Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Changing fluxes of sediments and salts as recorded in lower River Murray wetlands, Australia

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Abstract The River Murray basin, Australia's largest, has been significantly impacted by changed flow regimes and increased fluxes of salts and sediments since settlement in the 1840s. The river's flood plain hosts an array of cut-off meanders, levee lakes and basin depression lakes that archive historical changes. Pre-European sedimentation rates are typically approx. 0.1–1 mm year^{-1}, while those in the period after European arrival are typically 10 to 30 fold greater. This increased sedimentation corresponds to a shift in wetland trophic state from submerged macrophytes in clear waters to phytoplankton-dominated, turbid systems. There is evidence for a decline in sedimentation in some natural wetlands after river regulation from the 1920s, but with the maintenance of the phytoplankton state. Fossil diatom assemblages reveal that, while some wetlands had saline episodes before settlement, others became saline after, and as early as the 1880s. The oxidation of sulphurous salts deposited after regulation has induced hyperacidity in a number of wetlands in recent years. While these wetlands are rightly perceived as being heavily impacted, other, once open water systems, that have infilled and now support rich macrophyte beds, are used as interpretive sites. The rate of filling, however, suggests that the lifespan of these wetlands is short. The rate of wetland loss through such increased infilling is unlikely to be matched by future scouring as regulation has eliminated middle order floods from the lower catchment.

Key words diatoms; flood plain; phytoplankton; salinization; sedimentation; wetlands

INTRODUCTION

The River Murray is a substantially modified system suffering under the effects of over allocation of its flow to a substantial irrigation agriculture industry and domestic uses. Up to 90% of the mean annual flow (Commonwealth of Australia, 2001) has been allocated to consumptive use. This industry was built on the provision of more reliable water supply after the commissioning of a system of locks and barrages on the main river. The first of these were in place in 1922. By 1940, 26 barrages were impounding the flow of the river and its tributaries. This included an extensive system at the river's mouth established to limit the penetration of tidal water into the lower reaches to protect the integrity of freshwater supplies, again for irrigation agriculture (Bourman & Barnett, 1995). These changes have reduced mid-level floods, shifted the timing of peak flow from winter-spring to summer in the upper catchment when irrigation activity is at maximum in the upper Murray catchment (Maheshwari *et al.*, 1995), and brought saline aquifers to the surface (Macumber, 1991).

Prior to regulation, extensive grazing by sheep reduced the surface cover of vegetation and disturbed the soil surface rendering it more susceptible to surface erosion. Exposure of riverbanks and the introduction of benthic-feeding cyprinid fish mobilized soil and sediment within the bankfull zone supplementing the increased flux of sediments from terrestrial sources. It has been reported that 95% of river length in the Murray Darling Basin is degraded and that "...changes to nutrient and suspended sediment loads are the greatest contributors to this index of degradation" (Norris *et al.*, 2002). The biological consequences of these changes are many but include increased phytoplankton at the expense of aquatic macrophytes, the replacement of lotic biota, e.g. snails and decapods, with lentic sister taxa (Sheldon & Walker, 1997) and the decline in flood-driven breeding episodes and subsequent recruitment.

The declining ecological status of the wetlands of the River Murray is widely recognized and their rehabilitation, even restoration, has been written into State Government strategies (DEH & DWLBC, 2003) and interjurisdictional water resource allocation plans (e.g. The Living Murray Initiative). Reports suggesting that the provision of 4000 GL of water for environmental flows as the only scenario with "...a high probability of achieving a healthy working River Murray System..." (Jones *et al.*, 2002) have been challenged. Reports, some commissioned by the irrigation industry, stated that the claims by the scientific community for the degraded state of the river were overstated (e.g. Benson *et al.*, 2003). Given the functional link between the river channel and its flood plain, particularly in lowland systems, such a claim can be critically assessed by documenting the changing nature of the wetlands over the longer term. By examining the changing rates of sedimentation and salinization in wetlands over periods extending into the pre-industrial period, comparisons can more readily be made, and a better informed conclusion can be reached, as to the relative impact of regulation and agricultural development on the broader functioning of the river. Despite flood plain wetlands being critical sediment sinks in riverine systems, few studies have focused on the records of change archived in these sediments to reconstruct the history of sediment and salt flux. A clear exception is the wetlands of the River Murray and its tributaries where at least 30 wetlands have been examined, many in high detail, using palaeolimnological techniques (for a review see Gell *et al.*, 2005a). These records attest to substantial limnological change to these wetlands since European settlement in the early to mid 1800s. The documented changes include acidification, alkalinization, shifts from aquatic macrophyte to phytoplankton dominated trophic states, salinization, eutrophication and artificially maintained water levels.

