p < 0.001$). Wilcoxon pairwise comparisons for MHWS also showed that the end-point position (October 2015) was significantly different from the May 2011 position ($p < 0.001$). HAT changes conformed to a similar pattern, although statistical analysis showed no significant difference ($p = 0.81$) due to greater variation on individual transect lines (Fig. 5). These temporal effects are interpreted as a modest expansion of the tidal

Fig. 5 Mean shoreline position change since 2003 for the Avon Heathcote Estuary Ihutai as a whole, as recorded at each of three points in time during the Canterbury Earthquake Sequence. Error bars are one standard error of the mean. *HAT* Highest Astronomical Tide. *MHWS* Mean High Water Springs



lagoon basin between 2011 and 2015 that has reduced the initial contraction caused by the February 2011 earthquake. The same general trend can be seen in temporal patterns at most of the individual locations (Fig. 4b). However, these effects were not always directly proportional to the ground level changes shown in Fig. 3. For example, mean ground levels in 2015 at Southshore followed a trend of continuing subsidence whereas shoreline movement was in a seaward direction at the same time. This is potentially explained by the weathering of erodable surfaces accompanied by accretion elsewhere.

3.2 Intertidal area changes

Based on the most recent time point (2015), the total estuarine area below HAT has reduced by 54.7 ha, and 33.4 ha for MHWS (Table 3). The HAT-MHWS difference implies compression of the supratidal zone of around 21.4 ha (represented by the area bounded by HAT and MHWS). However, there were pronounced differences between time periods over the course of the CES with expansion evident between May and September 2011 but contraction at other times. In comparison to other localities, changes in the Avon area make a disproportionate contribution to the net overall impact (Fig. 6).

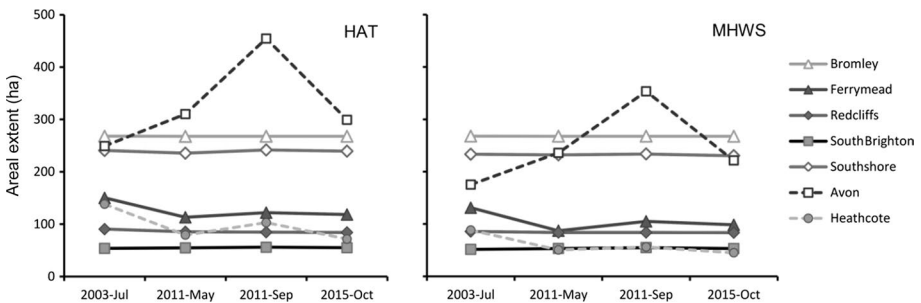


Fig. 6 Changes in the extent of estuarine areas below the elevation of Highest Astronomical Tide (HAT) and Mean High Water Spring tide (MHWS) for seven areas within the Avon Heathcote Estuary Ihutai catchment over 2003–2015

Impacts of the major February 2011 earthquake included reductions in the area below the elevation of both HAT and MHWS in Ferrymead and Heathcote, consistent with the dominance of uplift effects towards the southwest (Fig. 6). At the same time there were increases in the Avon area, consistent with subsidence effects further north. System-wide impacts are explained by a combination of tilting and a dominance of uplift in overall ground surface displacements, leading to reductions of 44.5 ha in the area below HAT, and 22.6 ha for MHWS (Table 4). In the next time period (May–September 2011), large increases were observed in the Avon Ōtākaro area (144.5 ha below HAT, 117.6 ha for MHWS), and small increases elsewhere, consistent with widespread subsidence. Relative to pre-quake (2003), the intertidal area was 139 ha larger and included a modest increase (16.9 ha) in the supratidal zone. However, this estuarine expansion was relatively short-lived due to a dramatic reversal in the Avon area in the next time period (to 2015). The overall results are illustrative of complex spatiotemporal patterns that reflect both co-seismic perturbations and re-equilibration processes (Fig. 6). The most recent measurements showed the estuarine area was similar to May 2011 and smaller than in 2003 (Table 3). See Supplementary Material Fig. S1 for a map of baseline (2003) and endpoint (2015) conditions.

Hydrodynamic modelling showed that subtidal area losses contributed additional intertidal area due to shallowing of the main estuary basin (Fig. 7). The biggest changes occurred in the uplifted southern parts of the estuary: Heathcote, Ferrymead, Redcliffs, and the southern parts of Bromley and Southshore (Fig. 7). In these areas the total intertidal area has generally increased due to the exposure of channels which were previously permanently submerged at low tide, and an accompanying reduction in the subtidal area. Areas which were already intertidal are now exposed for a longer duration on each tidal cycle. However, there are few areas which were previously intertidal and that are now above the modelled reach of the tide. This counterintuitive result can be explained by the observation of only small areas that were shallowly submerged at high tide in the pre-earthquake state. This is particularly evident for areas inundated for less than 30% of the time (Fig. 7) and is indicative of upper intertidal reclamations having already

Table 4 Effects of higher sea levels on mean estuarine shoreline position and intertidal area at South Brighton for three time points during the Canterbury Earthquake Sequence relative to pre-quake (2003) conditions

Key changes since 2003 ^a	Assessment dates		
	May 2011	Sep 2011	Oct 2015
Mean ground level elevation (m)	−0.09	−0.27	−0.16
Shoreline retreat (landward movement) (m)			
HAT	2.0	2.2	−14.2
MHWS	1.8	4.0	−7.5
Areal extent of intertidal areas ^a (ha)			
Area below HAT	0.9	2.1	1.3
Area below MHWS	1.7	3.4	1.6
Supratidal area between HAT and MHWS	−0.8	−1.3	−0.3

^acalculations assume full hydrological connectivity between adjacent basins within the elevation range of interest

