AN ENVIRONMENTAL HISTORY OF THE LOWER LAKES AND THE COORONG

Frontis: Tauwitchere Barrage presently separates the freshwaters of Lake Alexandrina (right) with those from the Coorong (left)

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Executive Summary

This report reviews the diatom-based evidence for the history of salinity and pH in Lake Alexandrina and The Coorong. Diatoms are a type of aquatic algae that have species compositions highly influenced by the salinity and pH of their host waters. In addition, because they build their cell wall from silica, diatoms preserve in sediment. Hence, by examining the species composition of diatoms in dated sediment cores, it is possible to obtain a record of pH and salinity change through time.

Our review has found for Lake Alexandrina:

- There is no evidence in the 7000 year record of substantial marine incursions into Lake Alexandrina.
- In addition, there is no evidence in the Lake Alexandrina record of any periods of significant acidification events. Indeed, our evidence suggests that pH at the sites examined has always remained well above seven.
- There were substantial alterations to the diatom community in Lake Alexandrina following European settlement and particularly after barrage installation.

Our review of The Coorong has found that:

- The pre – European diatom flora from The Coorong is dominated by diatoms associated with marine and estuarine environments
- Diatoms derived from the River Murray and Lake Alexandrina penetrated no further south than Noonameena in the North Coorong Lagoon
- These data suggest that the primary role of River Murray discharge was to:
    - keep the Murray Mouth open and allow sea water into The Coorong
    - generate estuarine conditions at the northern end of the North Lagoon during high flow periods
    - facilitate circulation and mixing in the North Lagoon such that salinities were maintained at or below those of seawater
- Fresh / brackish surface and groundwater flows from the South East region played a major role in controlling salinity levels in the South Lagoon
- The post – European diatom floras in The Coorong are substantially different to those of the pre – European and suggest a widespread increase in salinity

Project Background

Despite being Australia's largest river basin, the Holocene climatic and environmental history of the Murray River is surprisingly poorly known. These knowledge gaps are highly problematic in a policy setting in which governments, environmental managers and stakeholders seek to know whether the current period of low inflow has any precedent. It is axiomatic that the Murray Darling Basin provides a very large part of Australia's agricultural production, with an estimated $15 billion in agricultural production in 2005-2006 (with approximately 40% of the National total derived from the Basin). However, in recent years, this production has been dramatically curtailed due to a lack of water availability. Assessments of future water availability in the Basin predict reduced availability, but still suggest that prolonged dry periods such as those experienced at present will be rare. However, the natural frequency and length of extended dry periods is not known.

This report provides a reconstruction of environmental variability within the Lower Lakes and The Coorong, an ecosystem which reflects the end result of upstream Basin processes. The review concentrates on the recent past (500 years) but extends into the early Holocene (last 8000 years). An understanding of the long-term dynamics of this system is pertinent to successful management outcomes directed at rehabilitation. The national media, on a regular basis, reports differing opinions about the nature of the Lakes prior to barrage construction, with many purporting that opening the barrier between the two systems will simply return the system to its natural baseline (a brackish to marine system). Other reports, including the summation of archival, mainly oral history from the 1800s (Sim and Muller, 2004) suggest that the Lakes were always fresh, with negligible marine inflows. It is essential that this debate is informed as the proposed management options are costly and the many of the potential impacts are irreversible.

Methodology

A diatom based palaeolimnological approach was adopted to investigate the degree of historical connectivity between Lake Alexandrina and The Coorong and also the palaeo-salinity of these two systems. Diatoms were chosen as environmental proxies as they are strong salinity indicators (Gasse et al., 1995; Gell, 1997) and were known from previous work (Barnett, 1994; Fluin, 2002; Reid et al., 2002; Fluin et al. 2007) to be well preserved in the sediments of both environments.

Between 300 and 500 diatom valves were identified and enumerated from all cores, following Battarbee (2001), using an Olympus BH-2 microscope or an Eclipse 80i microscope, both with Normaski Differential Interference Contrast (DIC). Diatoms were identified by reference to the primary diatom floras (Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b) and Witkowski et al. (2001) as well as Foged (1978), Germain (1981), Archibald (1983), Gasse (1986) and John (1993).

Three cores were taken from Lake Alexandrina: one downstream of Wellington as the river enters the lake (LA1), one from the centre of the lake (LA2) and one behind the Goolwa Barrage (RS1). All cores were dated using conventional and accelerator mass spectroscopy (AMS) ^{14}C techniques and ^{210}Pb geochronology. Radiocarbon dates were calibrated to calendar years using the southern hemisphere atmospheric calibration data set of McCormac et al. (2004) with Calib 5.0.2. (Stuiver & Reimer, 2005). The ^{210}Pb activities of eleven samples from core LA1 and RS1 were determined by the Australian Nuclear Science and Technology Organisation (ANSTO). ^{210}Pb measurements were undertaken on core LA2 by Barnett (1994) at 2 cm intervals to a depth of 64 cm.

