Extreme water level decline effects sediment distribution and composition in Lake Alexandrina, South Australia

Dominic Skinner^{1,}, Rod Oliver², Kane Aldridge³, Justin Brookes³*

¹ School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, South Australia, 5005. Present Address: Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria, 3010, Australia

² Commonwealth Scientific and Industrial Research Organisation, Glen Osmond, South Australia, 5064, Australia

³ School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, South Australia, 5005.

* To whom correspondence should be addressed: dominic.skinner@unimelb.edu.au

Abstract

Water level decline affects the biophysical environment of shallow lakes. Unprecedented drought in Australia's Murray-Darling Basin resulted in extreme water level drawdown in the large, shallow Lake Alexandrina at the end of the River Murray. Surface sediment was collected from 22 sites in the lake before and after water levels declined to assess the integrated limnological changes over the period of drawdown. Results indicate an increase in the proportion of organic particles in profundal sediments, as well as an increase of fine particles (<19.9 µm) in peripheral sediments. These changes to sediment composition corresponded to higher concentrations of suspended particles at low water levels. Increased autochthony and a shift in primary production from macrophytes to phytoplankton in Lake Alexandrina support these findings. Inorganic carbon and other nutrients were lost from sandy sediments most likely through carbonate dissolution driven by a localized decrease in porewater pH from increased mineralization of organic matter.

Keywords: Drought, shallow lakes, carbon, sediment redistribution, sediment resuspension

37 **Introduction**

38 In semi-arid regions, rainfall variability exposes lakes to fluctuations in water
39 level that are forecast to increase in frequency and magnitude with climate
40 change and greater demand for water resources (Wetzel 1992; Vörösmarty *et*
41 *al.* 2000; Vörösmarty & Sahagian 2000). As sediments integrate changes to a
42 lake, they can be a good indicator of ecosystem responses to external changes
43 including water level decline (Williamson *et al.* 2009).

44 The recent (1997-2010) drought in southeastern Australia was unprecedented
45 in recorded history, having an estimated return interval of 1 in 1500 years
46 (Timbal 2009; Gallant & Gergis 2011). This led to severe basin-wide water
47 shortages (Leblanc *et al.* 2009) and to extreme water level decline in Lake
48 Alexandrina – a large, shallow, eutrophic system at the end of the River Murray
49 in South Australia (Figure 1; Skinner 2011). Five barrages, that separate
50 freshwater in Lake Alexandrina from a downstream estuary were constructed in
51 the 1930s and have kept water levels constant until 2006, with fluctuations less
52 than 0.4 m in previous droughts. However, between 2007 and 2009, water
53 levels dropped by 1.7 m, from +0.6 m AHD (Australian Height Datum, where 0
54 m is the average sea level recorded between 1966-68) in February 2007 to -1.1
55 m AHD in April 2009, as 64% of the lakes' volume was lost (Table 1).

56 Thus far, studies analyzing this extreme event have focused on changes to
57 water quality (e.g. Aldridge 2011; Mosley *et al.* 2012), the geochemistry of
58 exposed pyritic sediments that acidified pore-waters of some fringing wetlands
59 (Simpson *et al.* 2010), or management priorities (Kingsford *et al.* 2011). In this
60 study, our objective was to compare the changes to the distribution and

characteristics of surface sediments in Lake Alexandrina before and after the extreme water level declines. This enabled us to assess the extent to which sediments integrated the changes to water quality over the period of drawdown. Decreased bio-availability of both nitrogen and phosphorus during partial drying contrasts with a major release of both nutrients from the sediment upon complete desiccation (Baldwin & Mitchell 2000). Similarly, the effect of water level decline on sediments that remain submerged can occur through multiple, opposing mechanisms. Increased scouring from peripheral sediments (Gottgens 1994; James *et al.* 2001; Effler & Matthews 2004; Furey *et al.* 2004) contrasts with the higher volume of particle deposition resulting from a greater proportion of lake sediments exposed to sufficient wind shear to undergo frequent cycles of resuspension and deposition (Nagid *et al.* 2001; Håkanson 2005). Inundated peripheral sediments are thus simultaneously exposed to higher levels of oxic porewater recycling (Webster 2003) and organic material available for mineralisation (Den Heyer & Kalff 1998; Canavan *et al.* 2006).

