

Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray–Darling Basin, Australia

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ABSTRACT

Over the last decade there has been a deliberate focus on the application of paleolimnological research to address issues of sediment flux and water quality change in the wetlands of the Murray–Darling Basin of Australia. This paper reports on the research outcomes on cores collected from sixteen wetlands along the Murrumbidgee–Murray River continuum. In all sixteen wetlands radiometric techniques and exotic pollen biomarkers were used to establish sedimentation rates from the collected cores. Fossil diatom assemblages were used to identify water source and quality changes to the wetlands. The sedimentation rates of all wetlands accelerated after European settlement, as little as two-fold, and as much as eighty times the mean rate through the Late Holocene. Some wetlands completely infilled through the Holocene, while others have rapidly progressed towards a terrestrial state due to accelerated accretion rates. Increasing wetland salinity and turbidity commenced within decades of settlement, contributing to sediment inputs. The sedimentation rate was observed to slow after river regulation in one wetland, but has accelerated recently in others. The complex history of flooding and drying, and wetland salinisation and eutrophication, influence the reliability of models used to establish recent, fine-resolution chronologies with confidence and the capacity to attribute causes to documented effects.

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1. Introduction

Wetlands act as sediment sinks in catchments and so can be used as a means to establish mean sediment accumulation rates. The sediment input to lowland wetlands is potentially greater than their upland counterparts owing to the amplification of fluxes into higher order streams. The contribution of sediments carried by the main river to floodplain wetlands is influenced by the degree of connectivity between the river and the wetland and the frequency of floods of heights sufficient to connect the two. Allochthonous sources, which include direct inputs from the neighbouring floodplain, combine with endogenic production of sediments and organic matter that can further accelerate gross sediment accretion. The trajectory towards complete infilling may be balanced by declining sediment trapping efficiency as a wetland fills, and sediment scouring with high flow events. Human-induced increased flux of allochthonous sources down large rivers may come from surface erosion from the catchment, stream bank erosion and collapse and soil surface sodicity (Neave and Rayburg, 2006) and this may, at least in part, be balanced, in regulated

systems, by sediment trapping behind impoundments (Olley and Wallbrink, 2004). Endogenic drivers that accelerate accretion rates include wave-driven erosion of exposed littoral zones (Bourman and Barnett, 1995) and increased sediment trapping by aquatic macrophytes promoted by accelerated nutrient fluxes (see Table 1).

This paper synthesizes reported evidence on the sedimentation rates of a range of wetlands down a river continuum in the Murray River catchment of Australia (Fig. 1). Dating techniques comprising optically stimulated luminescence (OSL), ²¹⁰Pb, ¹³⁷Cs, ¹⁴C AMS and exotic pollen biomarkers were used to establish chronologies from core sequences extracted from the wetlands. Diatom microfossils provide evidence for changing wetland condition. The timing of increases in river plankton in wetlands closely linked to the main channel was used to aid the identification of the onset of river regulation in the mid-1920s AD.

2. Study area

The Murray–Darling Basin covers 1.073×10^6 km² and ranges from montane landscapes in the south-east that, in winter-spring, provide for most of the catchment runoff, to semi-arid and arid conditions in

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Table 1

Estimated change in mean sedimentation rates and water quality status in Murrumbidgee–Murray floodplain wetlands.