HAT Highest Astronomical Tide, MHWS Mean High Water Springs

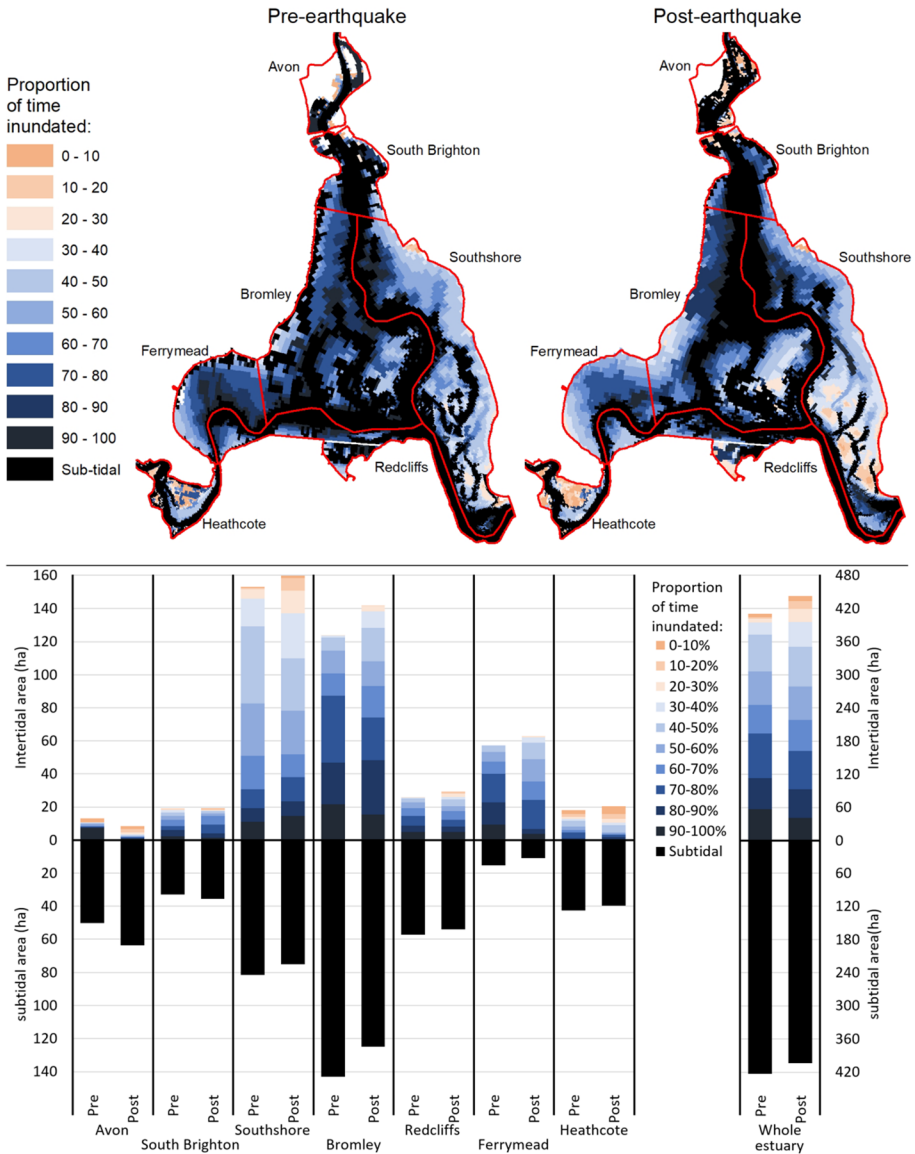


Fig. 7 Hydrodynamic model results for pre- and post-earthquake bed topographies representative of the Canterbury Earthquake Sequence and showing changes in the intertidal area inundated over a typical monthly tidal cycle. Both simulations used identical astronomic tidal conditions and median river flows (Avon Ōtakaro = 1.65 m³/s, Heathcote Opāwaho = 0.77 m³/s)

occupied those areas. The combination of both shallowing and an overall decrease in intertidal area at high tide, suggests a reduced tidal prism with the potential to drive further habitat shifts through direct effects on the salinity regime and interactions with water heights, currents, and patterns of erosion and deposition.

At Bromley, uplift was insufficient to move either HAT or MHWS shorelines. This shows that the ‘coastal squeeze’ impacts of seawalls had extended well into the intertidal range and exceeded the tipping point for persistence of a high tide beach, even with the benefit of uplift. Similar results indicative of pre-earthquake degradation were also evident in Southshore and Ferrymead where pre-quake upper intertidal zones were much smaller than lower intertidal zones, but expanded markedly following uplift (Fig. 7). The CES both illuminated and reversed the pre-quake situation where land-uses were occupying areas that would otherwise be regularly inundated on moderate-sized tides. Moreover, these results demonstrate that the post-quake state remains vulnerable to sea-level rise impacts due to the current position of seawalls. In areas that subsided (Avon and South Brighton), the hydrodynamic modelling is less reliable as an indicator of upper intertidal change due to limitations of model domain which excluded land outside of the estuary that is now subject to tidal inundation. However, these areas were captured within other assessments using the static DEMs.

3.3 Impacts of sea level rise

Appreciable subsidence occurred only in the Avon Ōtākaro catchment and adjacent South Brighton portion of the main lagoon basin. However, these areas provide an excellent opportunity to assess the actual effects of higher sea levels on a pre-disturbance landscape. At South Brighton, the measured sea-level rise was greatest in September 2011 with subsidence of 27 cm on the sampling transects versus 2003 (Table 4). Despite this, shoreline change analysis showed only small landward movements in the position of HAT and MHWS (means of 2.2 m and 4.1 m respectively). The increase in area below HAT (2.1 ha) was much less than for MHWS (3.4 ha), leading to a 1.3 ha (58%) reduction in the land available between HAT and MHWS. The 2015 results showed a general reversal of these effects consistent with the raising of ground levels. Relative to 2003, the end result was an intertidal area loss of 1.3 ha, and a 0.3 ha compression of the supratidal zone (Table 4).