Methods

Sediment sampling

Single sediment samples were collected from 22 sites in February 2007 as part of an earlier study by Aldridge *et al.* (2009). The same sites were revisited in February 2009 (Figure 1) and sampled in triplicate after water levels had fallen from +0.6 m AHD to -0.9 m AHD. Sites were relocated with a Garmin Global Positioning System (± 3 m accuracy). This allowed a simple before-after impact

study design of changes to surface sediment characteristics with water level decline.

After water level decline, nine peripheral sites were above the waterline, but were sampled nonetheless. These sites were classified according to their level of connectivity with the lake as either dry (5 sites), or still wet as a result of wind-induced seiching (4 sites). This left 3 sites that remained inundated and that were also classified as 'erosion' sediments according to the framework proposed by Håkanson and Jansson (1983) whereby the sediments had water content below 50%. The remaining 10 sites were also inundated, but were classified as 'accumulation' sediments, according to Håkanson and Jansson (1983) with water content above 50%.

Sediment cores, approximately 20 cm in length, were collected using a cylindrical PVC corer (internal diameter 5.8 cm). The corer was pushed into the sediment, sealed on top and raised vertically out of the sediment. The overlying water, when present, was siphoned off, sediment was extruded using a piston and the topmost 1 cm was homogenised and stored on ice in the dark until return to the laboratory. Under normal water levels, a long-term sedimentation rate of 3 mm yr⁻¹ in Lake Alexandrina (Herczeg *et al.* 2001) suggests that the topmost 1 cm of sediment represents approximately 3 years of deposition.

An aliquot of fresh sediment (~6 g) was diluted for analysis of sediment particle size distribution (PSD) using a Laser In-Situ Scattering and Transmissometry instrument fitted with a cuvette (LISST-100, Sequoia Scientific, Washington). Each sample was suspended in deionised water (20 mL), shaken to disaggregate any weakly flocculated particles and further diluted until laser

transmission was greater than 30% to avoid multiple scattering (Agrawal *et al.* 2008). PSD data were reported as the proportion of total volume concentration of particles in six size categories: <4.43 μm (clay), 4.43 – 6.24 μm (very fine silt), 7.36 – 19.9 μm (fine silt), 23.5 – 63.3 μm (silt), 74.7 – 186 μm (fine sand), and >219 μm (sand). A second aliquot of fresh material was sieved through a 600 μm stainless steel mesh to test for the presence of larger particles.

Sediment water content (WC) was determined with the remaining sediment after drying to constant weight at 55°C. Organic matter content (OMC) was determined gravimetrically following combustion at 550°C to constant weight and reported as a percentage of dry weight (Boyle 2004; Eaton *et al.* 2005) or wet weight for use in bulk density calculations. Total carbon (TC) and total nitrogen (TN) were determined by combustion to 1300°C with a LECO CNS 2000 Analyzer (Environmental Analysis Laboratory, Southern Cross University, New South Wales, NATA endorsed). Total phosphorus (TP) was determined following digestion at 150°C in aqua regia and analysis of the supernatant with inductively coupled plasma-atomic emission spectrometry (Waite Analytical Service, University of Adelaide, South Australia).

Organic carbon (OC) was estimated by dividing organic matter by a standard conversion factor of 1.7 (see Brady 1984, Boyd 1995). This assumes that the proportion of inorganic carbon was constant across all sediment types, which was supported by the high correlation between OMC and total nutrient concentration ($r^2 \geq 0.89$ for all OMC-nutrient combinations). Inorganic carbon (IC) was calculated as the difference between TC and OC, unless OC was greater than TC, in which case IC was assumed to be zero.

