Estuaries and lowland brackish habitats

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Wenderholm Regional Park (Photo: Alastair Jamieson/WildEarthMedia.com)

Introduction

New Zealand's estuaries formed between 12,000 and 7,000 years ago in the early Holocene, as rising sea level flooded lowland river valleys at the end of the last ice age. Epochs of change punctuated by periods of relative stability in mean sea level (MSL) have been the backdrop to the evolution of these dynamic coastal environments ever since that time. More recently, over the last 170 years, our estuaries have been unmistakably transformed by human activities. Increases in catchment sediment loads due to deforestation, subsequent development of pastoral agriculture, urbanisation and land-use intensification in recent decades have been the major drivers of environmental change. Receiving estuaries have infilled with eroded sediment and have been adversely impacted by nutrients and stormwater pollutants. Sediment accumulation rates (SAR) are now typically ten-fold higher than the prior several thousand years (which were 0.1 to 1 mm yr^{-1}). This rapid increase in SAR during the historical era has seen most estuaries transform from sand- to mud-dominated systems, accompanied with loss or degradation of ecosystems sensitive to increased water turbidity, reduced light levels and sedimentation (e.g. seagrass meadows, filter-feeding shellfish) (e.g. Thrush et al., 2004).

This pattern of environmental change in New Zealand estuaries mirrors that described by Roy et al. (2001) for southeastern Australian estuaries, and echoes the changes seen around the globe over a longer time frame. Estuaries will continue to be under increasing pressure in the foreseeable future as human activities in catchments intensify (PCE, 2020).

Historical reclamation and drainage of tidal flats has measurably altered tidal volumes, hydrodynamics, sediment dynamics and habitats, while extensive shoreline protection (e.g. seawalls, rock revetments) and infrastructure (e.g. roads, stopbanks) prevent any future landward adjustments in fringing habitats, as estuaries progressively infill and sea level rises (Kettles and Bell, 2016). The action of tides, waves, historical changes in the supply of sediment from rivers, vertical land movement (VLM), episodic 'disruptors' (i.e. storms, tsunami, earthquakes) and emergence of distinctive ecosystems have also shaped the estuaries and brackish habitats that we see today (see Figure 1). Future projected climate change impacts on estuaries include changes in freshwater flows and sediment and nutrient loads, changes to extreme storm-tide and rainfall event frequency and intensity, and a rise in the underlying groundwater level – all taking place on the back of ongoing sea level rise (SLR). These multiple pressures, from both the catchment and the sea, will magnify the issues and pressures already facing New Zealand's estuaries and lowland brackish habitats over the coming decades (Kettles and Bell, 2016).

Figure 1: Tairua estuary, Coromandel Peninsula. This former river valley, flooded by rising sea levels 12,000-7,000 years ago, has infilled with marine and catchment sediment (Source: Alastair Jamieson/WildEarthMedia.com).

In this chapter we review the potential impacts of SLR on the biophysical environments of New Zealand's estuaries and lowland brackish habitats. We also describe an adaptive pathways approach to planning for the challenges posed by SLR over the coming decades.

Classification

Estuaries form part of the spectrum of coastal hydrosystems. These hydrosystems comprise a diverse set of environments at the interface of terrestrial and marine systems where water is a dominant feature. Coastal hydrosystems span a spectrum from near-coast freshwater lakes and wetlands though to complex coastal-ocean systems such as inlets, fjords and coastal embayments (Hume et al., 2016; and 'Coastal hydrosystem responses to sea level rise', p45). In this spectrum, estuaries are represented on the basis of their basin morphometry and fluvial and marine dominance by tidal river mouths, tidal lagoons, shallow and deep drowned valleys, and fjords (Hume et al., 2016). Fjords and tidal river mouths are not considered in this chapter. Estuarine systems, being the transitional places where freshwater and saltwater mix, have their own distinct values, pressures and management needs. Just as changes in catchments and their waterways impact estuarine systems, changes in the marine environment also can impact lowland freshwater systems upstream, primarily through a rise in the base MSL (Kettles and Bell, 2016).

Context

New Zealand's estuaries are geologically recent coastal features that formed as rising sea level flooded lowland river valleys at the end of the last ice age. Sea levels were some 120 m lower than today at the peak of the last (Otira) ice age, 16,000-18,000 years ago. At that time, most of New Zealand's inner continental shelf was dry land occupied by lowland forests. Sea level fluctuated during the Holocene, with a temporary high-stand sea level 1–2 m higher than today occurring 6,000-7,000 years ago followed by a long period of relative stability until recently (Clement et al., 2016; King et al., 2020).

Estuaries progressively infill with river and marine sediment since their formation. Stages of development range along a continuum from youthful systems that have retained a substantial proportion of their original tidal volume, to mature estuaries that have largely infilled with sediment and have little accommodation volume for sediment. In these mature estuaries, new sediment accommodation volume is created by SLR and 'excess' sediment is exported to the adjoining coastal marine environment. In semi-mature estuaries, expansion of accreting intertidal flats progressively displaces subtidal basins. This biogeomorphic evolution of estuaries from youth to old age is summarised in Figure 2.