Figure 8 illustrates the mechanisms of change in supratidal zones as observed in South Brighton and the lower Avon Ōtākaro catchment under conditions of relative sea-level rise. This area has extensive anthropogenic shoreline modifications. In the Bexley wetlands (arrowed) impacts included a large loss of supratidal area (Fig. 8a). Contributing factors included the raising of nearby ground levels to facilitate a housing development that had the effect of truncating landward movement of the supratidal zone under conditions of sea-level rise. On the opposite (eastern) shoreline, land-fills are not prominent in the development pattern despite the close proximity of residential property to the estuary. Some of these properties are now exposed to inundation at water heights of HAT (and less). However, these areas were not subject to the government land acquisition. As a result, these areas are less likely to be candidates for managed retreat strategies that include the creation of future estuarine space despite ground levels being more favourable than in areas modified by land-fill (Fig. 1). On this eastern shoreline, the 2015 bounce-back effect (Table 4) is also notable as illustrated by the expansion of supratidal areas seaward of the shoreline armouring line (Fig. 8d). As yet, however, these changes are insufficient to restore the major losses incurred earlier in the CES.

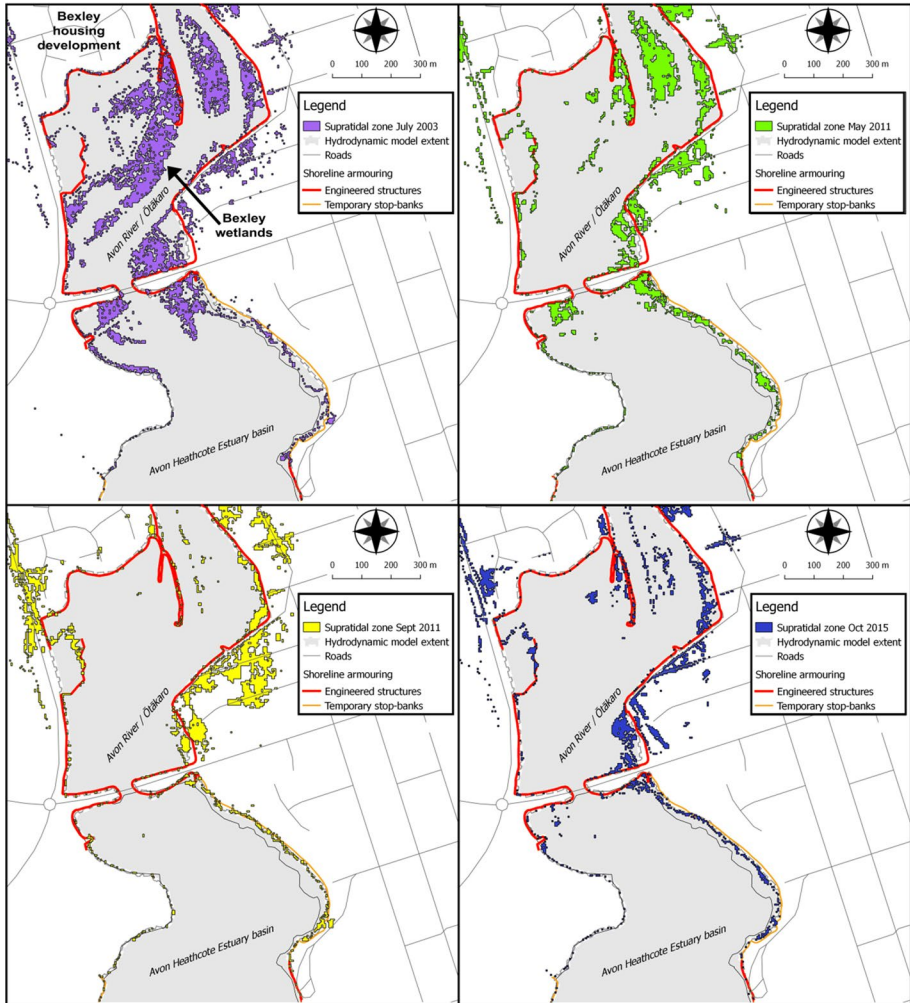


Fig. 8 Changes in the areal extent of the supratidal zone modelled as the elevation band between Highest Astronomical Tide and Mean High Water Springs over the period 2003–2015. The area shown is the lower Avon Ōtakaro catchment and northern portion of the main tidal lagoon basin of the Avon Heathcote Estuary Ihutai which experienced ground level subsidence during the Canterbury Earthquake Sequence

4 Discussion

Aside from their contribution to the longer-term relative sea-level trend, rare examples of tectonic subsidence can demonstrate the effects of rapid sea-level rise where they occur in coastal environments (Albert et al. 2016; Reed 1990; Saunders et al. 2016). Although the rates of sea-level change are more rapid than the equivalent results of climate change, they are nonetheless illustrative of extreme scenarios. The observed responses may help to identify mechanisms that can lead to adverse effects, and strategies to help avoid them. Recent examples provide unique opportunities to investigate

sea-level rise responses in contemporary socio-ecological contexts, and it is becoming increasingly important to understand these processes and their outcomes due to the prevalence of accelerated rates of sea-level rise within climate change predictions (Cazenave and Llovel 2010; Nicholls et al. 2011). Important consequences for coastal communities include the reduction of timelines for adaptation processes and the potential for greater impacts in the advent of delays or poorly designed responses. Because of the severe consequences associated with run-away climate change, many authors have recommended the consideration of extreme scenarios as an element of preparedness and in recognition of inherent uncertainties in current predictions (Duarte 2014; Nicholls et al. 2014; Polasky et al. 2011). These aspects indicate that tectonic subsidence events can offer useful insights for climate change adaptation in addition to their more immediate needs in the context of disaster recovery.