131 *Water sampling*

132 Monthly depth-integrated water samples were collected from the middle of Lake
133 Alexandrina between December 2006 and December 2009. Suspended
134 Particulate Matter (SPM) was measured gravimetrically after filtering a known
135 volume of water. Suspended Organic Matter (SOM) was determined by
136 difference after combustion of SPM as for sediments.

137 *Data analysis*

138 Bulk density was calculated from WC and OMC according to the formula of
139 Håkanson and Janson (1983)

$$\rho = \frac{100 * \rho_m}{100 + (WC + IG_o) * (\rho_m - 1)}$$

140 where ρ_m is the density of inorganic particles taken to be 2.6 and IG_o is the
141 OMC reported as a percentage of fresh weight. This calculated bulk density was
142 used to convert TC, OC, IC, TN and TP from mg g^{-1} to g cm^{-3} .
143 Triplicate data from sediment samples in 2009 were averaged before statistical
144 comparison with 2007 data. Lake-wide changes were compared by matched
145 pairs t-tests for sites pre- and post- water level decline. Analysis revealed two
146 distinct sediment types, so interactions and differences in characteristics
147 between sediment types and between sampling years were tested using a two-
148 way ANOVA. When significant interactions were found, a comparison of means
149 using Tukey's HSD post hoc test was performed. Differences between sediment
150 types in the same year were tested with a one-way ANOVA and Tukey's test.
151 All statistical analyses were conducted with JMP-IN 8.0 (SAS Institute Inc.) with

152 an α of less than 0.05 deemed significant. Normality was tested with the
153 Shapiro-Wilk test for goodness of fit and data were log-transformed where
154 necessary.

155 **Results**

156 The WC of Lake Alexandrina sediments increased with water depth, as did
157 OMC. Bottom substrate was bimodal, transitioning from an erosion bottom
158 (<50% WC) to an accumulation bottom (>50% WC) according to the framework
159 proposed by Håkanson and Jansson (1983). This corresponded with changes
160 to the physical appearance of sediments from coarse sandy sediments under
161 shallow water to soft black mud under deeper water. The transition occurred at
162 a water depth of approximately 2.5 m in 2007 and at a depth of 1.4 m in 2009,
163 reflecting the decline in water levels. WC was significantly related to OMC both
164 before and after water level decline (Figure 2).

165 Matched pairs, two-way ANOVA and subsequent post-hoc analysis showed
166 significant changes in sediment properties that coincided with declining water
167 levels (Table 2). Lake-wide changes included a loss of TC and IC, as well as a
168 reduction in coarse sand particles and a corresponding increase in clay, very
169 fine silts and fine silts. The OMC and OC of sediment in the accumulation zone
170 were higher after water level had declined, as was the amount of clay, very fine
171 silt, and fine silt (Table 2). The concentration of fine sand decreased after water
172 level decline for sediment in the accumulation zone. For sediment in the erosion
173 zone below shallow water, there was an increase in fine silt after water levels

had declined. TP, TN, TC and IC decreased significantly in the same sediment after water level decline.

The inorganic proportion of nutrients decreased after water level decline in all sediments, which was made clear by the shift in the intercept of regressions towards zero (Figure 3). Regressions of OMC with sediment nutrients (Table 3) showed that for accumulation sediments, TC, TN and TP were significantly related to OMC in both sampling years. However, for erosion sediments, only TC showed a significant regression with OMC after water levels had declined, but not before. In addition, TC and IC were lost from all erosion sediments, regardless of their level of connectivity with the lake (Figure 4).

Water samples collected over the period of drawdown showed an increase in both SPM and SOM (Figure 5). Regression between SPM and water level was significant ($r^2 = 0.38$, $p = 0.05$), as was that between SOM and water level ($r^2 = 0.60$, $p < 0.05$).