METHODS

Several wetlands were selected from the lower reaches of the River Murray (Fig. 1) for analysis of sedimentation rates and diatom-inferred water salinity. Most of the sites

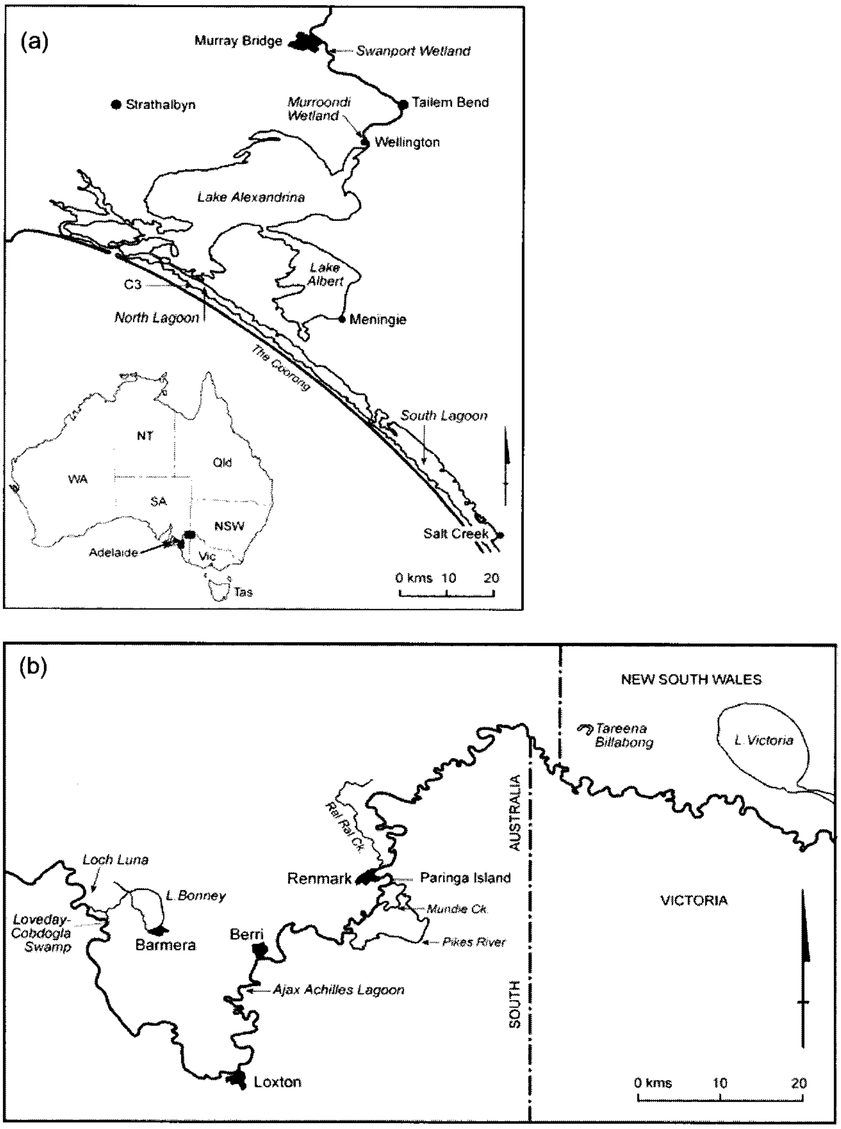

Fig. 1 The lower River Murray and its associated flood plain lakes: (a) the Riverland region of South Australia; (b) the lower reaches of the river, terminal lakes and coastal lagoon.

were cored with either a field piston corer, a Russian (d-section) corer or simply by pushing PVC pipes into the sediments, capping and extracting. A range of dating approaches was applied to each site including ^{14}C AMS and optically stimulated luminescence (OSL). Recent samples were taken for alpha and gamma spectrometry to generate a ^{210}Pb decay profile and to gain evidence for ^{137}Cs activity. Upper sediments were subsampled to identify the arrival of exotic *Pinus* pollen (*sensu* Ogden, 1996). Subsamples were collected to extract fossil diatom algae for the purposes of reconstructing past salinity using established training sets of modern flora calibrated to wetland water chemistry (e.g. Tibby & Reid, 2004). Samples were prepared using standard HCl and H_2O_2 digestion techniques and mounted on slides using Naphrax. Coverslips were traversed and diatom taxa identified and enumerated. Identification was supported by reference to standard texts including Witkowski *et al.* (2001).

