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# Past and Future Ecosystem Change in the Coastal Zone

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**Abstract.** The coastal zone is in a constant state of flux. Long term records of change attest to high amplitude sea level changes. Relative stability though the Late Holocene has allowed for the evolution of barrier dune systems, estuaries and coastal lakes with associated plant and faunal associations. This evolution has been interspersed with changes in the balance between climate driven changes in outflow from catchments. These interactions have been considerably disturbed through the impacts of industrialised people who have diverted and consumed water and invested in infrastructure that has impacted on river flows and the tidal prism in estuaries. This has impacted their provisioning services to humans. It has also impacted their regulating services in that development along the coastline has impacted on the resilience of the littoral zone to absorb natural climate extremes. Looking from the past we can see the pathway to the future and more easily recognise the steps needed to avoid further coastal degradation. This will increasingly need to accommodate the impacts of future climate trends, increased climate extremes and rising seas. Coastal societies would do well to identify their long term pathway to adaptation to the challenges that lie ahead and plan to invest accordingly.

**Keywords.** estuaries, paleolimnology, climate change, hydroecology, sediments, nutrients, salinization

## 1. Introduction

The coastal zone is in a constant state of change. This is most evident through the daily cycles of the tides that, particularly in the macrotidal zones of the world, inundate and then strand the marine littoral zones. This alone demands that the biological communities affected by the rise and fall of tides be adaptable to inundation and exposure, and in estuaries, exposed variously by marine waters and those flowing from the hinterland which are usually fresh to oligosaline. This balance varies seasonally with, in temperate zones, wet seasons coinciding with destructive waves regimes leading to the opening of estuary mouths, while the dry season and associated constructive wave regimes lead to mouth closure and the establishment of lagoonal conditions. The consequences are a winter of tidal and river flushing with oxygenated water and a summer with little flow, stratification, hypersalinity and de-oxygenation. These seasonal patterns are taken to extreme under multi-year (e.g. El Nino Southern Oscillation) and even multi-decadal (Inter-decadal Pacific Oscillation) phases of wet and dry conditions exacerbating or subduing the contrasts between seasons. Further the frequency of these cycles extends out to multi-



millennial scales with the highest amplitude variations coming from the substantial eustatic rises and falls in sea level documented on the Huon Peninsula [1]. These occur on account of the orbital cycles (Milankovitch) of the Earth which, in south-east South Australia [2], have left a series of fossil coastal dunes, each one hundred thousand years older than their more coastal neighbour.

Within the present high sea level stand it is tempting to consider that most variations in estuarine condition relate to natural climate and tidal cycles. However, there is also ongoing linear change. Once river valleys were inundated as seas reached maximum level after the last post-glacial transition the river gradients declined and waters in the new coastal zones estuaries became relatively quiescent. This allowed for the transported sediment to settle and so set in place a long extended phase of estuarine evolution that persists into the present[3]. Depending on the balance between the onshore wave environment and river flow an estuary gradually fills with sediment progressing from a wide, open estuary, to a narrow estuary in a wide delta, to an intermittently closed and open lagoon and, ultimately, to a largely closed system with coastal lakes.

A further directional change exists in the form of humanity. Human populations have grown over millennia accelerating after the industrial revolution and more so since the 1950s during the 'Great Acceleration' leading to the identification of a new geological epoch, the Anthropocene [4]. At the coast protective mangrove forests have been removed, coastlines reclaimed, harbours dredged and hard infrastructure commissioned to defend the coast against the tides and waves. Catchments have been cleared leading to increases in the volume of salts and sediments they leak, and nutrients have been mobilised and washed or leached into waterways after deliberate or inadvertent application. River flows have been held behind weirs, diverted for human consumption or regulated with hard infrastructure to allow for navigation and limit flooding. At the coast this results in the reduction of flushing flows, yet increasing loads of nutrients, metals, and sediments. Salinity levels increase owing to increased flux from inland but also due to the reduction in diluting flows[5].