Discussion

Sediments in Lake Alexandrina were characteristically bimodal both before and after water level decline. Peripheral sediments below shallow water were sandy and had a large grain size with low water and organic content. Profundal sediments were black and composed of fine grains with high water and organic content. However, an increase in the concentration of fine particles in peripheral sediment and organic matter in profundal sediments corresponded with water level decline. This is in contrast to previous studies that showed declining water

level increase the erosion and removal of fine sediments and organic matter in peripheral sediments of shallow lakes (Gottgens 1994; James *et al.* 2001). As water levels decline, the resuspension and redistribution of sediments can increase if the downward movement of the wave-mixed layer towards the sediment surface influences a larger area (Nagid *et al.* 2001), or disturbs sediments that are more easily resuspended (Håkanson 2005). Following water level decline in Lake Alexandrina, fine sediments (7.36 – 19.9 μm) were significantly more prevalent in sediment below shallow water, but OMC was unchanged. Increasing suspended particulate matter in the water column as water levels declined, and initial modeling by Mosley *et al.* (2012) showing median wind speeds over Lake Alexandrina would overcome the critical shear stress of fine sediments at water levels of about -0.1 m AHD, both suggest that fine profundal sediments were becoming more frequently resuspended and redistributed following drawdown.

A fivefold decrease in the carbon content of peripheral sediments and a decrease of similar magnitude for nitrogen and phosphorus content with water level decline contrasted to the unchanged nutrient concentration of profundal sediments. This corresponded to a shift in nutrient composition of peripheral sediments from inorganic prior to water level decline, to an organic form after. Cook *et al.* (2009) showed that Lake Alexandrina has historically transformed soluble, inorganic fluvial-derived nutrients into organic nutrients. The conversion was hypothesized to have occurred by the assimilation and growth of phytoplankton, which subsequently settled onto the bottom substrate. During the drought-induced low inflows in this study, particulate nutrients were shown

to become concentrated and to accumulate in Lake Alexandrina (Mosley *et al.* 2012). According to Meyers and Ishiwatari (1993) sediments with C:N ratios between 7 – 11 are indicative of aquatic plant remains and ratios of 4 – 10 indicate phytoplankton material. Before water level declined, C:N ratios for peripheral sediments were about 15 and were above 9 for profundal sediments. After water level declined, profundal sediments had C:N ratios of 7-8, while peripheral sediments had ratios of 4 – 6.5. The combination of receding shoreline and increasing salinity also extirpated all submerged macrophytes in Lake Alexandrina by 2008 (Gehrig *et al.* 2011). Given this, it appears that recently deposited or transported algal matter has become the predominant source of nutrients in sediments after water levels in Lake Alexandrina had declined.

The loss of total carbon without any corresponding decline in organic matter in peripheral sediments suggests that inorganic carbon, most likely in the form of carbonates, was depleted during water level decline. While there was well-documented oxidation and acidification of sulfidic sediments that became exposed to air around Lake Alexandrina (Simpson *et al.* 2008; Kingsford *et al.* 2011), we don't believe the resultant decrease in pH of pore water explains our observation of inorganic carbon loss for several reasons. For a start, sediments that did acidify in Lake Alexandrina during the course of this study were limited to isolated fringing wetlands, tributary creeks and lagoons near the barrages (EPA 2009). In addition, the loss of inorganic carbon occurred in sediments that remained inundated and were thus not exposed to the atmosphere. It is plausible that some of the peripheral sediments that became unsaturated during

the water level drawdown lost inorganic carbon due to acidification due to pyrite oxidation (Fitzpatrick et al. 2010). However, it is likely that this process relates to only a small number of our sites. Finally, water quality analysis showed that pH remained above 8, alkalinity was above 180 mg/L CaCO₃ equivalents and the saturation index for calcium carbonate in water remained positive (Skinner 2011), indicating that the water column was over-saturated with respect to calcium carbonate and that precipitation of calcium carbonate was likely (Cole et al. 1994).