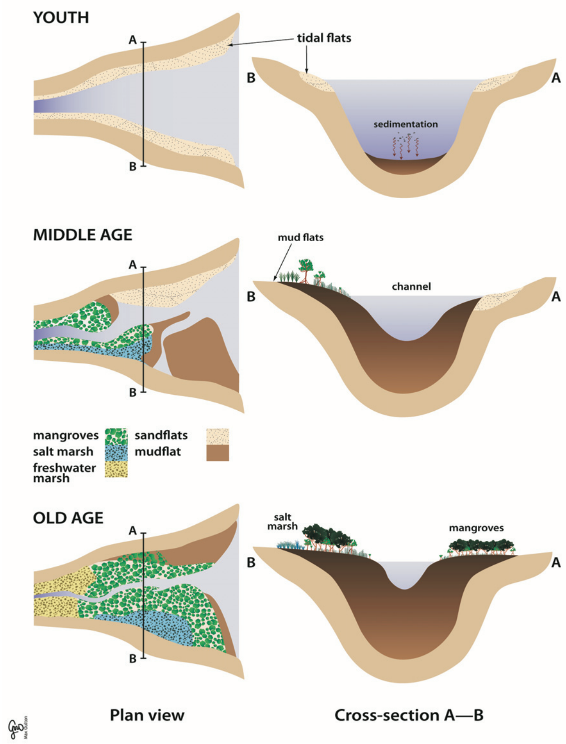

Figure 2: Biogeomorphic evolution of estuaries. Estuaries follow a cycle of development, the rate of which is determined by the size (volume) of the ancestral basin/flooded river valley and the sediment supply trapping efficiency of the system. Sediment trapping efficiency typically reduces as estuaries infill due to reduction in accommodation volume and increased efficiency of sediment remobilisation and transport by fetch-limited waves, tidal currents and export to the coastal marine environment. Reproduced with permission (Swales et al., 2020).

Intertidal habitats are most vulnerable to inundation from rising seas as they attempt to maintain their bed elevation in adapting to the relative SLR (RSLR)* of the area, by trapping additional sediment, primarily delivered by rivers (Leuven et al., 2019). In turn, the rate at which estuaries infill reflects the original volume of the ancestral river valley, sediment supply and changes in sea level. Evidence from global sedimentary records indicate that low rates of sea level change (i.e. tenths of mm yr^{-1}) persisted until as recently as the start of the 20th century (King et al., 2020). Both sedimentary and tide-gauge records in New Zealand show that average rates of RSLR have increased to the order of a few mm yr^{-1} in the modern era (King et al., 2020; MfE/StatsNZ, 2019).

The relationship between the rate of sediment supply and an estuary's sediment accommodation volume has been demonstrated for large drowned-valley systems in New South Wales (Australia) that have high-tide surface areas of tens of km^2 (Fig. 7, Roy et al., 2001). This relationship between sediment supply and estuary maturity is also demonstrated for Auckland estuaries of various geomorphic/hydrosystem types using the ratio of intertidal to high-tide area as a metric of estuary infilling. The relationship is described as the relative area of intertidal flat above MSL compared to the predicted annual catchment sediment load normalised by tidal prism volume based on average spring-tide range (see Figure 3) (Hume et al., 2007; Swales et al., 2020).

The analysis shows that intertidal area above MSL in these estuaries can be predicted from catchment annual sediment loads (r^2 = 0.69, P = < 0.001). Sediment yields from these largely rural lowland catchment-estuary systems vary from ~80 t km^2 yr^{-1} (funnel-type estuaries) to ~160 t km^2 yr^{-1} (barrier-enclosed estuaries) and are relatively modest compared to yields from New Zealand's upland/steepland catchments that deliver several thousand tonnes km^2 yr^{-1}

* RSLR includes vertical land-mass movement by tectonic and/or sedimentary basin compaction processes.

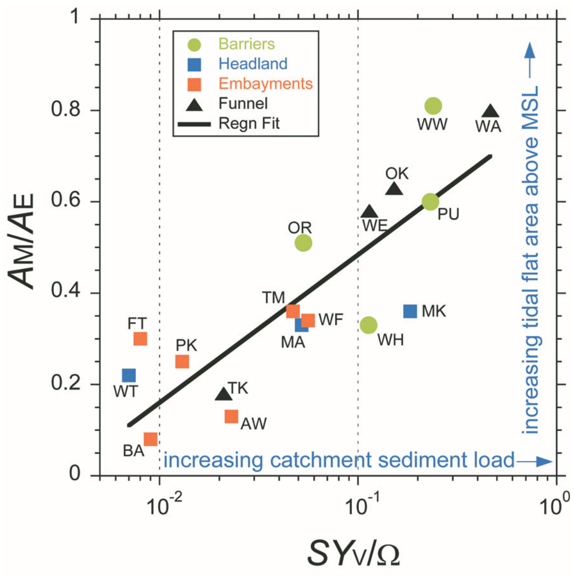

*Figure 3: Auckland east-coast estuaries – relationship between annual catchment sediment load to estuary tidal prism volume (SY_V/Ω) ratio and intertidal-flat above MSL to estuary area (A_M/A_E) ratio. **Model fit**: $A_M/A_E = 0.139*LN(SY_V/\Omega) + 0.808$ ($r^2 = 0.69$, $P = < 0.001$). **Geomorphic class** (after Hume and Herdendorf, 1988): (1) Barrier-enclosed estuaries with inlets formed by Holocene spits. Estuaries: Waiwera (WW), Puhoi (PU), Orewa (OR) and Whangateau (WH); (2) Headland-enclosed estuaries with inlets restricted by rocky headlands. Estuaries: Matakana (MK), Mahurangi (MA) and Waitemata (WT); (3) Coastal embayments typically with small catchments. Estuaries: Te Matuku (TM), Whitford (WF), Awaawaroa (AW), Putiki (PK), Firth of Thames (FT) and Bon Accord (BA); and (4) Funnel-shaped estuaries that have no inlet barrier, are simple or branched and form on low-energy coasts. Estuaries: Wairoa (WA), Weiti (WE) and Okura (OK). **Definitions**: (vertical axis) A_M/A_E – ratio of the tidal flat above MSL to the estuary mean high-tide surface area (km^2), (horizontal axis) SY_V/Ω– ratio of the estimated annual average catchment sediment load (m^3) to the spring-tidal prism volume (m^3). Annual load is converted from tonnes to m^3 using a typical wet-bulk sediment density of 1.2 t m^3. Reproduced with permission (Swales et al., 2020).*

to the coast (Hicks et al., 2011). Coastal embayment-type estuaries are less infilled due to their relatively modest catchment sediment supply. By contrast, barrier-enclosed estuaries formed in drowned river valleys are substantially more infilled than coastal embayments due to their larger sediment supply (see Figure 3).