Recent changes, and cyclical variations with short return times, are more familiar to people than those masked by the passing of time. However, because changes are more familiar is no reason why they are greater or have a more substantial impact on coastal ecosystems. The tendency to neglect infrequent cyclical change, or events deeper in the past, leaves society less well informed about the drivers of change and so less well armed to diagnose and treat coastal management issues. Historical evidence of environmental change is reliant on documentary or photographic evidence which tends to be patchy, or on memory which has proven to be unreliable[6]. Deep-in-time and continuous records of change are available, however, in the sediments of inundated coastal systems. Estuaries and lagoons provide a service to historical studies by archiving fossil remains of the biological, chemical and physical nature of waterways as they infill with sediment. The paleolimnological approaches that retrieve this evidence are now widely used globally and provide clear evidence of the influence of climate and people on ecosystems, including in the coastal zone.

## **2. Paleolimnological approaches**

Sedimentary sequences accumulate offshore over long time periods. Onshore they accumulate when depressions are inundated as the still water allows sediment to settle and the anoxia in the littoral zones allow dead remains to be preserved with each deposited layer. As sea levels stabilised ~ 7000 years BP most near-shore records of change extend back to this time. Sophisticated sediment coring techniques are able to extract continuous sediment sequences[7] spanning this period and radiometric dating techniques are able to align a timeline to the extracted core. Being at the end of river catchments the sedimentation rates are often relatively large allowing for high resolution reconstruction of estuary condition through time. The physical nature of the sediment (e.g. particle size) can inform on variations in fluvial energy and so the impact of infilling[8]. Chemical analyses can inform on the source of the sediment (magnetic susceptibility, X-Ray Fluorescence) and the foundations of the food web and trophic status (stable isotopes of nitrogen and carbon) [9]. A wide range of biological remains can be extracted, including gastropods[10], ostracods [11], algal pigments [12], pollen [13], diatom algae [14] and plant

fragments [15]. These may provide evidence of changing habitat and substrate availability, the balance between tidal and inland water, salinity and nutrient status, the existence of anoxia and the nature of the light environment of the water body (see [16]). Integrated, multi-proxy investigations of sediment layers provide a means of reconstructing many elements of ever-changing nearshore ecosystems, albeit with the evidence of short time (daily to monthly) variations blended into single samples. Similar proxies may reflect onshore changes to catchments and this evidence, combined with archaeological or ethnohistoric records, can allow for responses to be attributed to particular human or climatic causes [17].

### **3. South-east South Australia.**

The region between Brisbane and Adelaide is the most heavily settled in Australia. There is evidence for indigenous settlement since the Pleistocene and archaeological remains attesting to their activities, living sedentary, rather than nomadic lifestyles and manipulating coastal waterways, at least where resources were plentiful [18]. European settlement commenced in the 18<sup>th</sup> century and the goldrush of the 1850s brought large numbers of immigrants that saw a rapid expansion in population, much at the expense of the indigenous populations that suffered from disease and conflict. Coastal-flowing catchments were impacted by clearing and grazing and the populations of coastal margins increased dramatically from the mid-20<sup>th</sup> century and societal wealth increased. Most Australians now live in close proximity to the south-east coastline driving much landscape disturbance and ecosystem change in the near shore zones.

### **4. Evidence for Ecosystem Change**

The first calls for action to mitigate this impact of European activities on coastal ecosystems emerged in the 1960s and 1970s and the first EPA departments was established in 1971 in Victoria [19] but as late as 1991 in NSW. National State of the Environment reporting commenced in 1996[20]. A cap was placed on the extraction of water from the nation's largest basin in 1995 and the Murray River estuary was deemed to be in ecological crisis in 2011[21]. This, however, does not reflect the timing of the impact of the expansion of settlement and associated industries such as mining and agriculture. In fact, long term records of change attest to considerable coastal change from the 1840s [22] and substantial changes in floodplain sedimentation rates and salinity from the 1880s [23].