RESULTS

Sedimentation

The excess ^{210}Pb curve from Ral Ral Creek wetland shows a linear decline with time and the constant initial concentration (CIC) modelling of the excess ^{210}Pb data (Fig. 2) indicates that sediments in the upper 29 cm were deposited in the last 32–37 years (9.1 and 9.7 mm year^{-1}). The excess ^{210}Pb-depth relationship extends to 60 cm suggesting that this age–depth relationship could be extended to this depth of sediment. Sedimentation rates for recent sediments in Pikes Creek wetland are very high, with an estimated 30 mm year^{-1} accumulating in the upper 60 cm (Fig. 2). Hence, these deposits are apparently only 20 years old. Sediments between 60 and 100 cm were deposited at a much slower rate (3.3 mm year^{-1}) rendering the age of the sediments at 100 cm approximately 140 years old (*c.*1865 AD).

A typical record of sediment accretion and wetland change is evident in results from Swanport Wetland. The initial diatom flora are mainly of planktonic (*Aulacoseira* spp., *Cyclotella stelligera*) and facultative planktonic (*Fragilaria capucina*, *Staurosirella pinnata*) forms suggesting a wetland water depth of 2 m or greater. At the inferred point of European arrival, aerophilous diatoms, often brought in with eroding sediment, increase. These then yield dominance to benthic (*Epithemia* spp.) and epiphytic (*Gomphonema* spp.) forms. The frequency of *Myriophyllum* (water milfoil) pollen increases in the European phase. The upper sediments appear to have accumulated

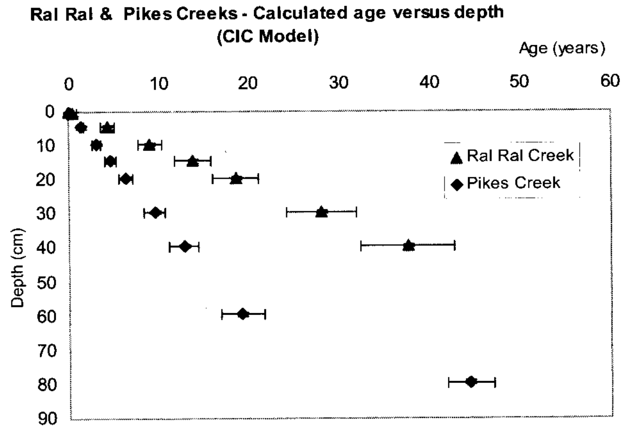

Fig. 2 Calculated age *vs* depth for Ral Ral and Pikes Creek cores. The age of the sediment layers in both cores were calculated using the respective CIC model sedimentation rates for each core.

at ~17 mm year^{-1} and an open water body has rapidly evolved into a shallow, macrophyte bed.

The ^{210}Pb and ^{14}C AMS-derived chronology for the Coorong also suggests a change in sedimentation rate, but also sediment type. The lower sediments are carbonate-rich marls. The ^{14}C AMS age for the base of core C3 is 6327 ± 40 years BP (Wk–17294; uncal.) giving a pre-European sedimentation rate of 0.19 mm year^{-1}. After regulation in the 1930s, the sediments shifted abruptly to fine, dark clays. Between 23 to 17 cm the sedimentation rate increased to 1.1 mm year^{-1}, and from 17 cm (*c.*1982 AD) to the surface, 7.7 mm year^{-1}. This represents a 40-fold increase in sedimentation relative to a pre-European baseline.

Salinity

Several sediment sequences show an increase in wetland salinity. The diatom record from the northern lagoon of the Coorong shows high proportions of estuarine or marine taxa before European settlement. This assemblage includes moderate proportions of the brackish taxon *Campylodiscus clypeus*. The European phase is marked by an increase in small diatoms in the family Fragilariaceae that are known to prefer turbid or closed systems. Elsewhere in the Coorong, the uppermost sediments support higher numbers of benthic taxa (e.g. *Amphora coffeaeformis*) that can tolerate hypersaline waters (Gell, 1997). The chronology ties this change with the closing of the River Murray mouth after the 1982/1983 drought.