Other possibilities could explain the loss of inorganic carbon from peripheral sediments. Firstly, declining water levels have resulted in increased salinity (Mosley et al. 2012) that led to an increase in the concentration of magnesium in the water column (EPA 2013). Magnesium has been shown experimentally to inhibit calcite precipitation through surface disruption of the crystallisation process (Morse et al. 1997; Zhang & Dawe 2000) and a concomitant increase in the solubility of the resultant mineral (Möller & Parekh 1975). Similar disruptions to the crystal lattice formation of calcium carbonate from dissolved and particulate organic substances have been empirically established (Hoch et al. 2000). Secondly, pore water in surficial sediments becomes increasingly oxic through enhanced wave energy over shallower water (e.g. Webster 2003) that could increase the decomposition rate of organic matter. Morse et al. (1985) have shown neritic carbonate dissolution from sediments below marine waters over-saturated in calcium carbonate as a result of pore water mineralisation of organic matter and the resultant increase in local $p\text{CO}_2$. Finally, Müller et al. (2003) demonstrated that calcite in surface sediments of a freshwater lake

underwent dissolution that was driven by aerobic decomposition of organic carbon as the pH immediately below the sediment surface dropped. This observation occurred despite overlying water quality that would promote calcite precipitation (Müller *et al.* 2003). Further research and direct measurement of pH, dissolved oxygen and CaCO₃ in porewater would be required to confirm any specific mechanism of inorganic carbon loss from surface sediments.

Lake Alexandrina showed an increase in organic matter in profundal sediments over the period of water level decline. Increased dominance of phytoplankton would promote the accumulation of fine, organic-rich sediments that remain unconsolidated, provide poor substrate for macrophyte colonization, and hence are readily resuspended (Bachmann *et al.* 1999; Schutten *et al.* 2005; van Wichelen *et al.* 2007). During drought, external nutrient inputs from catchment runoff tend to decrease (Bond *et al.* 2008), which often leads to a transient clear water state in many shallow lakes as phytoplankton production is limited (Wallsten & Forsgren 1989; Havens *et al.* 2004; van Geest *et al.* 2007).

However, water level decline can also shift internal nutrient cycles towards an increase in total nutrient loads (Zohary & Ostrovsky 2011). If these changes are larger than the reduction in external nutrient supply, a lake can become eutrophied and turbid. The drought discussed in this paper increased nutrient concentrations in the water column due to evaporative concentration, a lack of flushing and increased productivity (Mosley *et al.* 2012), which was observed as an increase in organic deposition.

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304 **Table 1: Physical characteristics of Lake Alexandrina when full and after water level decline.**

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307 **Table 2: Changes to sediment characteristics as shown by matched pair t-tests for all sediments,**
308 **and a comparison of means from the two-way ANOVA with Tukey's HSD post hoc analysis**
309 **between sediment type and sampling date. All data shown with $\pm$ standard error and an asterisk to**
310 **denote significance.**

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312 **Table 3: Linear regression results of OMC with sediment nutrients before and after water level**
313 **decline. An asterisk indicates a significant regression.**

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330 **Figure 1: Map of Lake Alexandrina showing sediment sampling locations (●). Water samples were**
331 **collected at the x. The five barrages are shown by thick black bars.**

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334 **Figure 2: The effect of water depth (top) and sediment organic matter content (bottom) on water**
335 **content of sediment before and after water level decline.**

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338 **Figure 3: Regressions of sediment nutrients (total carbon, top; total nitrogen, middle; total**
339 **phosphorus, bottom) against sediment organic matter content.**

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341 **Figure 4: Box plots of total carbon for different sediment groups both before and after water level**
342 **decline. Error bars show the range of all total carbon measurements, the top and bottom of the box**

343 show the 25th and 75th percentile of total carbon distribution, and the centre line within each box
344 indicates the median total carbon for each category.

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346 **Figure 5: Water level decline increased concentration of suspended particulate matter and**
347 **suspended organic matter. Data taken from the middle of Lake Alexandrina.**

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510 **Table 2: Physical characteristics of Lake Alexandrina when full and after water level decline.**

Morphological parameter	Before Water Level Decline	After Water Level Decline
Surface area	580.6 km ²	420.1 km ²
Volume	1550 GL	480 GL
Mean depth	2.9 m	1.1 m
Maximum depth	4.1 m	2.45 m
Surface elevation	0.6 m above mean sea level	0.9 m below mean sea level