The present study investigated a significant displacement event on the east coast of New Zealand. Globally, there have been few empirical studies of similar events due to their relative scarcity in modern times. Examples include post-earthquake investigations in South America (Reed 1990; Reed et al. 1988), California (Jacoby et al. 1995), and the Solomon Islands (Albert et al. 2016, 2017; Saunders et al. 2016), and deep subsidence caused by a mine collapse in Australia (Rogers et al. 2019). However, other insightful studies have come from examples of shallow subsidence in river deltas (Al Mukaimi et al. 2018; Schmidt 2015). These include large-scale effects in the Mississippi and Mekong deltas where subsidence trends have been linked with wetland losses (Day et al. 2000; Morton et al. 2010; Phan et al. 2015; Storms et al. 2008). Despite the unique opportunity afforded by these events for the study of sea-level rise, the potential for transferable learning is generally constrained by their occurrence in markedly different environments and socio-ecological contexts. Unique aspects of the present study include the co-occurrence of subsidence and relative sea-level rise with urban development on a temperate shoreline typical of many worldwide.

4.1 Patterns of change and implications

Empirical findings from this case describe the landscape-scale reconfiguration of a coastal hydrosystem. Area losses were highly variable between sites but often driven by the position of shoreline armouring in relation to the post-disturbance intertidal range. The availability of space within critical elevations bands is identified as a key consideration for natural hazards planning and the design of flood defences in the post-disaster context. For example, our results indicate negative impacts on the availability of high tide roosting habitat for shorebirds, an already well-established conservation concern in New Zealand (Woodley 2012), and elsewhere (Green et al. 2015; Zharikov and Milton 2009). Another important site-specific effect involved the potential for estuarine expansion driven by subsidence in the Avon Ōtākaro catchment, to offset losses experienced elsewhere, as occurred in areas of uplift. This indicates the need for a whole-system view when planning future land uses. Additionally, these observations present a compelling case for assisting the migration of important ecosystems to areas where they would be expected to move if unhindered by anthropogenic barriers. In this case, the government acquisition of riparian and floodplain land greatly facilitates such possibilities, and includes the potential for rewilding of formerly urbanised areas.

4.2 Principles for holistic responses

Areas experiencing subsidence provide opportunities to identify resilience-building principles by considering the space now available in the intertidal elevation range. At several locations, seawalls constrained shoreline movement exemplifying the potential for habitat loss where sea-level rise coincides with anthropogenic modifications. At Bexley, the infilling of land for a housing development limits the opportunities for assisted habitat migration (Hällfors et al. 2014), despite being within the area of government-acquired land (Fig. 1). Accommodation space with critical intertidal ranges cannot readily be created unless major earthworks are undertaken to remove the filled land. On the opposite shoreline, the upland migration of natural ecosystems could be assisted using relatively simple breaches of existing shoreline defences based on our modelled results. However, residential properties remain present in these areas since they were not included in the government land acquisition initiative. These examples illustrate how past and recent land-use decisions have each contributed to resiliency and opportunities for managed retreat.

These findings highlight the potential for natural resources to become degraded unless a whole-system view of resilience is adopted in which trade-offs are identified and managed (Folke 2006; Gunderson et al. 2010). Their consequences become more obvious once conditions change and risks become manifested as losses, yet it is important that they are identified proactively in advance of tipping points being reached. Key principles evident in this case include the need to consider both built and natural environments in the design of adaptation initiatives such as managed retreat, and the legacy effect of land-filling activities which dramatically alter the ‘rewildability’ of the underlying landscape as conditions change. Alternatives include land uses that do not rely on extreme landscape modification, or the adoption of more dynamic and evolving land-use approaches in which change is more easily accommodated.

4.3 Ongoing change and the need for dynamic responses

The considerable amount of ongoing change in the estuary and environs over the post-quake study period highlights the importance of re-equilibrium processes that are additional to the immediate effects of periodic extreme events. These dynamic aspects indicate the need for sustained and relatively fine-scale monitoring to quantify ongoing spatiotemporal change, as needed to assess vulnerability to future hydrological alterations, and the potential role of accretion as a modulator of relative sea-level rise (Gedan et al. 2011).

Conversely, the CES has also highlighted the role of tectonic displacement as a landscape-shaping force. In seismically active regions, the movement of land masses can strongly and unpredictably influence relative sea levels. The interaction between land motion and eustatic sea-level change that is arguably more difficult to quantify than the phenomenon of glacial isostasy, which results in similar considerations (Barlow et al. 2012; Cazenave and Llovel 2010). Periodic events, such as earthquakes, operate at variable time scales and are difficult to accommodate in predictive models, yet have the potential to introduce major step changes. This has profound implications for the efficiency of risk reduction plans that are typically geared towards established return periods and incremental future changes (Glavovic et al. 2010). Considerations for management include the need for preparedness to change in areas exposed to less predictable natural hazards, and this could include the promotion of more flexible land-use arrangements as a strategy for risk reduction.

4.4 Relating co-seismic changes to eustatic sea-level rise

Important learning for climate change adaptation may be identified from this case by treating the empirical observations as a scenario that illuminates the potential effects of sea-level rise, and relationships with anthropogenic responses. However, the observed impacts should not be taken as a prediction of the actual effects of climate change, due (in part) to the expectation of different societal responses. Rather, this case exemplifies a period of rapid change in which the implementation of comprehensive responses has yet to occur, providing the opportunity to assess impacts in their absence.

