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Viewpoint

Microtidal estuaries warrant special management measures that recognise their critical vulnerability to pollution and climate change

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ABSTRACT

Not all estuaries are equally susceptible to anthropogenic perturbation. Microtidal estuaries with long residence times are intrinsically less robust than well-flushed macrotidal estuaries, facilitating the accumulation of contaminants. This promotes development of blooms of non-toxic and toxic phytoplankton, and hypoxia and anoxia may occur in deeper sections of the typically stratified water column. In Mediterranean and arid climates, high temperatures and low and/or seasonal rainfall can result in marked hypersalinity. Thus, any increase in anthropogenic perturbation will further decrease the health of a system in which the biota already experiences natural stress. Microtidal estuaries are also more susceptible to climate change, the detrimental longer-term effects of which are becoming manifestly obvious. Numerous attempts have been made to develop novel solutions to problems caused by eutrophication, phytoplankton blooms, hypoxia and hypersalinity, which have met with various levels of success, but the need for such measures and effective legislation is increasingly critical.

1. Introduction

Estuaries are highly productive and ecologically important from an ecosystem services perspective and in particular for fisheries (Schelske and Odum, 1961; Potter et al., 2015). Yet, temperate estuaries are regarded as the most degraded of all marine ecosystems (Jackson et al., 2001; Kennish, 2002). Most of this degradation has resulted from anthropogenic effects that have arisen as a direct consequence of human colonization and development of the estuary and its catchment, the production and release of human and industrial waste, some of which is toxic, and from nutrient run-off from urban and agricultural land use (Wilson, 1988; McLusky and Elliott, 2004; Tweedley et al., 2015). Not all estuaries are equally susceptible to perturbation, however, and we argue below that the extent of perturbation largely depends on the tidal regime and is exacerbated by climate.

In this essay, we adhere to the following definition of an estuary as given in Potter et al. (2010). “An estuary is a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives at least periodic discharge from a river(s), and thus, while its salinity is typically less than that of natural sea water and varies temporally and along its length, it can become hypersaline in regions when evaporative water loss is high and freshwater and tidal inputs are negligible”. Microtidal estuaries, *i.e.* those with a tidal range < 2 m, in Mediterranean climates generally have narrow mouths, are poorly flushed and have relatively long water residence times, *i.e.* typically weeks to months, whereas macrotidal estuaries are generally funnel-shaped and well-flushed, with relatively short residence times, *i.e.* typically hours to days (Uncles et al., 2002; Tweedley et al., 2016b). For the purposes of this essay, the term macrotidal estuary includes mesotidal estuaries with a tidal range of 2–4 m and those with greater tidal ranges. As we have published elsewhere a detailed review of the contrasting features of the ecology of macrotidal and microtidal estuaries (Tweedley et al., 2016b), we allude only briefly to those features that are directly relevant to environmental management in order to produce a concise and readable Viewpoint and avoid unacceptable repetition.

In some microtidal estuaries, highly seasonal and/or low rainfall results in a sand bar forming at the mouth of the estuary, which prevents the exchange of water with the ocean and further increases the residence time (Ranasinghe and Pattiaratchi, 1998; Chuwen et al., 2009). Estuaries can become closed to the ocean either intermittently, seasonally or normally, and in the last case the residence time is infinite for the years of closure. These estuaries that become closed from the ocean for periods are numerically dominant in microtidal Mediterranean climates and constitute 39 (82%) of the 47 estuaries in south-western Australia (Tweedley et al., 2017b) and 75% of the total number

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of ~250 estuaries in southern Africa (Whitfield, 1998).

2. Susceptibility to pollution

Estuaries with long residence times are intrinsically less robust than better flushed estuaries, because they facilitate the accumulation of contaminants. Furthermore, even when there are no anthropogenic inputs, naturally-occurring dissolved and particulate organic material from terrestrial sources accumulate in these systems and this can lead to a marked depletion in dissolved oxygen (Nixon et al., 1996; Wolanski, 2007).

This problem is exacerbated in the microtidal estuaries of south-western Australia because the residence times are longest in the warmer months of the year, when rainfall is very low, and will be particularly marked in those systems in which the mouth closes and thereby prevents flushing. For example, the residence time in the upper reaches of the permanently-open Swan-Canning Estuary is estimated to be 235 days in summer but only 1 day in winter (Kalnejais et al., 1999). High temperatures increase the rates at which particulate organic matter becomes decomposed and dissolved nutrients are utilized, sometimes giving rise to excessive blooms of phytoplankton (Lukatelich and McComb, 1986; Robson and Hamilton, 2004). In a climate with less seasonal rainfall, such as in Denmark, microtidal estuaries become stratified during periods of low rainfall, have high nutrient concentrations and feature large plankton blooms, hypoxia and anoxia (Conley et al., 2000). However, these estuaries are fjordic, with hard bottoms that support high densities of filter-feeding macrobenthos, such as the bivalve *Mytilus* and ascidian *Ciona*, that can greatly reduce phytoplankton concentrations and ameliorate these effects to some degree (Conley et al., 2000).