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514 **Table 2: Changes to sediment characteristics as shown by matched pair t-tests for all sediments,**
 515 **and a comparison of means from the two-way ANOVA with Tukey's HSD post hoc analysis**
 516 **between sediment type and sampling date. All data shown with ± standard error and an asterisk to**
 517 **denote significance.**

Parameter	Units	Increase after water level decline...	Average value for sediment types			
			Erosion		Accumulation	
			Before	After	Before	After
Organic Matter Content	%	1.99 ± 4.79	0.4 ± 1.2	0.9 ± 0.6	7.87 ± 1.3	12.6 ± 0.7*
Bulk Density	g.cm ⁻³	0.067 ± 0.27*	2.0 ± 0.05	2.0 ± 0.03	1.19 ± 0.06	1.2 ± 0.03
Clay	μL.L ⁻¹	2.02 ± 2.57*	0.1 ± 0.6	0.9 ± 0.3	2.76 ± 0.7	6.8 ± 0.4*
Very Fine Silt	μL.L ⁻¹	4.35 ± 4.15*	0.1 ± 0.5	1.3 ± 0.2	2.12 ± 0.5	10.8 ± 0.3*
Fine Silt	μL.L ⁻¹	13.45 ± 11.12*	0.8 ± 1.5	6.3 ± 0.8*	12.79 ± 1.6	37.7 ± 0.9*

Silt	$\mu L.L^{-1}$	-2.3 ± 7.4	2.6 ± 2.2	7.1 ± 1.1	35.04 ± 2.3	28.3 ± 1.3
Fine Sand	$\mu L.L^{-1}$	$-10.88 \pm 16.24^*$	43.9 ± 4.2	35.9 ± 2.1	33.63 ± 4.4	$12.7 \pm 2.6^*$
Sand	$\mu L.L^{-1}$	-6.65 ± 15.46	52.5 ± 5.6	48.5 ± 2.8	13.67 ± 5.9	3.7 ± 3.4
Total Phosphorus	$mg.cm^3$	$-0.096 \pm 0.166^*$	0.18 ± 0.02	$0.05 \pm 0.008^*$	0.47 ± 0.05	0.44 ± 0.04
Total Nitrogen	$mg.cm^3$	-0.73 ± 2.29	1.74 ± 0.2	$0.52 \pm 0.03^*$	4.87 ± 0.5	4.98 ± 0.5
Total Carbon	$mg.cm^3$	$-13.65 \pm 18.5^*$	22.43 ± 1.3	$4.64 \pm 0.8^*$	44.4 ± 4.4	38.01 ± 3.9
Organic Carbon	$mg.cm^3$	$14.5 \pm 28.3^*$	4.88 ± 0.5	60.33 ± 13.1	56.34 ± 7.04	$37.97 \pm 8.3^*$
Inorganic Carbon	$mg.cm^3$	$-9.64 \pm 9.36^*$	17.56 ± 1.3	$0.09 \pm 0.06^*$	1.72 ± 1.6	$20.86 \pm 4.4^*$
C : N ratio		-7.04 ± 16.1	30.36 ± 6.2	8.70 ± 1.5	11.14 ± 1.1	7.63 ± 0.03
N : P ratio		$7.54 \pm 13.33^*$	22.04 ± 3.1	17.03 ± 1.4	12.31 ± 0.69	11.34 ± 0.3

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520 **Table 3: Linear regression results of OMC with sediment nutrients before and after water level**
521 **decline. An asterisk indicates a significant regression.**

OMC regressed with:	Before water level decline		After water level decline	
	<i>Slope</i>	<i>r</i> ²	<i>Slope</i>	<i>r</i> ²
Erosion				
TC	0.47	0.09	0.21	0.70*
TN	-0.07	0.12	0.006	0.25
TP	0.002	0.004	0.0006	0.04
Accumulation				
TC	0.30	0.69*	0.31	0.96*
TN	0.04	0.88*	0.04	0.95*
TP	0.003	0.71*	0.003	0.90*

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Author/s:

Skinner, D;Oliver, R;Aldridge, K;Brookes, J

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