Although many authors point out that the effects of incremental sea-level rise will manifest as variable outcomes due to the influence of non-climatic factors (Nicholls et al. 2008), the observed scenario in this case (elevation of water level heights by ca. 0.5 m on the pre-existing landscape) could readily be generated by a combination of such effects. Therefore, despite the expectation of different trajectories of change, the proposal that comparable effects may be produced with eustatic sea-level rise is highly plausible given current predictions (IPCC 2013). Moreover, similar effects are likely in situations where water levels rise and fixed infrastructure remains in place, as exemplified here. Although regional variation in sea-level change is expected (Cazenave and Cozannet 2014), the consequences for natural environments will depend considerably on human attitudes to coastal transgression due the prevalence of competing land uses in the areas involved (Kirwan and Megonigal 2013; Schuerch et al. 2018). For these reasons, scenario analysis provides a useful approach for evaluating uncertain futures by illustrating the potential outcomes of altered sea levels and beneficial strategies in response.

4.5 Concluding remarks

There are widely transferable principles of importance in this study and close analogies with the seminal work of Turner (1978) on the man-made aspects of natural disasters. In this paradigm, risk reduction *decisions* are highlighted as key influences on outcomes. As applied to natural environments, decisions are required to prevent the reaching of tipping points that result in loss of natural features and resources. This study illustrates the potential for rapid sea-level changes to exceed such tipping points with deleterious effects that result largely from anthropogenic influences.

Empirical studies can help improve the understanding socio-ecological factors and specific mechanisms leading to adverse effects, thereby helping to avoid them. Knowledge of the mechanisms of loss may help to improve concepts of risk and provide insights for the development of holistic solutions to deal with a range of sea-level rise situations. Although the progression of this knowledge base may not always coincide with high levels of motivation for adopting new and proactive measures, we believe that it will assist by highlighting trade-offs and illustrating alternatives to business-as-usual approaches in successive planning and development cycles.

Specific principles for the attention of coastal land-use planners include the need for hazard management approaches that are inclusive of natural environments and address the upland migration requirements of ecosystems vulnerable to coastal transgression. Such strategies are desperately needed, and will be enabled by identifying opportunities for building whole-system resilience, and measuring performance in the same terms. The mainstreaming of these measures requires much greater attention within the societal

discourse on natural hazards due to the likelihood of competing land-use demands in the areas involved. However, these aspects may be assisted by improving the awareness of trade-offs and legacy effects. Disaster recovery contexts also deserve greater attention due to the unique opportunities for land-use reconfiguration and the uptake of new approaches that may be enabled in these times. We highlight the benefits of preparedness for post-disaster planning, and the importance of disaster recovery processes for adaptation to climate change.

Acknowledgements We thank the Ngāi Tahu Research Centre, Brian Mason Scientific and Technical Trust, and National Institute for Water and Atmospheric Research (NIWA) for funding support. We thank Jochen Bind for assisting the development of bathymetric datasets, and the Ministry of Business, Innovation and Employment (MBIE) and Environment Canterbury for funding the original hydrodynamic model.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Al Mukaimi ME, Dellapenna TM, Williams JR (2018) Enhanced land subsidence in Galveston Bay, Texas: interaction between sediment accumulation rates and relative sea level rise. *Estuar Coast Shelf Sci* 207:183–193. <https://doi.org/10.1016/j.ecss.2018.03.023>
- Albert S, Leon JX, Grinham AR, Church JA, Gibbes BR, Woodroffe CD (2016) Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environ Res Lett* 11(5):54011. <https://doi.org/10.1088/1748-9326/11/5/054011>
- Albert S, Saunders MI, Roelfsema CM, Leon JX, Johnstone E, Mackenzie JR, Woodroffe CD et al (2017) Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environ Res Lett* 12(9):94009. <https://doi.org/10.1088/1748-9326/aa7e68>
- Barbier EB, Hacker SD, Kennedy C, Koch EW, Stier AC, Silliman BR (2011) The value of estuarine and coastal ecosystem services. *Ecol Monogr* 81(2):169–193. <https://doi.org/10.1890/10-1510.1>
- Bardsley DK, Sweeney SM (2010) Guiding climate change adaptation within vulnerable natural resource management systems. *Environ Manage* 45(5):1127–1141. <https://doi.org/10.1007/s00267-010-9487-1>
- Barlow NLM, Shennan I, Long AJ (2012) Relative sea-level response to little ice age ice mass change in south central Alaska: reconciling model predictions and geological evidence. *Earth Planet Sci Lett* 315–316:62–75. <https://doi.org/10.1016/j.epsl.2011.09.048>
- Beavan J, Motagh M, Fielding EJ, Donnelly N, Collett D (2012) Fault slip models of the 2010–2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation. *NZ J Geol Geophys* 55(3):207–221. <https://doi.org/10.1080/00288306.2012.697472>
- Berry A, Fahey S, Meyers N (2013) Changing of the guard: adaptation options that maintain ecologically resilient sandy beach ecosystems. *J Coastal Res* 29(4):899–908. <https://doi.org/10.2112/JCOASTRES-D-12-00150.1>
- Bradley BA, Quigley MC, Van Dissen RJ, Litchfield NJ (2014) Ground motion and seismic source aspects of the Canterbury earthquake sequence. *Earthq Spectra* 30(1):1–15. <https://doi.org/10.1193/030113EQS060M>
- Canterbury Geotechnical Database (2014) Verification of LiDAR acquired before and after the Canterbury Earthquake Sequence. CGD Technical Specification 03 April 2014. p 52. Canterbury Geotechnical Database, Christchurch
- Cazenave A, Cozannet GL (2014) Sea level rise and its coastal impacts. *Earth's Future* 2(2):15–34. <https://doi.org/10.1002/2013EF000188>
- Cazenave A, Llovel W (2010) Contemporary sea level rise. *Ann Rev Mar Sci* 2(1):145–173. <https://doi.org/10.1146/annurev-marine-120308-081105>
- Chapman PM (2012) Management of coastal lagoons under climate change. *Estuar Coast Shelf Sci* 110:32. <https://doi.org/10.1016/j.ecss.2012.01.010>
- Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, Walters G et al (2019) Core principles for successfully implementing and upscaling Nature-based Solutions. *Environ Sci Policy* 98:20–29. <https://doi.org/10.1016/j.envsci.2019.04.014>

- Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, van den Belt M et al (1998) The value of the world's ecosystem services and natural capital. *Ecol Econ* 25(1):3–15. [https://doi.org/10.1016/S0921-8009\(98\)00020-2](https://doi.org/10.1016/S0921-8009(98)00020-2)
- Crossland AC (2013) Wetland bird monitoring at the Avon-Heathcote Estuary and Bromley Oxidation Ponds, Christchurch : August 2009 to July 2010. *Notornis* 60(2):151–157
- Day JW, Britsch LD, Hawes SR, Shaffer GP, Reed DJ, Cahoon D (2000) Pattern and process of land loss in the Mississippi Delta: a spatial and temporal analysis of wetland habitat change. *Estuaries* 23(4):425–438. <https://doi.org/10.2307/1353136>
- Delaney S, Scott D (2006) *Waterbird Population Estimates*, 4th edn. Wetlands International, Wageningen, The Netherlands
- Duarte CM (2014) Global change and the future ocean: a grand challenge for marine sciences. *Front Mar Sci*. <https://doi.org/10.3389/fmars.2014.00063>
- Duarte CM, Borja A, Carstensen J, Elliott M, Krause-Jensen D, Marbà N (2015) Paradigms in the recovery of estuarine and coastal ecosystems. *Estuaries Coasts* 38(4):1202–1212. <https://doi.org/10.1007/s12237-013-9750-9>
- Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. *Glob Environ Change* 16(3):253–267. <https://doi.org/10.1016/j.gloenvcha.2006.04.002>
- Füssel HM (2007) Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustain Sci* 2(2):265–275. <https://doi.org/10.1007/s11625-007-0032-y>
- Gedan KB, Kirwan ML, Wolanski E, Barbier EB, Silliman BR (2011) The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim Change* 106(1):7–29. <https://doi.org/10.1007/s10584-010-0003-7>
- Glavovic BC, Saunders WSA, Becker JS (2010) Land-use planning for natural hazards in New Zealand: the setting, barriers, ‘burning issues’ and priority actions. *Nat Hazards* 54(3):679–706. <https://doi.org/10.1007/s11069-009-9494-9>
- Green JMH, Sripanomyom S, Giam X, Wilcove DS, Fuller R (2015) The ecology and economics of shore-bird conservation in a tropical human-modified landscape. *J Appl Ecol* 52(6):1483–1491. <https://doi.org/10.1111/1365-2664.12508>
- Gunderson LH, Allen CR, Holling CS (2010) *Foundations of ecological resilience*. Island Press, Washington
- Hällfors MH, Vaara EM, Hyvärinen M, Oksanen M, Schulman LE, Siipi H, Lehvävirta S (2014) Coming to terms with the concept of moving species threatened by climate change – A systematic review of the terminology and definitions. *PLoS ONE* 9(7):e102979. <https://doi.org/10.1371/journal.pone.0102979>
- Hicks DM (1998) Sediment budgets for the Canterbury Coast—a review, with particular reference to the importance of river sediment. Report CHC98/2 prepared for Canterbury Regional Council. NIWA, Christchurch
- Hughes MW, Quigley MC, van Ballegooy S, Deam BL, Bradley BA, Hart DE, Measures R (2015) The sinking city: earthquakes increase flood hazard in Christchurch New Zealand. *GSA Today* 25(3–4):4–10
- Hume TM, Snelder T, Weatherhead M, Liefing R (2007) A controlling factor approach to estuary classification. *Ocean Coast Manag* 50(11):905–929. <https://doi.org/10.1016/j.ocecoaman.2007.05.009>
- IPCC (2013) Climate change 2013: the physical science basis. In: Stocker, Qin, Plattner, Tignor, Allen, Boschung, Nauels, Xia, Bex, Midgley (eds) Working group contribution to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Jackson CW, Alexander CR, Bush DM (2012) Application of the AMBUR R package for spatio-temporal analysis of shoreline change: Jekyll Island, Georgia, USA. *Comput Geosci* 41:199–207. <https://doi.org/10.1016/j.cageo.2011.08.009>
- Jacoby G, Carver G, Wagner W (1995) Trees and herbs killed by an earthquake around 300 yr ago at Humboldt Bay. *Calif Geol* 23(1):77
- Joll D, Ngā Papatipu Rūnanga Working Group (2013) *Mahaanui Iwi Management Plan 2013*. Mahaanui Kurataiao Ltd., Ōtautahi Christchurch
- Jones MB, Marsden ID (2007) *Life in the Estuary: Illustrated guide and ecology*. Canterbury University Press, Christchurch, p 179
- Kabisch N, Frantzeskaki N, Pauleit S, Naumann S, Davis M, Artmann M, Bonn A et al (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society* 21(2):39. <https://doi.org/10.5751/ES-08373-210239>
- Kaiser A, Holden C, Beavan J, Beetham D, Benites R, Celentano A, Zhao J et al (2012) The Mw 6.2 Christchurch earthquake of February 2011: preliminary report. *N Z J Geol Geophys* 55(1):67. <https://doi.org/10.1080/00288306.2011.641182>
- Kennish MJ (1986) *Ecology of estuaries*. CRC Press, Boca Raton