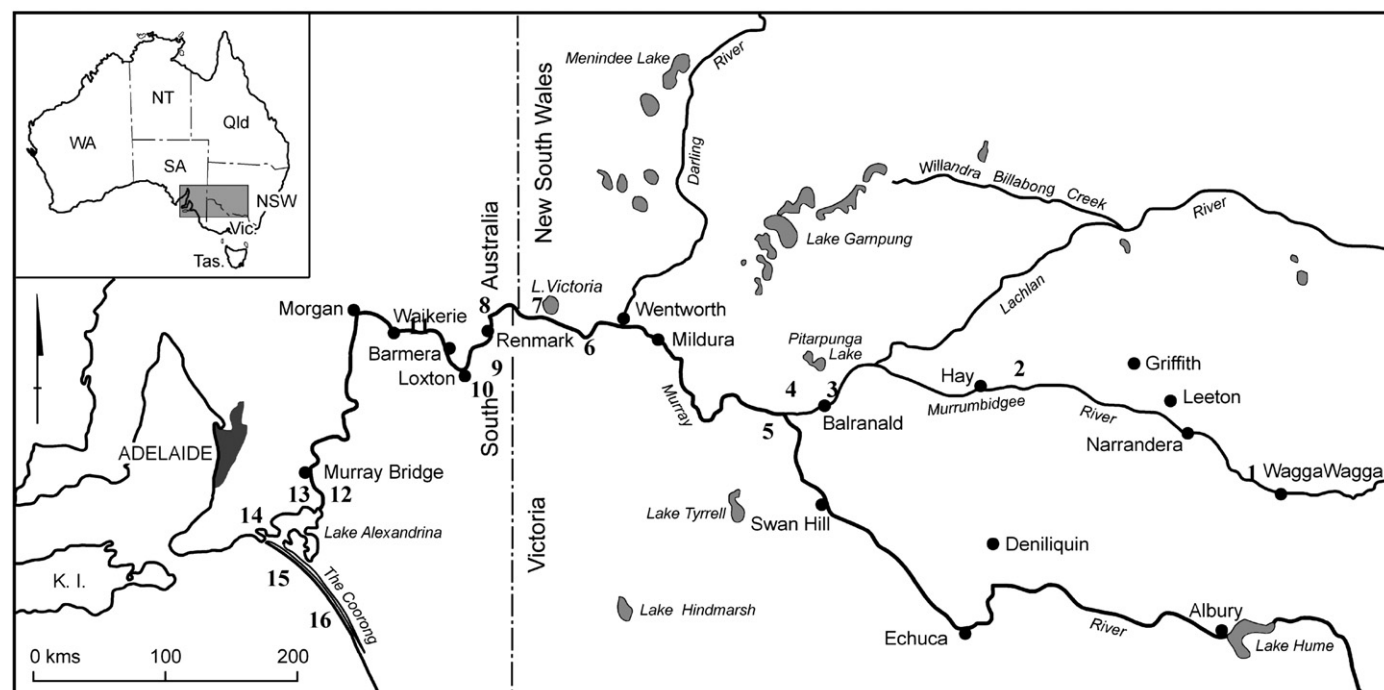
Wetland	Wetland type	Dating technique	Sedimentation rate (mm/yr)		Water quality status change	
			Baseline	Post impact	Salinity	Nutrients
1. Berri Jerri Lagoon ^a	Floodplain oxbow lake	Pollen ²¹⁰ Pb, ¹³⁷ Cs	n.a.	6	↑ then ↓	↑
2. Coonooococabil Lagoon ^a	Floodplain oxbow lake	Pollen ²¹⁰ Pb, ¹³⁷ Cs	n.a.	6	↑	↑
3. Balranald Weir ^a	Weir	Pollen ²¹⁰ Pb, ¹³⁷ Cs	n.a.	9	↑	↑
4. Junction Park Billabong ^b	Floodplain oxbow lake	Pollen, ¹⁴ C (AMS pollen preparations)	0.7	3.8		↑
5. Hopcrofts Billabong ^c	Floodplain oxbow lake	Pollen, ¹⁴ C (AMS pollen preparations)	~2	~5		
6. Lake Cullulleraine ^{b,d,e}	Retention basin	²¹⁰ Pb	n.a.	5		
7. Tareena Billabong ^{c,f}	Floodplain oxbow lake	Pollen, ²¹⁰ Pb, ¹³⁷ Cs, OSL, ¹⁴ C	0.6	2–20	↑	↑
8. Ral Ral Creek ^g	Floodplain oxbow lake	²¹⁰ Pb	n.d.	9.5	n.d.	n.d.
9. Pikes Creek ^g	Floodplain oxbow lake	²¹⁰ Pb	n.d.	30	n.d.	n.d.
10. Ajax Achilles ^h	Levee lake	²¹⁰ Pb, OSL	n.d.	~10	n.d.	n.d.
11. Loveday–Cobdogla Wetland ⁱ	Floodplain oxbow lake	Pollen, ²¹⁰ Pb, ¹³⁷ Cs, OSL	1.0	6	↑	↑
12. Swanport Wetland ^g	Levee swamp	Pollen	1.2	17		↑
13. Murroondi Wetland ^c	Levee swamp	Pollen, ¹³⁷ Cs, ¹⁴ C (AMS sediment)	2.8	5–10		↑
14. Lake Alexandrina ^{d,j,c,h}	Terminal lagoon	Pollen, ²¹⁰ Pb, ¹⁴ C (AMS sediment)	0.3–0.7	1.7	↓	↑
15. Coorong North Lagoon ^j	Barrier lagoon	Pollen, ¹³⁷ Cs, ¹⁴ C, OSL	0.1–1.0	1.0–8.8	↑	↑
16. Coorong South Lagoon ^j	Barrier lagoon	Pollen, ¹³⁷ Cs, ¹⁴ C, OSL	0.1–1.0	0.5–17.7	↑	