Relative sea level trends

Ultimately, the local RSLR trend in an estuary is largely determined by the interaction of VLM with the regional increase in sea level. Depending on the direction of VLM (i.e. subsidence or uplift) the rate of RSLR will be increased or decreased. For example, in the Wellington/Hutt area, if the secular trend in subsidence of 2.5-3 mm/year (excluding co- and post-seismic influences from earthquakes) continues (Denys et al., 2020), it would bring forward the effective RSLR for lower- and upper-range projections by five decades and one to two decades respectively within a 100-year planning timeframe. Key drivers of VLM include ongoing glacial isostatic adjustment from the last ice age, tectonic processes at active plate margins (e.g. co-seismic, post-seismic, inter-seismic crustal slip) and, particularly relevant for estuaries, the subsidence due to compaction of deep unconsolidated sediment at river deltas and in coastal sedimentary basins (Swales et al., 2016). The rates of compaction can be further exacerbated by fluid extraction (e.g. groundwater and surface drainage).

In New Zealand, near instantaneous changes in RSLR in some estuaries due to co-seismic rupturing and liquefaction during strong earthquakes have been documented for the Porirua (1855, magnitude [MW] ~8.1, uplift of 0.6 m) and Avon-Heathcote (2010–2011, MW ~7.1, spatially-varying uplift and subsidence of ±0.5 m) systems (Grapes and Downes, 1997; Orchard et al., 2020). In the Avon-Heathcote Estuary, the upper intertidal area, between the Highest Astronomical Tide (HAT) and Mean High Water Spring (MHWS) marks, reduced in area by 21.4 ha (2011-2015) due to compression (Orchard et al., 2020). In the southern Firth of Thames, RSLR of ~10 mm yr^{-1} is largely driven by gradual compaction of a sedimentary basin, whereas the long-term sea level trend at the Port of Auckland (74 km to NW) is only 1.5 mm yr^{-1} over the same period (Swales et al., 2016). Overall, across New Zealand, based on the four long-term main port gauge records back to ~1900, the average RSLR has doubled to 2.44±0.10 mm yr^{-1} since 1960, compared with a similar timeframe before 1960 of 1.22±0.12 mm yr^{-1} (StatsNZ/MfE, 2019).

Coastal squeeze and the flood sandwich

Two colloquial terms – 'coastal squeeze' and 'flood sandwich'– are now in vogue to describe emergent changes in estuaries and coastal lowlands caused by climate change, RSLR and physical interventions to adapt to climate change and protect the built environment.

In the absence of physical barriers, estuarine habitats will naturally migrate landwards to occupy fringing brackish/freshwater habitats as sea level rises (see Figure 4a). Where artificial barriers prevent this natural response, estuarine habitats maybe lost where the supply of sediment is not sufficient for vertical accretion to keep pace with RSLR (Mangan et al., 2020) and if the barrier inhibits sediment accumulation. This so called **coastal squeeze** has varying definitions, but a narrower focus is the definition by Pontee (2013): *Coastal squeeze is one form of coastal habitat loss, where intertidal habitat is lost due to the high water mark being fixed by a defense or structure (i.e. the high water mark residing against a hard structure such as a seawall) and the low water mark migrating landwards in response to SLR* (see Figure 4b). Where the landward margin of these intertidal habitats, including wetlands and marshes, are constrained naturally by rising topographic features (see Figure 4c), which may be the case in many of our estuaries situated in New Zealand's seismically-active setting, a less emotive term for this similar, but natural, process, is '**coastal narrowing**' as a general description for natural shrinking of intertidal area (Pontee, 2013).

Consequently, running in parallel with the projected impacts of climate change and RSLR on estuarine systems will be the ongoing direct and indirect pressures of society's responses to climate change adaptation. If cascading climate change effects are not thoroughly explored and evaluated in a holistic manner, attempts to counteract the impacts on the built environment and existing land-use rights (e.g. shoreline protection works, reclamations to reinstate shoreline buffers,