#### *4.1. Hydrological Change.*

Rivers were impounded to retain water supplies for expanding urban populations from the 1860s such as Thorndon Park reservoir in Adelaide. Closer to the coast barrages were established at Geelong in 1840 and at the Murray mouth in 1940 to preserve freshwater resources from the impact of tidal inflows. At Geelong this immediately shifted an estuary to a freshwater lagoon [22] which was gradually colonised by *Phragmites* reedbeds. It also limited the outflow of freshwater from the Barwon River leading to increasing salinity levels in the estuary below the weir [22]. At the Murray mouth regulation constrained the tidal prism leading to the permanent freshening of Lake Alexandrina [24] but led to rapid sedimentation at the mouth driving the formation of new islands and closing the outlet [25]. This turned the coastal lagoon into a closed system leading to hypersalinity[26], hypoxia and the collapse of critical *Ruppia* seagrass habitats [27],[ 28]. In the Gippsland lakes a temporary mouth was dredged for navigation leading to a permanent shift in the halo-ecology of the estuary[12]. While this led to the death of fringing vegetation[29] increased flushing limiting the high cyanobacterial character [12]. The largest engineering feat in Australia, the Snowy River Scheme, diverted ~ 98% of the Snowy River's mean annual flow inland to drive the expansion of the irrigation industry and to generate power. Starved of freshwater supplies, Lake Curlip in the coastal floodplain shifted from a dystrophic lake to a system 50 times more saline than the pre-European baseline[30]. At Tuckean Swamp weirs reduced the tidal

prism leading to a freshening of surface waters but deliberate drainage exposed sediments leading to unprecedented acidification [31].

#### 4.2. *Pollutants*

While the waters at the end of catchments are typically more enriched and saline than their upland counterparts there is clear evidence for the eutrophication of coastal systems through the 20<sup>th</sup> century (e.g. The Coorong; [26]) and, in the Gippsland Lakes, a return to the cyanobacterial conditions the prevailed before artificial opening, albeit with a novel bloom risk species emerging [12]. Coastal lakes receiving industry waste have seen nutrients rise and the onset of eutrophic conditions [32]. Mining, and industrial development in the coastal zone, are evident in high levels on heavy metals in upper sediments in the lower Barwon River estuary [33] and in Botany Bay in Sydney [34]. The Gippsland Lakes receive drainage from several catchments including the La Trobe River valley which has been long the focus of coal mines and coal-fired power stations, and a native and plantation timber pulp mill, which has lead to fears of high loads of metals including mercury into the estuary sediments and food chain.

#### 4.3. *Sedimentation*

Catchment development in the Murray River basin has accelerated sediment accumulation rates in floodplain wetlands in the order of 5-30 times and up to 80-fold in the estuary [35]. In parts of the Coorong Lagoon in excess of 50 cm of sediment has accumulated in less than a century and aerial photographs attest to massive deposition of sediments around the river mouth. The barrages have maintained high water levels that have lead to the scouring of exposed littoral margins in Lake Alexandrina and accretion in sheltered zones[25]. The flux of sediments has increased in most situations impacting on the light environment and placing stress on submerged macrophyte communities.

#### 4.4. *Salinity*

Some lagoons have shown an increase in salinity on account of the reduction in the flushing of freshwater (Reeves et al. 2014) or the construction of openings to the sea ([29],[12]) while others, once saline or tidal, have become relatively fresh on account of barrages restricting inflow of tidal water [33] or the redirection of freshwater into once saline coastal lagoons [26]. In the south lagoon of the Coorong the increase in salinity was from a high base, with the most notable feature being the replacement of salt tolerant thalassic species with euryhaline inland taxa of both diatoms and ostracods ([33]; [24]).

#### 4.5. *Ecological Implications*

Many estuaries have been impacted by the development of agriculture and intensive industries since the arrival of European settlers. The impact of water quality change is greatest near to large populations e.g. Sydney, or at the end of larger, disturbed catchments e.g. the River Murray. Many of the ecological impacts remain unclear while others had become evident in recent decades and critical with the extended drought period that commenced in 1997. Extreme hypersalinity in the Coorong lead to a shift from a community dominated by *Ruppia megacarpa*, through a *Ruppia tuberosa* ([28]) community phase, to a phytoplankton-brine shrimp state that lead to a decline in ducks and swans and their replacement by Banded Stilt (*Cladorhynchus leucocephalus*) ([24]), as well as declines in fish stocks. Rapid recent accumulation of high acid potential sediments drew an alarming acidification risk in the Murray River's lower lakes while, in the Gippsland Lakes, high river flows in 2007 lead to an unprecedented bloom of the toxic cyanobacterium *Synechococcus* [12] with impacts on seagrasses and bivalve populations. Migratory waterbird populations have declined owing to reduced habitat suitability and, possibly,

reduced food stocks, although the impact of modifications to resting sites in their Asian flyway are also implicated.