- Kennish MJ (2002) Environmental threats and environmental future of estuaries. *Environ Conserv* 29(1):78–107. <https://doi.org/10.1017/s0376892902000061>
- Kirk RM (1979) Dynamics and management of sand beaches in southern Pegasus Bay. Morris and Wilson Consulting Engineers Limited, Christchurch
- Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 504(7478):53–60. <https://doi.org/10.1038/nature12856>
- Lang M, Orchard S, Falwasser T, Rupene M, Williams C, Tirikatene-Nash N, Couch R (2012) State of the Takiwā 2012 -Te Āhuetanga o Te Ihutai. Cultural Health Assessment of the Avon-Heathcote Estuary and its Catchment. Mahaanui Kurataiao Ltd., Christchurch, p 41
- Lichter M, Vafeidis AT, Nicholls RJ, Kaiser G (2011) Exploring data-related uncertainties in analyses of land area and population in the “Low-Elevation Coastal Zone” (LECZ). *J Coastal Res* 27(4):757–768. <https://doi.org/10.2112/JCOASTRES-D-10-00072.1>
- LINZ (2016) Christchurch 0.075m Urban Aerial Photos (2015–16). Imported on Oct. 3, 2016 from 6993 Geo-TIFF sources in NZGD2000 / New Zealand Transverse Mercator 2000
- LINZ (2017) Canterbury—Christchurch and Selwyn LiDAR 1m DEM (2015). Accessed 3 March 2019 from <https://data.linz.govt.nz/layer/53587-canterbury-christchurch-and-selwyn-lidar-1m-dem-2015/>
- LINZ (2018a) Local mean sea level datums. Updated 22 March 2018. Accessed 4 April 2019 from <https://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/>
- LINZ (2018) New Zealand Nautical Almanac, 2018/2019 edition, NZ 204. Land Information New Zealand, Wellington, p 271
- Macreadie PI, Nielsen DA, Kelleway JJ, Atwood TB, Seymour JR, Petrou K, Ralph PJ et al (2017) Can we manage coastal ecosystems to sequester more blue carbon? *Front Ecol Environ* 15(4):206–213. <https://doi.org/10.1002/fee.1484>
- Martínez ML, Intralawan A, Vázquez G, Pérez-Maqueo O, Sutton P, Landgrave R (2007) The coasts of our world: Ecological, economic and social importance. *Ecol Econ* 63(2):254–272. <https://doi.org/10.1016/j.ecolecon.2006.10.022>
- Martínez ML, Mendoza-Gonzalez G, Silva-Casarin R, Mendoza-Baldwin E (2014) Land use changes and sea level rise may induce a “coastal squeeze” on the coasts of Veracruz, Mexico. *Glob Environ Change* 29:180. <https://doi.org/10.1016/j.gloenvcha.2014.09.009>
- McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ Urban* 19(1):17–37. <https://doi.org/10.1177/0956247807076960>
- Measures R, Bind J (2013) Hydrodynamic model of the avon heathcote estuary: model build and calibration, NIWA client report CHC2013-116. NIWA, Christchurch, p 29
- Morton RA, Bernier JC, Kelso KW, Barras JA (2010) Quantifying large-scale historical formation of accommodation in the Mississippi Delta. *Earth Surf Proc Land* 35(14):1625–1641. <https://doi.org/10.1002/esp.2000>
- Nicholls RJ, Hanson SE, Lowe JA, Warrick RA, Lu X, Long AJ (2014) Sea-level scenarios for evaluating coastal impacts. *Wiley Interdiscip Rev Clim Change* 5(1):129–150. <https://doi.org/10.1002/wcc.253>
- Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, Gusmão DD, Richard SJT et al (2011) Sea-level rise and its possible impacts given a ‘beyond 4°C world’ in the twenty-first century. *Philos Trans Math Phys Eng Sci* 369(1934):161–181. <https://doi.org/10.1098/rsta.2010.0291>
- Nicholls RJ, Wong PP, Burkett V, Woodroffe CD, Hay J (2008) Climate change and coastal vulnerability assessment: scenarios for integrated assessment. *Sustain Sci* 3(1):89–102. <https://doi.org/10.1007/s11662-008-0050-4>
- Orchard S (2011) Implications of the New Zealand Coastal Policy Statement for New Zealand communities. Report prepared for Environment and Conservation Organisations of New Zealand, Wellington, p 46
- Orchard S (2017) Floodplain restoration principles for the Avon-Ōtākaro Red Zone. Case studies and recommendations. Report prepared for Avon Ōtākaro Network, Christchurch, p 40
- Pauling C, Lenihan TM, Rupene M, Tirikatene-Nash N, Couch R (2007) State of the Takiwā -Te Āhuetanga o Te Ihutai Cultural Health Assessment of the Avon-Heathcote Estuary and its Catchment. Te Rūnanga o Ngāi Tahu, Christchurch, p 35
- Pendleton LH (2008) The economic and market value of coasts and estuaries: what’s at stake. *Restore America’s Estuaries*, Arlington, p 182
- Perkins MJ, Ng TPT, Dudgeon D, Bonebrake TC, Leung KMY (2015) Conserving intertidal habitats: What is the potential of ecological engineering to mitigate impacts of coastal structures? *Estuar Coast Shelf Sci* 167:504–515. <https://doi.org/10.1016/j.ecss.2015.10.033>
- Phan LK, Jaap SMVTDV, Stive MJF (2015) Coastal mangrove squeeze in the Mekong Delta. *J Coast Res* 31(2):233–243. <https://doi.org/10.2112/JCOASTRES-D-14-00049.1>
- Polasky S, Carpenter SR, Folke C, Keeler B (2011) Decision-making under great uncertainty: environmental management in an era of global change. *Trends Ecol Evol* 26(8):398–404. <https://doi.org/10.1016/j.tree.2011.04.007>