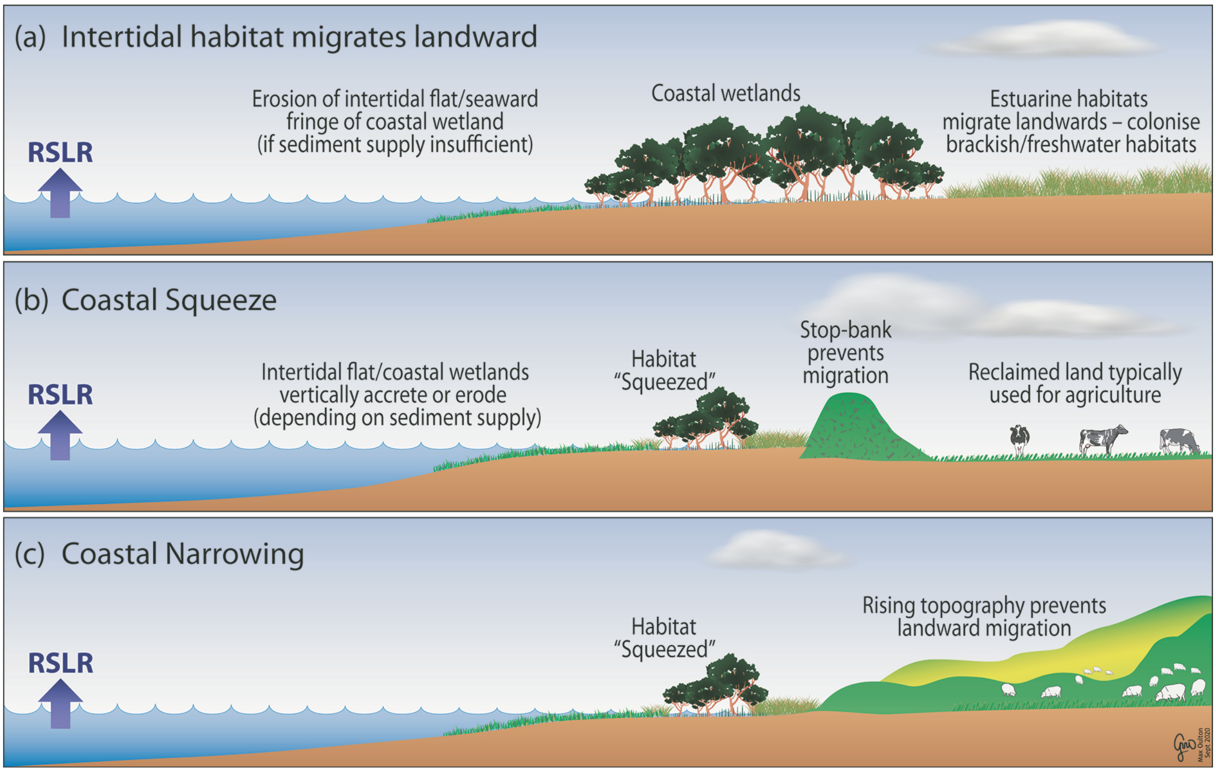

Figure 4: Potential estuarine habitat responses to relative sea level rise (RSLR): (a) habitats naturally migrate landward to displace brackish/freshwater habitats where there are no physical barriers; (b) coastal squeeze occurs where natural landward migration of estuarine habitats is prevented by hard protection structures and/or reclamation; and (c) migration is prevented by rising land topography (i.e. coastal narrowing). Adapted from Pontee (2013).

stopbanks and alteration to drainage schemes), will invariably lead to coastal squeeze (Kettles and Bell, 2016). This would result in reduced intertidal habitat and eventual submergence, if the rate of tidal-flat elevation gain (i.e. related to but not necessarily equivalent to SAR) does not keep pace with RSLR. However, emergent research is focusing on creating living edges to enable inland habitat migration through a range of financial, policy, planning, and on-the-ground management tools (Leo et al., 2019).

Estimating future change in estuaries and coastal lowland hydrosystems is challenging due to compounding complexities (Passeri et al., 2015). These complexities arise from the interplay between marine and freshwater systems and how these are likely to shift under climate change. One of the main compounding effects, is the so-called 'flood sandwich' that arises from the progressive increase in MSL and compound freshwater/coastal flooding processes. These processes include: changes in freshwater flows and sediment loads; sequencing of dry periods interspersed with more intense rainfall and river flood events; spatial changes in wave characteristics and sediment transport arising from estuary deepening or shallowing; rising groundwater; and increased occurrence of coastal storm-tide impacts up estuaries and lowland rivers (e.g. Ganguli and Merz, 2019; Passeri et al., 2019). The balance between sea level and catchment drivers of the flood sandwich will also change over time and spatially, as these lowland coastal systems strive to migrate landward, where they are not constrained by engineered barriers or natural topographic features.

Hydrodynamics and sediment transport

Sea level rise induces nonlinear changes in hydrodynamics of estuarine systems, which in turn influences sediment transport, ecological and nutrient processes (Passeri et al., 2015). Changes in water depth and bathymetry will alter tidal characteristics due to the net effect of RSLR and SAR. Accommodating the gradual changes from increased tidal volume through the mouth over each tide phase as the ocean level rises, and changes upstream in river slope (i.e. water surface), will also influence tides. A balance between bed friction and channel-width, convergence and expanding length determines whether the tidal range amplifies, remains constant or dampens in the landward direction (Leuven et al., 2019; Du et al., 2018). A future increase in MSL generally reduces bed friction so that tides are amplified. However, landward expansion of intertidal areas (if not constrained – see Figure 4a), provide storage volume and additional friction for the tidal wave propagating through an estuary. This process naturally reduces the tidal range and flood risk that would have otherwise been the case if shoreline protection was implemented. In contrast, infilling through sedimentation can reduce tidal range, but at the cost of a higher mean tide level (Palmer et al., 2019). Although estuarine systems are known to be dynamic and likely to exhibit non-linear behavior under rising sea level, many studies have employed a simplistic static ('bathtub') modelling approach. Recent work has considered the dynamic and compounding inundation effects associated with SLR, such as tidal and storm-surge hydrodynamics under SLR and the balance between hydrodynamics, estuary basin infilling and fluvial flow regimes (Leuven et al., 2019; Palmer et al., 2019; Moftakhari et al., 2018).

Future impacts of SLR

Looking to the future, SLR during the 21st century and beyond will fundamentally drive major environmental changes in New Zealand's estuaries, with secondary compounding effects arising from other climate change drivers (see Figure 5). Running in parallel with the impacts of climate change, are the ongoing direct and indirect anthropogenic pressures that already significantly affect many estuarine systems. These pressures include urbanisation along estuarine margins associated with population growth, catchment-related stressors (e.g. water abstraction, soil erosion), drainage schemes, and in-situ changes to habitats (e.g. dredging or reclamation, shoreline armouring, shellfish harvesting and introduced marine pests) (Kettles and Bell, 2016). Recent work by Mangan et al., (2020) in a hypsometric analysis (hypsometry: distribution of surface area versus depth) of 11 New Zealand estuaries suggests 27% to 94% loss of intertidal area with a 1.4 m increase in sea level that could occur by the end of this century or beyond. Estuaries with more gently sloping intertidal areas were projected to have the earliest and largest losses of intertidal area, in the absence of compensating sedimentation. The relationship between SLR and predicted intertidal habitat loss was also highly non-linear in some estuaries, however, with sharp declines in intertidal habitat occurring only after RSLR reached a certain threshold (e.g. after 0.6 m RSLR for Mahurangi Estuary), in relation to the shape of the intertidal seabed profile.