DISCUSSION

Before European settlement the flood plain wetlands of the lower River Murray evolved hydroserally and in response to climate change and the subsequent response of the biota and landscape. Some wetlands have filled by as much as 14 m of sediment and are now reedbeds when they were once open water. Two of the major changes since European settlement have been the heightened flux of sediments and the concentrations of salts. The establishment of a chronology for several flood plain wetland sediment sequences has been problematic (Gell *et al.*, 2005a). However, ages can be estimated to provide indicative rates of change to compare with the present regime.

Sedimentation

Before European settlement the sedimentation rates of most wetlands were slow at ~0.1–1.0 mm year^{-1}. The pollen spectra from the longest sequence, Muroondi Wetland, support a mid-Holocene age for its origin inferring a pre-European sedimentation rate of between 1.3 and 3.0 mm year^{-1}. The post-European sedimentation rates in the majority of wetlands exceed even this upper estimate. The early post-European sedimentation rate in Tareena Billabong was 20 mm year^{-1}, while recent rates for Pikes

Creek and Ajax Achilles Lagoon could be 30 and 40 mm year^{-1}, respectively. Lower in the system, at Swanport Wetland the post-settlement rate is ~17 mm year^{-1} and, at Lake Alexandrina, 1.7 mm year^{-1}. Near the coast in the Coorong Lagoon, post-European sedimentation rates are as low as 0.5 mm year^{-1} at some sites, but as much as ~8 (north lagoon) and 18 mm year^{-1} (south lagoon) elsewhere. These computed 10- to 70-fold increases are partly accounted for by the uncompacted nature of the upper sediments, but moisture content data suggest that this may account for less than a doubling in rate. The rates determined here are of the same order, and in some instances greater than, those gained for the upper Murray River billabongs (Thoms *et al.*, 1999). In a few sites, sedimentation rates appear to have increased only marginally, or slowed down. At Tareena Billabong, the rate slowed to ~2.0 mm year^{-1} after regulation, still three times that before settlement.

These elevated post-settlement rates of sedimentation have a long history and are believed to have commenced early in European settlement. It appears likely, and is argued for elsewhere (Gale & Haworth, 2002), that Australian soils were highly sensitive to disturbance and the upper soil horizons were readily eroded. High stocking rates and droughts (e.g. 1862–1865) may have exposed surfaces to wind and water erosion. River barrages are likely to have trapped channel-borne sediments (Thoms *et al.*, 1999) reducing the availability of sediments for deposition in wetlands but this effect appears to have been exceeded as the rates at some sites are now at their greatest. The major agents of erosion to provide sediments to account for these recent high rates may include benthos-feeding cyprinid fish introduced to the system in 1966, or the increased dispersiveness of salinized land surfaces due to increasing sodicity.

Heightened sedimentation rates represent considerable threats to wetland ecosystems. Increased sediment flux is usually accompanied by greater water column turbidity. These shade macrophytes and drive stable states from macrophyte-rich, clear water systems to turbid ones that advantage phytoplankton (Ogden, 1996). This is exacerbated by the ferrying of sediment-bound phosphorus that augments algal productivity.

Most of the wetlands examined are relatively shallow. If the recent high rates are widespread many wetlands are approaching a terminal condition at an ever-increasing rate. In some this may be due to the trapping role of aquatic vegetation; however, some actively accreting sites lack extensive macrophyte beds. So, sedimentation rates appear to be accelerating when, intuitively, a reduced rate of sediment trapping might be expected as depressions fill. Swanport Wetland may have been over 200 cm deep before European settlement with a sedimentation rate of ~1 mm year^{-1}. This wetland then, had a probable life-span of 2000 years. A modern rate of 20 mm year^{-1} has rapidly accelerated this ageing and it now, in the absence of scouring, has a much shorter prognosis as a permanent wetland. This should be alarming for managers who have recently promoted the wetland as a site of high macrophyte diversity—a condition that it appears to have reached due to recent sediment accumulation.