## 5. Management Implications

The long term record of change in south-east Australia attests to substantial modifications to coastal waterways from early in European settlement. These shifts are the result of the direct effects of the construction of barrages or the chronic release of sediments, salts and nutrients from various industrial sources and through catchment disturbance from widespread vegetation clearance. While observation and monitoring programs had lead to concerns being raised as to the health of these systems, the onset of record drought conditions rapidly brought forward substantial change in ecosystems and likely ecological regime shifts. Ecosystem managers failed to read the impending crisis and, in several situations, are now left with limited options to halt or reverse the impacts without massive intervention (e.g. [23]).

South-east Australia has been identified as a climate hotspot on account of scenarios of large declines in wet season rainfall and contraction of the winter growing season [36]. This is likely to exacerbate the declining ameliorative effect of freshwater flows into coastal systems leading to further concentration of nutrients and salts. The impact of this in the mobility and accumulation of sediment-bound metals raises issues of concern for the safety of any harvest from these waterways. High nutrients loads, coupled with warmer temperatures and higher concentrations of atmospheric CO<sub>2</sub> are likely to exacerbate cyanobacterial blooms [37] and expand hypoxic zones.

Australia's population is growing at a rapid rate and coastal development is increasing accordingly. There is a seeming reluctance to adequately care for the provisioning, regulating and cultural services these systems provide now, and may do in the future, in the rush to exploit them today. The long term record reveals that the post-1950 Great Acceleration, clearly evident in south-east Australia, rides on the shoulders of a century of ecosystem change wrought by early European settlers. Present practices and population growth is clearly unsustainable. Evidence for non-linear shifts in aquatic ecosystems in highly populated regions elsewhere [38] forewarn of the potential of catastrophic ecological collapses and substantial declines in aquatic resources. This also has the potential to challenge the capacity of society to deal with the risks associated with ongoing warming, a continuing drying trend and the prospects of coastal erosion and inundation with rising sea levels.

These case studies reveal that the provision of evidence of coastal change from long term sedimentary records provides clear insights unavailable from even long term monitoring programs. These provide evidence for long term trajectories of change and so can distinguish cyclical shifts from directional change. This can assist management in assessing the need for action and the level of urgency that measures need to be applied. Societies who are embarking on monitoring programs for coastal system assessment more recently could be well advised to supplement the accumulating survey data with that archived in sediments. In combination these would provide the data bank necessary to both identify slow and low frequency drivers of change and to qualify the importance of monitored variations by setting them in a longer term context.

## 6. Conclusion

Increasing capacity to observe changes in our environment has enabled humanity to better recognise the opportunity costs of catchment and coastal development to provide services and goods to human economies. In south-east Australia evidence is increasingly being assembled to provide a strong case that many coastal systems have been severely impacted by this development. The assembly of several records of change reaching back further into the past provides an earlier baseline and documents much change before technological advances and concern drew contemporary scientists to monitor long term change. These centennial scale records available in continuous sediment sequences reveal that substantial changes occurred in coastal waterways with years of the building of first settlements. These

changes are evident in changed assemblages of fossil biota and the physical and chemical evidence contained in sediment cores. It is clear that coastal systems have been impacted by the increased flux of sediments, nutrients, salts and metals or more than 150 years. Over this time they have been greatly impacted by hydrological change ranging from reduced flows from catchments through inland diversion, increasing or decreasing freshwater inflow or tidal penetration owing to near-mouth impoundments or freshening through the diversion of unwanted fresh floodwaters. All sites studied have changed relative to a pre-settlement baseline in one of these ways, some catastrophically.

Australia is a signatory to the Ramsar Convention on wetlands that obliges it to advise the Secretariat whenever a listed wetland has changed, is changing or is about to change. This convention also requires signatory nations to ensure wise use of all wetlands. Reference to evidence of change (e.g. [29]) from contemporary approaches questions whether Australia is fulfilling those obligations. Independent assessment of condition from long term sedimentary records (e.g. [12]) shows clearly that most wetlands have changed and that regulating, and provisioning services are being compromised. In line with the observations of Finlayson et al. [39] the government should embark on a program that assesses the present condition of its listed wetlands against more realistic, long term baselines to implement measures to avoid them passing irrevocably into degraded states.

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