Retaining intertidal habitats, including coastal wetlands, and the ecosystem services they provide in the future will also depend on vertical sediment accretion keeping up with RSLR. Cahoon and Guntenspergen (2010) have defined the term 'elevation capital' for coastal wetlands, but this concept is broadly applicable to intertidal habitats. The elevation capital of an intertidal habitat is the vertical difference between the upper and lower elevation limits of its range relative to sea level. Elevation capital will therefore also increase or decrease with the local tidal range. A salt marsh, for example, located in the upper-intertidal zone with a lower growth limit at MSL will have more elevation capital than a salt marsh growing close to MSL. Consequently, the upper salt marsh has greater capacity to maintain itself for decades even without sedimentation.

Numerical models are used to explore interactions and biophysical feedbacks that drive the maintenance of elevation capital as well as simulate the long-term biogeomorphic evolution of estuaries over decadal to centennial time scales. One such modelling approach, the zero-dimensional (0-D) or point model, has a relatively simple numerical scheme that can encapsulate the biophysical feedbacks controlling the long-term biogeomorphic development of estuaries (e.g. Marani et al., 2010). Such a model has been used to investigate how SLR is likely to affect intertidal habitats in Auckland estuaries of varying sizes over the next century (see box below).

The results for a 20th Century hindcast indicate that an average sediment supply rate (i.e. SSC) of about 40 mg l^{-1} was sufficient to develop intertidal flats matching present day average elevations (~0.3 m above MSL) across all three estuary scales by the early-2000s (see Figure 6). These conditions correspond with a sediment supply rate averaging ~120 t km^2 yr^{-1} for these largely rural lowland catchments (Swales et al., 2020).

Simulations for the 21st Century IPCC scenarios of low- and high-SLR rates (i.e. 4.8 and 9.2 mm yr^{-1}) suggest that intertidal flat habitats in tidal creeks (0.1 km fetch) and small estuaries (1 km fetch) will be able to keep pace with SLR even at relatively low sediment-supply rates (see Figure 6). By contrast, intertidal flats in the largest estuaries (10 km fetch) will be more susceptible to erosion and inundation even at the lower rate of SLR anticipated under the IPCC RCP2.6 scenario.

Zero-D model

The 0-D m model was calibrated using measurements from the study estuaries to estimate an initial platform height (IPH) (i.e. circa 1900) and tune model parameters to achieve realistic IPH values by the early-2000s. Data included present-day average intertidal flat elevation and sediment accumulation rates from dated cores. An IPH (1900 AD) of -0.3 m MSL (1900 AD) was based on average elevation of +0.3 m MSL (2008 AD) and average SAR of 5 mm yr^{-1} in the study estuaries. Estuary-average intertidal platform elevations ranged from -0.14 to 0.59 m MSL.

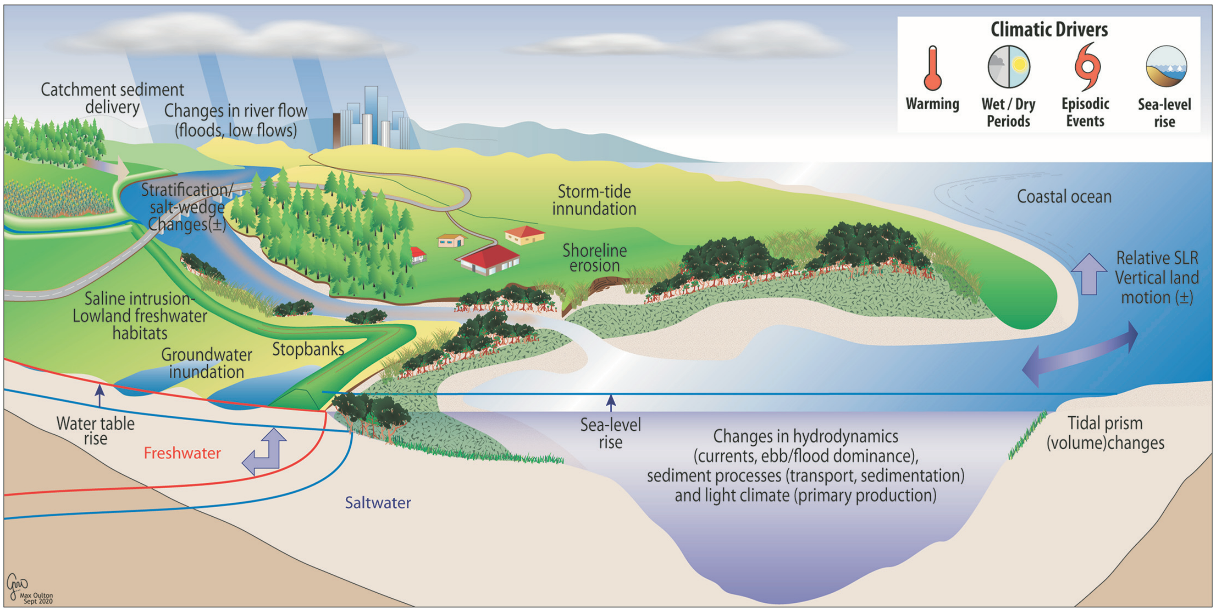

Figure 5: Potential effects of climate change and sea level rise in estuaries.