Ral Ral Creek wetland was 1.2 m deep at the time of coring. The present sedimenttation rate of ~9.5 mm year^{-1} suggests that this wetland will gradually fill with sediment over the next 150 years. Pikes Creek wetland may have also been deep (~2 m). However, this wetland has accumulated 120 cm of sediment, 30 mm year^{-1} over the last 20 years. Its prognosis is for complete filling in the next two decades. Such sites may replicate the Swanport Wetland experience and become macrophyte-rich in future years before a terminal state is reached, provided the germinants overcome light limitation in the turbid waters.

In a system where regulation and abstraction have eliminated middle-level floods, wetland regeneration is increasingly dependent on large floods to replace those senescing through sediment accretion. Large floods are infrequent and unless the next La Niña event occurs soon, and unless it is highly competent and scours soft sediments from existing wetlands or creates new ones, River Murray wetlands are on a steep trend towards an overmature state.

Salinity

The salinity of most flood plain wetlands was originally low. The pre-European diatom flora of Loveday-Cobdogla Wetland however, includes taxa that are reliable indicators of high salinity (e.g. *Gyrosigma attenuatum* tolerates TDS > 60 000 mg L^{-1}). The large Pleistocene dune nearby may have leached salts to the wetland under past climates. The terminal wetlands of the River Murray show a tidal influence for most of the Holocene (Fluin, 2002). Prior to the 1900s the Coorong was dominated by diatom species with affinities for seawater, but for subsaline concentrations. Lake Alexandrina, the terminal lake of the river, supported a river flora, but also marine diatoms reflecting a tidal connection throughout the Holocene.

Since European settlement much of the Murray Darling Basin has been impacted by dryland and irrigation salinization (Macumber, 1991). Most of this impact was revealed in the late 1900s. In the southern plains, the extent of dryland salinization accelerated rapidly through the mid 1970s owing to the increased accessions to the groundwater from the exceptional rainfall associated with a strong La Niña signal. Extensive Red Gum (*Eucalyptus camaldulensis*) stands in Loddon River sub-catchment wetlands died abruptly as groundwaters reached the capillary zone (Macumber, 1991). At Tareena Billabong increased salinity was detected from ~1880 AD (Gell *et al.*, 2005b), owing to intensive agriculture early in European settlement. Loveday-Cobdogla Swamp and Loch Luna show gradually increasing wetland salinity through European settlement. Today, large dead red gum trees attest to an earlier fresh and ephemeral state. Dead trees also surround Ramco Lagoon that is now covered with a 2 cm crust of halite.

The wetlands lower in the system reflect not salinization, but eutrophication and sedimentation. Barriers constructed in 1940 to reduce tidal influence have acted to freshen Lake Alexandrina. The Coorong however, became more saline through the 1900s due to the diversion, to the ocean, of freshwater flows from the hinterland and the gradual closure of the Murray Mouth eliminating the flushing of tidal water.

Acidification

Loveday-Cobdogla Swamp shows an increase, post regulation, of a diatom species, *Haslea spicula*, known to prefer sulphate salts. The elevated water levels in the wetland, the typical condition since the commissioning of the channel locks, possibly allowed for the accumulation of sulphur salts in a reduced state. Drought, and the imposition of wetting and drying regimes, appears to have oxidized the salts and driven the release of sulphuric acid (Lamontagne *et al.*, 2004). This phenomenon is now evident from as many as six wetlands that have salinized since regulation. The sediment core from Martin's Bend Wetland near Berri reveals a sustained shift to acidophilous diatom taxa (*Pinnularia* spp.) showing that this is a sustained, unprecedented change in wetland condition.

CONCLUSION

The wetlands of the lower River Murray have continually evolved over 5000 or more years of climate change. Only one of the flood plain lakes provides evidence of elevated water salinity before the arrival of European settlers. Despite being a lowland system, most wetlands appear to have accumulated sediments at a slow rate. Since European settlement, most wetlands have been impacted by a substantial acceleration in sedimentation rate. Given the subdued topography and shallow wetland depth, this is accelerating the transition of several wetlands to a terminal, probably terrestrial, state. Many flood plain wetlands have accumulated high concentrations of salts. Several, that once supported diverse Red Gum swamps, now have a halite crust. Others that have accumulated sulphur salts are becoming acidified with the exposure of sulphides upon drying. Some coastal lakes at the end of the system have been impacted by loss of connection to tidal flows. Rather than the degraded state of the River Murray being exaggerated, as is claimed by the irrigation industry, the sedimentary sequences of the flood plain wetlands reveal that they have been heavily impacted, and most are presently in a state that is unprecedented in the Holocene.

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