- Potter SH, Becker JS, Johnston DM, Rossiter KP (2015) An overview of the impacts of the 2010–2011 Canterbury earthquakes. *Int J Disaster Risk Reduct* 14(1):6–14. <https://doi.org/10.1016/j.ijdrr.2015.01.014>
- QGIS Development Team (2019) QGIS Geographic Information System. Open Source Geospatial Foundation Project. <https://qgis.org>
- Quigley MC, Bastin S, Bradley BA (2013) Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. *Geology* 41(4):419–422. <https://doi.org/10.1130/G33944.1>
- Quigley MC, Hughes MW, Bradley BA, van Ballegooy S, Reid C, Morgenroth J, Pettinga JR et al (2016) The 2010–2011 canterbury earthquake sequence: environmental effects, seismic triggering thresholds and geologic legacy. *Tectonophysics* 672–673:228–274. <https://doi.org/10.1016/j.tecto.2016.01.044>
- R Core Team (2017) R: a language and environment for statistical computing. R foundation for statistical computing. Vienna, Austria
- Reed DJ (1990) The impact of sea-level rise on coastal salt marshes. *Prog Phys Geogr* 14(4):465–481. <https://doi.org/10.1177/030913339001400403>
- Reed DJ, Wood RM, Best J (1988) Earthquakes, rivers and ice: scientific research at the Laguna San Rafael, Southern Chile, 1986. *Geogr J* 154(3):392–405. <https://doi.org/10.2307/634611>
- Renaud FG, Sudmeier-Rieux K, Estrella M, Nehren U, SpringerLink. (2016) Ecosystem-based disaster risk reduction and adaptation in practice, vol 42. Springer International Publishing, Cham
- Robins PE, Skov MW, Lewis MJ, Giménez L, Davies AG, Malham SK, Jago CF et al (2016) Impact of climate change on UK estuaries: a review of past trends and potential projections. *Estuar Coast Shelf Sci* 169:119–135. <https://doi.org/10.1016/j.ecss.2015.12.016>
- Robinson K, Hughes M, Cubrinovski M, Orense R, Taylor M (2012) Lateral spreading and its impacts in urban areas in the 2010–2011 Christchurch earthquakes. *NZ J Geol Geophys* 55(3):255. <https://doi.org/10.1080/00288306.2012.699895>
- Rogers K, Kelleway JJ, Saintilan N, Meconigal JP, Adams JB, Holmquist JR, Woodroffe CD et al (2019) Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature* 567(7746):91–95. <https://doi.org/10.1038/s41586-019-0951-7>
- Saunders MI, Saunders MI, Albert S, Albert S, Roelfsema CM, Roelfsema CM, Mumby PJ et al (2016) Tectonic subsidence provides insight into possible coral reef futures under rapid sea-level rise. *Coral Reefs* 35(1):155–167. <https://doi.org/10.1007/s00338-015-1365-0>
- Schleupner C (2008) Evaluation of coastal squeeze and its consequences for the Caribbean island Martinique. *Ocean Coast Manag* 51(5):383–390. <https://doi.org/10.1016/j.ocecoaman.2008.01.008>
- Schmidt CW (2015) Delta subsidence: An imminent threat to coastal populations. *Environ Health Perspect* 123(8):A204–A209. <https://doi.org/10.1289/ehp.123-A204>
- Schuerch M, Spencer T, Temmerman S, Kirwan ML, Wolff C, Lincke D, Brown S et al (2018) Future response of global coastal wetlands to sea-level rise. *Nature* 561(7722):231–234. <https://doi.org/10.1038/s41586-018-0476-5>
- Storms JEA, Blaauw M, Wallace DJ, van Dam RL, Meijneken C, Klerks CJW, Snijders EMA et al (2008) Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nat Geosci* 1(3):173–176. <https://doi.org/10.1038/ngeo129>
- Tau TM, Goodall A, Palmer D, Tau R (1990) Te Whakatau Kaupapa—the Ngāi Tahu resource management strategy for the Canterbury Region. Aoraki Press, Ōtautahi Christchurch
- Thrush SF, Townsend M, Hewitt JE, Davies K, Lohrer AM, Lundquist C, Dymond J et al (2013) The many uses and values of estuarine ecosystems ecosystem services in New Zealand—conditions and trends. Manaaki Whenua Press, Lincoln
- Turner BA (1978) Man-made disasters. London, England, New York, vol 53. Wykeham Publications, London
- UNEP (2010) Ecosystem-based Adaptation Programme Paris, France: United Nations Environment Programme
- Woodley K (2012) Shorebirds of New Zealand: sharing the margins. Puffin, Auckland
- Zeldis J, Skilton J, South P, Schiel D (2011) Effects of the Canterbury earthquakes on Avon-Heathcote Estuary/ Ihutai ecology. Environment Canterbury Report No. U11/14. Environment Canterbury, Christchurch, p 27
- Zharikov Y, Milton DA (2009) Valuing coastal habitats: predicting high-tide roosts of non-breeding migratory shorebirds from landscape composition. *Emu Austral Ornithol* 109(2):107–120. <https://doi.org/10.1071/MU08017>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Shane Orchard^{1,2}  · **Kenneth F. D. Hughey**^{3,4} · **Richard Measures**⁵ · **David R. Schiel**²

¹ Waterways Centre for Freshwater Management, University of Canterbury and Lincoln University, Private Bag 4800, Christchurch 8140, New Zealand

² Marine Ecology Research Group, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

³ Department of Environmental Management, Lincoln University, P.O. Box 85084, Lincoln, Canterbury 7647, New Zealand

⁴ Department of Conservation, P.O. Box 10420, Wellington 6143, New Zealand

⁵ National Institute of Water and Atmospheric Research (NIWA), P.O. Box 8602, Christchurch 8440, New Zealand