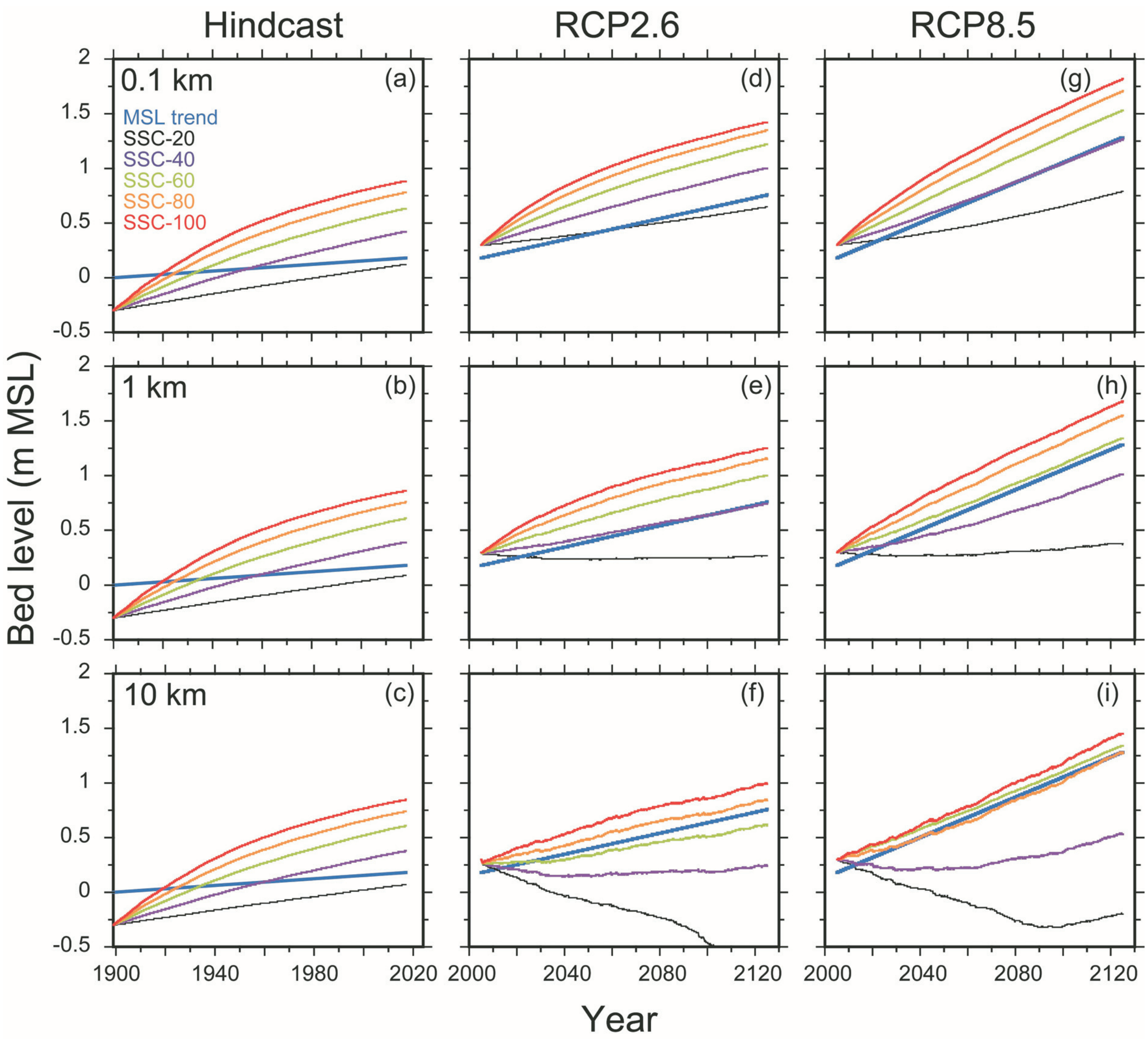

Figure 6: Zero-dimensional (0-D) model simulations of intertidal flat evolution for Auckland's east-coast estuaries for a range of time-average suspended sediment concentrations (SSC, mg l^{-1}) and fetch (0.1-10 km, successive rows) for the historical period 1900-2018 (a-c) and future climate-change scenarios (2005-2125, d-i). Bed-level is relative to Auckland Vertical Datum-1946. Future scenarios are based on IPCC (2013) climate and SLR for the Representative Concentration Pathways RCP2.6 (d-f, SLR = 4.8 mm yr^{-1}) and RCP8.5 (g-I, SLR = 9.2 mm yr^{-1}). The MSL trend for the historical period is for the Port of Auckland (1.6 mm yr^{-1}, 1899-2015, Swales et al., 2016). Note: minimum bed level for scenario RCP2.6 with 10 km fetch is -0.57 m MSL. Reproduced with permission (Swales et al., 2020).

Loss of intertidal flats could begin as early as the 2020s if rates of RSLR exceed ~5 mm yr^{-1} and where sediment supply is limited. Catchment sediment supply to these largest estuaries would need to be two-fold higher than historical rates (~40 mg l^{-1}) that sustained the vertical accretion of intertidal flats during the 20th century (see Figure 6f). Sediment-poor estuarine systems, such as coastal embayments with small land catchments (see Figure 3), are likely to be most susceptible to loss of intertidal flat habitats.

These results are generally consistent with previous modelling studies, with intertidal flats replaced by subtidal habitats at higher rates of SLR. Sediment supply rates are critical to maintenance of intertidal flats and coastal wetlands, with a transition from stable to unstable systems likely to occur at higher rates of SLR (5-10 mm yr^{-1} for systems with limited sediment inputs (e.g. Kirwan and Murray, 2007; Kakeh et al., 2016)). Large estuaries are more susceptible to loss of intertidal flats due to insufficient sediment supply (Leuven et al., 2019).