n.a. not applicable, n.d. not determined (research ongoing).

^a Gell and Little (2006).^b Adamson et al. (in preparation).^c Gell et al. (2005a).^d Fluin (2002).^e Reid et al. (2002).^f Gell et al. (2005b).^g Gell et al. (2006).^h Khanum (unpublished data).ⁱ Gell et al. (2007).^j Fluin et al. (2007).

the south-west. The northernmost extent of the catchment extends into sub-tropical climates that can provide sporadic high flows in summer–autumn. The catchment was settled from the 1840s and now provides 40% of Australia's agricultural gross domestic product, however this has come at vast environmental cost. In excess of 80% of the 14×10^9 GI mean annual discharge has been diverted for irrigation agriculture and domestic use (Commonwealth of Australia, 2001). In many lowland parts of the catchment saline regional

groundwater tables are perennially within the capillary zone and large areas of the catchment have been impacted by secondary salinisation. Nutrients are released from urban sources, fertiliser application, irrigation return drains and from clays mobilised from exposed riverbanks. Stock grazing rates were high within a few years of settlement and the controlling influence of ENSO cycles has exacerbated erosion through extreme droughts and flood events. Widespread recognition of the degraded nature of the catchment has

**Fig. 1.** The Murrumbidgee and Murray Rivers in south-eastern Australia. Site numbers correspond to those in Table 1.

generated government and community-based measures to limit abstraction, reduce the flow of saline groundwaters, revegetate sub-catchments and restore floodplain wetlands. The wetlands under study range from levee and oxbow lakes along the river floodplain to terminal lakes that owe their origin to the reduction in gradient and formation of barrier spits after the stabilisation of sea levels in the mid Holocene. Most floodplain wetlands are shallow (<1 m) and they tend to dry regularly. Some have been maintained by connection to weirs along the rivers and so are deeper (1–3 m). The terminal lakes are perennial and slightly deeper (1–4 m). The upper wetlands (Berri Jerri Lagoon to Pikes Creek) are within a broad floodplain while the lower wetlands (Ajax Achilles Lagoon to Murroondi) are within a gorge and lie between the main river channel and high, limestone cliffs.

3. Methods

Over the last decade over 40 floodplain and terminal wetlands within the Murray Darling Basin have been cored for paleolimnological research (Barnett, 1994; Thoms et al., 1999; Ogden, 2000; Reid et al., 2002; Tibby et al., 2003; Gell and Little, 2006; Gell et al., 2005a,b, 2006, 2007; Fluin et al., 2007). Here, evidence from 16 wetlands along a river continuum from Wagga Wagga on the Murrumbidgee River to the Coorong at the mouth of the River Murray is selected to generate a regional synthesis to reveal broadscale wetland sedimentation rates, the challenges of radiometric dating of floodplain and terminal wetland sediments and to demonstrate the use of microfossil indicators to reveal generalised changes to river and wetland conditions. In most sites a Russian (d-section) corer (after Jowsey, 1966) was used to retain the depth/age profile but often a field piston corer (after Chambers and Cameron, 2001) was used to increase sediment volume for analysis. In several wetlands cores were taken from two or three locations. At several sites samples were taken for ^{14}C AMS dating. Elsewhere core chronology was supported using OSL dating. In most instances, recent samples were taken for alpha or gamma spectrometry to generate a ^{210}Pb decay profile and to gain evidence for ^{137}Cs activity. Given the variable nature of the flux of sediments in fluvial, and particularly lowland, contexts, the constant initial concentration model (Walling et al., 2002) for ^{210}Pb was usually applied to derive recent age-depth profiles and sedimentation rates. The upper sediments of most cores were sub-sampled to identify the arrival of *Pinus* pollen (after Ogden, 1996). The changing nature of the sediments in many cores was analysed utilising magnetic susceptibility analysis by passing unopened PVC cores through a Bartington BS2 loop. Subsamples were collected from all cores to extract fossil diatom algae to reconstruct changes in wetland condition according to the known preferences of species for salinity and nutrients. Samples were prepared and enumerated using standard methods (after Battarbee et al., 2001). Species identification was supported by reference to Krammer and Lange-Bertalot (1986, 1988, 1991a,b) and Witkowski et al. (2001). The ecological inferences from each species are based on van Dam et al. (1994), Gell (1997), Sonneman et al. (2000), Gell et al. (2002), Tibby (2004) and Tibby and Reid (2004).