In contrast, macrotidal estuaries are usually very turbid because strong tidal scour re-suspends bottom sediments, producing local accumulations of suspended particles at the turbidity maximum which, together with riverine inputs of terrestrial material and irrespective of nutrient concentrations, inhibits light penetration so that primary production is strongly light-limited, for example in the Schelde (Soetaert and Herman, 1994), Gironde (Irigoien and Castel, 1997) and Severn estuaries (Underwood, 2010; Kadiri et al., 2014). In these estuaries, only a small proportion of the nutrients supplied by the rivers is used by the phytoplankton and the incidence of toxic algal blooms is minimal. On the other hand, a large proportion of the nutrients is utilized by the phytoplankton in microtidal estuaries, where low turbidity results in clear water, making these systems far more sensitive to increases in nutrient input that might lead to excessively high phytoplankton biomass (Monbet, 1992).

Elevated concentrations of dinoflagellates and cyanobacteria are characteristic of these blooms. They are symptomatic of eutrophication in microtidal estuaries and may result in environmental problems since many species in these two taxa are toxic and mainly responsible for the harmful algal blooms that frequently occur in microtidal estuaries throughout the world (Hall et al., 2008; Place et al., 2012). These blooms have serious consequences, including large fish kills, as for example in the Peel-Harvey and Swan-Canning estuaries in south-western Australia (Potter et al., 1983; Lenanton et al., 1985; Hallett et al., 2016), and an increased danger to human health through diarrhetic and paralytic shellfish poisoning, as for example in Alfacs Bay on the Mediterranean coast of Spain (Artigas et al., 2014). Many estuaries with the greatest annual phytoplankton production are microtidal, such as Chesapeake Bay on the eastern coast of the USA and the Swan-Canning Estuary (Cloern et al., 2014). Within a single microtidal estuary, short-term variation in phytoplankton production may be related to variations in residence time, for example in the Patos Lagoon Estuary in southern Brazil (Odebrecht et al., 2005).

While the water column in macrotidal estuaries is well- or at least partially-mixed, driven by tidal action, microtidal estuaries are typically highly stratified, with little or no mixing between the fresh water on the surface and the salt water below, resulting in the production of a halocline (Dyer, 1997). Strong salinity stratification encourages high rates of sediment deposition (Traykovski et al., 2004; Ralston et al., 2012), thus enhancing nutrient recycling (Hopkinson et al., 1999; Watanabe et al., 2014) and which can lead to conditions that produce hypoxia (< 2 mg oxygen L^{-1}) and even anoxia (Paerl et al., 1998; Kurup and Hamilton, 2002; Tweedley et al., 2016a). Vertical mixing in macrotidal estuaries tends to prevent hypoxia, which is thus not generally a problem in these systems (Lanoux et al., 2013). Although cycles of sediment erosion and deposition occur in macrotidal estuaries on daily, weekly, lunar, equinoctial and seasonal cycles (Wolanski and Elliott, 2016), posing a physical stress not present in microtidal estuaries, these events have been operating over evolutionary time scales so that the biota have become well adapted to them. This ability to absorb stress without adverse effects has been termed "environmental homeostasis" by Elliott and Quintino (2007) and estuarine organisms may regard this environmental stress as a subsidy whereby they successfully capitalise on such conditions, which may only be regarded as stressful for marine or freshwater-adapted organisms.

Naturally high levels of organic matter and oxygen depletion will encourage the success of families of benthic macroinvertebrates (*e.g.* Capitellidae, Spionidae and Chironomidae) that are characterized by high AMBI scores and even occur in the essentially-pristine Broke Inlet in south-western Australia (Tweedley et al., 2014, 2017b). AMBI (the AZTI marine biotic index) is based on scoring benthic macroinvertebrate species according to their known sensitivities to environmental perturbations, thus enabling an average score to be obtained for the assemblage as a whole (Borja et al., 2000). Such high AMBI scores elsewhere would be associated with pollution produced by anthropogenic sources of organic matter (Borja et al., 2000). Thus, any increase in anthropogenic perturbation will further decrease the health of a system in which the biota is already under stress from natural causes.

3. Susceptibility to climate change

The nature of climate change and its effects on the macrotidal estuaries of the northern hemisphere are variable, although none of the predictions imply catastrophic environmental consequences (Robins et al., 2016). Microtidal estuaries are likely to be more susceptible to climate change, the longer-term effects of which are obvious and already manifesting themselves, while their causes are not being adequately addressed at a global scale. The estuaries of south-western Australia, for example, have been subjected to sustained warming and drying. Annual mean air temperatures in this region rose by 1.1 °C between 1910 and 2013 and, by 2030, are predicted to be 0.5–1.1 °C above the 1986–2005 average, with respective increases of 1.2–2.0 °C and 2.6–4.0 °C by 2090 under moderate (Representative Concentration Pathway; RCP4.5) and high (RCP8.5) emission scenarios (Hope et al., 2015; Hallett et al., 2018). Representative concentration pathways (RCPs) have been developed for the climate modelling community as a basis for long-term and near-term modelling experiments and are referred to as pathways in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas concentrations (van Vuuren et al., 2011).

The ~15% decline in rainfall, which has occurred in south-western Australia since the mid-1970s, has led to a 70% reduction in runoff into reservoirs (Petrone et al., 2010; McFarlane et al., 2012). Similarly, the average annual freshwater flow into the Coorong in South Australia has been reduced by about 70% over recent decades and is highly variable, with no flow over the barrages that have been built across the estuary for several consecutive years during a "Millennium Drought" between 1997 and 2009 (Kingsford et al., 2011; Leblanc et al., 2012). Decreased river flows resulted in an increase in residence time and the frequency of mouth closure, thereby producing stressful hypoxic and hypersaline (> 40) conditions, with the maximum recorded salinity approaching 200 (Wedderburn et al., 2016). Other examples of extreme