Legacy sediment

Legacy sediments* have played a formative role in the biogeomorphic evolution of New Zealand's estuaries over the last ~150 years. The development of intertidal habitats, including rapid expansion of mangrove forests in our northern estuaries, has followed historical pulses of legacy sediment delivery associated with catchment deforestation, agriculture, and land use intensification (Morrisey et al., 2010). Catchment sediment delivery to many New Zealand estuaries following the historical peak approximately a century ago have been sufficient to maintain intertidal habitats (e.g. Figure 6). It is also likely that flood-defence stop banks in the lower reaches of rivers has enhanced sediment delivery to estuaries by reducing the frequency of over-bank flood flows and associated sediment deposition on floodplains.

* Accelerated deposition of sediments in estuaries from human activities over the historic period (usually post-European development).

The potential role of legacy sediment stored in estuaries, as well as contemporary river inputs, in maintaining intertidal habitats as SLR accelerates is not well understood. Legacy sediment in the Firth of Thames has sustained rapid accretion of intertidal flats and triggered mangrove colonisation in the early 1960s (Swales et al., 2015) despite a rapid rate of RSLR (~10 mm yr^{-1}, Swales et al., 2016). This RSLR is similar to what is anticipated to occur in many New Zealand estuaries by the late 21st century under business-as-usual global emissions scenarios. Coastal wetlands are major sinks for legacy fine sediment and associated stormwater contaminants, however where sediment supply is insufficient to maintain these habitats, there is a risk that this legacy sediment and contaminants will be released, resulting in adverse outcomes for estuarine ecosystems. Paradoxically, improvements in catchment soil conservation associated with limits setting for estuaries could lead to unanticipated negative outcomes – this emphasises the need for holistic/integrated management of catchment-estuary systems.

Estuarine ecosystems

Estuaries are among Earth's most dynamic and productive environments and they play critical roles in ecosystem service provision and represent global hotspots for organic matter processing, nutrient cycling, and primary production. Marshes, mangroves, and seagrass meadows are the most visibly obvious sources of productivity in estuaries. These estuarine plant communities provide essential habitat for birds and fisheries species and can alter current and wave energy, stabilise sediment with root mats and affect drainage patterns, thereby influencing estuary morphology.

In most New Zealand estuaries, emergent salt marsh and mangroves (in the upper North island) are restricted to the upper intertidal zone, with the area of vegetated habitat generally being many times less than that of unvegetated tidal flats. Microphytobenthos, composed of microscopic photosynthetic algae (e.g. diatoms) and bacteria (e.g. cyanophytes), occur in surficial sediment from the upper intertidal to the subtidal zone.

Although emergent vegetation can be highly productive (i.e. per m^2) microphytobenthos likely dominates benthic primary productivity in most of our estuaries due to its vastly greater spatial coverage. This productivity supports a wealth of secondary and tertiary consumers (e.g. molluscs, crustaceans and polychaetes) that feed on fresh sedimentary organic material, and demersal fish and wading birds that feed on the invertebrates. This productivity and the biodiversity it supports contributes to the many ecosystem services recognised and valued by New Zealanders (Thrush et al., 2013; Rullens et al., 2019; PCE 2020).

Although microphytobenthos can thrive at a range of depths, they are likely to be more productive in shallow estuaries. This is because there is more sunlight available for photosynthesis in shallow water, due to the reduction in light with increasing depth in the water column. The rate of light attenuation is largely influenced by suspended sediment concentrations. As a result, the quantity and quality of light reaching the seabed may be insufficient to support benthic primary production, thereby excluding sea grasses and microphytobenthos from subtidal habitats.

Intertidal habitats uncover and receive direct unattenuated sunlight at low tide (even if turbidity limits productivity while submerged). The importance of low tide primary production in turbid estuaries (Drylie et al., 2018) and the potential for SLR-related losses of intertidal habitat to impact ecosystem function (Mangan et al., 2020) is now recognised. Thus, gradual increases in sea level and resulting increase in mean water depth and/or reduction in intertidal habitat have the potential to exacerbate reductions in estuarine productivity. This is one of the lesser recognised threats of SLR, including to ecosystem services.

The role of microphytobenthic productivity is not limited to underpinning estuarine foodwebs (Hope et al., 2019; Thrush et al., 2012). For example, microphytobenthos oxygenate surface sediment, which accelerates the organic matter degradation and affects subsequent transformations of the remineralised products (e.g. conversion of ammonium to nitrate). Pratt et al. (2014) showed how reductions in benthic primary production resulted in less efficient trapping of ammonium (NH_4^+) and thus greater effluxes of ammonium from the sediment to the overlying water. This suggests that the problem of nutrient overloading into estuaries may be exacerbated if coupled with inputs of suspended sediment. Reduced microphytobenthic primary productivity with SLR could have similar indirect effects and alter the outcomes of multiple stressor interactions.

Overall, SLR has the potential to affect multiple estuarine ecosystem components directly and indirectly, which makes predicting the future ecological status of New Zealand estuaries difficult (O'Meara et al., 2017). Research at large spatial scales and that incorporates the potential for multiple interacting stressors, including SLR, is urgently needed.

Management strategies

There is certainty that by the 2050s, SLR in New Zealand will lie in a narrow range of 0.2-0.3 m. Towards the end of this century and beyond, SLR projections are subject to widening or deep uncertainty (MfE, 2017). This uncertainty arises mostly from the uncertain rate at which global emissions can be reduced and the spectre of runaway polar ice-sheet instabilities once a tipping point is reached (see 'Future sea level rise around NZ's dynamic coastline', p11). Further, MSL will continue rising for centuries, albeit at a rate tied intricately to global mitigation efforts to reduce emissions. This presents a challenge now to planners and decision-makers, as the New Zealand Coastal Policy Statement (NZCPS, 2010), requires a planning timeframe for considering climate change effects out to 'at least 100 years' (i.e. to at least 2120 and beyond) for our coastal environments that includes estuaries, marshes, brackish wetlands, and their margins.