4. Results

The cores extracted from many of the selected wetlands were only 0.5–2 m in length. Those taken from larger oxbows are longer, ranging from 4.6 m (Tareena Billabong) to 14 m (Murroondi Wetland). The stratigraphy of most floodplain wetland sediment sequences was continuous grey or grey–brown clay. In sites where surface salinity was high, the uppermost sediments were blackened, presumably through reduction of sulphurous salts. Otherwise, most sequences provided little stratigraphic evidence for changing sedimentation rates or wetland condition. The 14 m sequence extracted from Murroondi Wetland was an exception in that it showed transition from grey clay to a dark brown organic matrix with increasing detrital

matter towards the surface, consistent with hydrosereal shifts as the wetland filled with sediment (Gell et al., 2005a).

The longer term chronologies of several wetlands were determined using ^{14}C AMS (Table 1; wetland nos. 4, 5, 7, 13, 14, 15, 16) and OSL (7, 10, 11, 15, 16) dating. In some cases (e.g. 7, 13) the radiocarbon results were implausible (Gell et al., 2005a), perhaps affected by the prevalence of carbonate in the landscape. Elsewhere, the radiocarbon analyses provided plausible chronologies and ages of wetland origin. At Tareena Billabong the chronology was greatly improved by several OSL dates (Gell et al., 2005b). These were on fine sand, but plausible dates were also retrieved from analyses on clay fractions. Most $^{210}\text{Pb}/^{137}\text{Cs}$ sequences provided plausible chronologies for recent sediments despite the known challenges faced when applying these techniques in riverine landscapes. At Tareena Billabong the ^{210}Pb sequence may have been influenced by the shift to salinities >3 g/l due to the desorption of ^{226}Ra (Hancock and Murray, 1996). In most Coorong sequences ^{137}Cs activity persisted in sediments below the lowest point of ^{210}Pb detection. High salinity and organic levels are known to mobilise ^{137}Cs and these conditions fit those in the modern Coorong. In two wetlands these recent chronologies were also well supported by OSL analyses on the clay fraction. In some samples however, there was insufficient luminescence to gain a plausible date. The results of some samples were verified by identical results from two laboratories, one utilising bulk sediment and the other single grains. In one sequence (wetland 11), aware of the influence of sediment pore water content on the radiation dose, dates were provided for both lake full, and lake dry, scenarios. In the absence of independent water level data this effectively provides additional error margins to the determined dates (Gell et al., 2007). The first evidence of *Pinus* pollen in the cores was compared to the ^{210}Pb derived ages. In Tareena Billabong, pine pollen was identified from sediments considered to be equivalent to ~1880 AD however, in the Coorong sequences, the arrival of pine pollen was estimated to have been as late as the 1950s AD.

Due to the particular challenges inherent in dating sediment sequences from floodplain wetlands, the sedimentation rates are estimated based on the most plausible chronologies. The sedimentation rates reported here are, therefore, not definitive and, given the highly variable hydrologic context, may remain so until new techniques can be applied to this temporal 'blind spot' (Fitzsimmons et al., 2008). The typical pre-European settlement sedimentation rates are between 0.1 and 1.0 mm/yr. Unless the radiocarbon dates returned for Murroondi Wetland substantially underestimate the age of the basal sediments, then the baseline sedimentation for this wetland is 2–3 mm/yr (Gell et al., 2005a), probably augmented by the sediment trapping role of wetland macrophytes. In many wetlands recent sedimentation rates are near 10 mm/yr and, at Pikes Creek, 30 mm/yr (Gell et al., 2006). The estimated changes to net sedimentation rates ranged from two to three-fold increases to 20 fold in the floodplain lakes and 80 fold in the terminal wetlands of the Coorong (Fluin et al., 2007).