Estuaries also exhibit uncertainties from compounding impacts of VLM (i.e. RSLR), groundwater rise, increasing rainfall intensities and changes in river flow regimes (baseflow and flood intensity/frequency). Consequently, planning and management of existing and new land use (including settlements, cultural sites and the built environment) around estuaries must explicitly tackle deep uncertainty. This must be purposely framed for an ongoing changing risk environment, rather than persist with conventional 'predict-and-act' or 'hold-the-line' management paradigms. Adaptive decision-making approaches specifically address the deep uncertainty, through methods such as Dynamic Adaptive Pathways Planning (DAPP) and Robust Decision Making (Marchau et al., 2019). Second guessing the future (e.g. selecting a best- or most-likely estimate, or 'worst case' through a single- or once-only investment perspective) invariably results in inflexible options or actions that are difficult to unravel if there are surprises either way (e.g. if RSLR is faster or slower than the selected case). Rather, adaptive approaches such as DAPP, which is a framework on which New Zealand's national coastal guidance is based (MfE, 2017), encourage stakeholders, communities and iwi/hapū to map out a range of alternative pathways for adapting to climate change and RSLR. These alternative pathways, which keep options open until the next local adaptation threshold is nearing, comprise a mix of short-term actions and/or longer-term options that meet specific objectives or levels of service for flooding, road access or other utility services.

However, a timely response (i.e. not too early/late) to the compound effects on estuaries and adjoining lowland environments of climate drivers and anthropogenic pressures, will require more detailed monitoring on the changing state of these hydrosystems (PCE, 2020). Furthermore, improved monitor and review cycles need to be integrated into an adaptive planning framework like DAPP. This can be achieved with the development of indicators that provide both an early signal of declining performance and triggers, which act as decision points to implement the next option in the suite of pathways set out in the DAPP, allowing for sufficient lead time to implement the next option (Lawrence et al., 2020b). Further research is needed to develop approaches and mechanisms to evaluate the benefits (including blue carbon, that is, carbon dioxide sequestered in coastal and marine habitats by marine plants, such as salt marsh, mangroves, seagrass), ecosystem services and the cost of delaying decisions or interventions. This must be considered in the context of a continually changing environment for implementing adaptation options and pathways that address the four well-beings (i.e. environment, social, cultural, economic). Ongoing decision making on estuaries and their land margins, where compound flooding from both ends and coastal squeeze or narrowing of intertidal habitats, presents an increasingly contested space around safeguarding natural resources and/or adaptation of the built environment and communities. Leo et al. (2019) identified mechanisms and enabling conditions to accommodate migration of intertidal/wetland habitats through a range of financial, policy, planning and on-the-ground management tools. These tools can be implemented or modified to enable inland habitat migration to reduce coastal squeeze.

Given that RSLR will continue for centuries and estuarine areas are by definition low-lying, it will be inevitable that communities and infrastructure in many parts of Aotearoa-New Zealand will need to consider and sequentially plan for managed retreat (Lawrence et al., 2020a). Part of that long-term adaptive planning will also need to consider re-purposing the land-use around the margins of estuaries after retreat of the built environment. This includes implementation of managed realignment of the shoreline if coastal defences or stopbanks are present, taking in the lessons and the need for scale from projects undertaken in the UK (Esteves, 2013; Kiesel et al., 2020).

Conclusions

New Zealand's sediment-infilled estuaries are now increasingly facing the compounding impacts of SLR, storm surge, catchment flooding, groundwater rise, drainage issues, and coastal squeeze/narrowing. Intertidal flats and coastal wetlands will evolve with local conditions (e.g. RSLR, sediment supply) as estuary morphology strives to achieve a new equilibrium. However, this will be in the context of ongoing changing climate drivers and a MSL that continues rising for several centuries at an uncertain rate that is substantially higher than during the recent geological timescale when these estuaries were formed (Holocene). As the PCE (2020) rightly identifies, climate change impacts, including the unavoidable prospect of accelerating SLR, will magnify the issues and pressures already facing New Zealand's estuaries. Adaptive decision-making approaches, which specifically address deep uncertainty in future RSLR (e.g. DAPP), are now embedded in the national coastal guidance (MfE, 2017) and provide opportunities to make robust and informed management decisions. Given that RSLR will continue for centuries and estuarine areas are invariably low-lying, it will be inevitable that communities and infrastructure in many parts of Aotearoa-New Zealand will need to consider and sequentially plan for managed retreat, and re-purpose to alternative land uses. New Zealand has much of the know-how and adaptive frameworks needed to transform the way we manage estuaries. But the pressing needs are the improved coupling of research capacity with local government, matauranga Māori and communities to achieve sustainable and durable inter-generational outcomes.

Acknowledgements

We thank Max Oulton for drafting Figures 2, 4 and 5, and Dr Terry Hume for providing guidance on the coastal hydrosystem classification. The aerial photograph of Tairua Estuary (Figure 1) is reproduced with the permission of Alastair Jamieson (Wild Earth Media). Figures 2, 3 and 6 are reproduced from Swales et al. (2020) 'Biogeomorphic evolution and expansion of mangrove forests in New Zealand's sediment-rich estuarine systems' In Sidik, F, and Friess, D (eds.) *Dynamic sedimentary environments of mangrove coasts* (ISBN: 9780128164372), Copyright Elsevier (2020). Finally, we thank Dr Michael Allis (NIWA) for reviewing this chapter.

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