The fossil diatoms archived in sediments provide evidence of changing wetland condition. Taxa known to prefer salinity concentrations in excess of 3 g/l became common components of the diatom flora at Tareena Billabong from ~1880 AD (Gell et al., 2005b). In the Murrumbidgee wetlands several planktonic forms widely known to inhabit eutrophic waters are restricted to the upper sediments, but in several instances, pre-dating the arrival of exotic *Pinus* pollen (Gell and Little, 2006). In the sediment sequences of wetlands close to the main river, a substantial rise in the abundance of *Aulacoseira* spp., planktonic diatoms abundant in the main river (Tibby and Reid, 2004) may mark the beginning of river regulation (sensu Reid et al., 2002). Taxa known to dominate in disturbed, turbid conditions became common elements of the diatom flora of several of the lowland wetlands from early European settlement. Both of the latter two groups however, have shown to be abundant in some of the wetlands for centuries before the arrival of European settlers.

5. Discussion

Most wetlands along this Murrumbidgee–Murray River continuum exhibit pre-European sedimentation rates in the order of 0.1–1.0 mm/yr. Rates in excess of 1.0 mm/yr occurred in large meanders that were scoured deeply in the mid-Holocene. In all sites with the dating strength to allow comparison, the post-European sedimentation rates increased, in some instances by almost two orders of magnitude. Early post-European sedimentation rates were as high as 20 mm/yr in sites impacted by nearby sheep runs (Gell et al., 2005b). These declined post regulation owing to the trapping of coarser sediments behind weirs and reduced supply of mobile soils. Recent rates as high as 10–30 mm/yr are occurring, possibly driven by the increased sensitivity of floodplain surfaces to erosion through drought and increased sodicity. Given the shallow nature of many wetlands, and the elimination of medium level floods (Jones et al., 2002), the terrestrialisation of wetlands is likely to proceed at a pace greater than wetland renewal.

Lowland, limestone-rich landscapes are challenging sites to derive robust sediment chronologies (Gell et al., 2005a). This is due to the episodic transport of sediment, elevated wetland salinity concentrations and natural and artificial wetting and drying regimes. Despite this, plausible chronologies can be established by utilising a range of dating techniques. These chronologies can be supported by the assembly of a set of paleorecords that identify regional patterns in microfossil assemblage changes. Once established, the arrival of exotic pollen biomarkers and switches to river plankton-dominated assemblages can be used as corroborative evidence to support independent radiometric-based time lines. The pursuit of additional, more definitive, chronometers, is a focus of future collaborative research (Fitzsimmons et al., 2008) and will allow for the refinement of estimated sedimentation rates and allow better analysis of the timing of change and responsiveness of systems relative to the pre-European settlement baseline.

Lowland systems aggregate the sediments, nutrients and salts derived from the impact of humans on landscapes up-catchment as well as those derived nearby. The interrelationships between salinisation, erosion and nutrient release (Prosser et al., 2001) make it difficult to attribute changes in sensitive microfossils to particular drivers of change, and so to particular changes in land use. The abundance of diatom species such as *Cyclotella meneghiniana* or *Staurosirella pinnata* may increase under combinations of higher water turbidity, salinity and nutrient concentrations. The expansion of calibration data sets linking diatom taxa with water quality and wetland habitat will increase the capacity to make inferences of change from diatom assemblages. The extension of the suite of organisms extracted from sediment sequences will better reveal the ecological impacts of this phase of accelerated sediment, salt and nutrient flux to floodplain wetlands.

6. Conclusion

The natural, pre-European settlement sedimentation rate in most wetlands examined in this review was low with some sites accumulating as much as 2–3 mm/yr. Sedimentation rates increased soon after settlement and, at some sites, continue to increase to the present. While regulation may be limiting the flux of sediments down the river channels, other allochthonous, as well as autochthonous material are the likely sources. The restoration, or even rehabilitation, of these wetlands needs to recognise the threat of accelerating terrestrialisation and will require an understanding of the main sources of sediment supply.

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