Thirty one sites spanning ~80 km down the length of The Coorong were cored. Sixteen have been subjected to a variety of analyses (see Table 1) and dating results and diatom data from 6 representative cores, 4 in the North Lagoon (NL), 2 in the SL are summarised here (see Figure 5). All cores were examined for the presence of exotic *Pinus* pollen, to identify sediments deposited since European settlement. Used in conjunction with the detection of ^{210}Pb and ^{137}Cs isotopes, the depth at which *Pinus* pollen appears has been confidently dated to 1955 ± 5 yrs AD in all Coorong cores, at depths that varied between sites and lagoons. Older sediments from 12 cores were dated using ^{14}C AMS and 5 of these were also dated using Optically Stimulated Luminescence (OSL) dating (see table 1). Radiocarbon dates were calibrated utilising OxCal v.4.0.5 (Bronk Ramsey, 2001); additional calibrations were applied to sediment samples using the southern hemisphere curve SHCal04 (McCormac et al., 2004); and to shell samples using the marine curve Marine04 (Hughen et al., 2004), incorporating a ΔR of 84 ± 57 years, determined from 3 Map No Sites (382, 390 and 391) (14CHRONO Marine Reservoir Database).

In the summary diagram of Coorong diatom data, taxa are classified as “non-marine” or “marine”. The five non-marine taxa are considered such in the sense that they are not known to reproduce in marine environments (*Aulacoseira* spp.); or their salinity tolerances

1) are <5‰ (*Cocconeis* spp.)
2) can range from brackish to saline (*Cyclotella* spp. and Fragilariaceae)
3) are unknown, but likely to be euryhaline-saline (*Fragilaria* sp. 10).

The remaining seven taxa are classified as marine, though some have salinity tolerances (15 – 35‰) and / or life strategies that advantage them in estuaries (*Cocconeis* spp., *Cyclotella striata*), or in coastal / lagoonal environments that may periodically have salinities >35‰ (*Paralia sulcata*), and may thus be classified as euryhaline – saline.

Results

Lake Alexandrina

The spatial representation of sediment cores attempted to capture the influence of marine incursion over time, as shown in Figure 1.

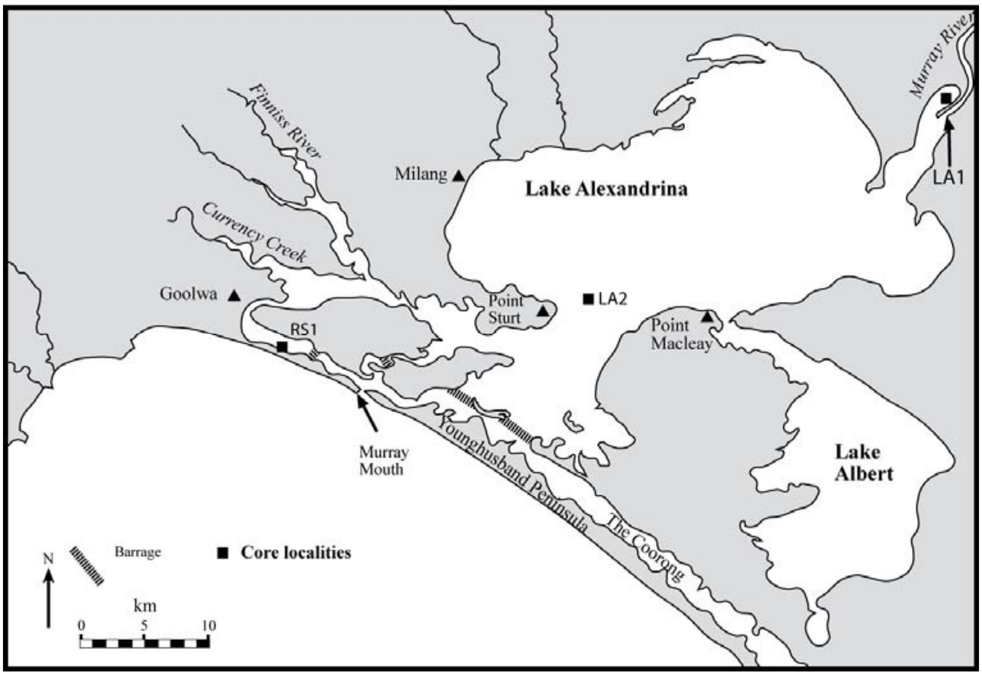

Figure 1: Location of Lake Alexandrina coring sites

Diatoms are the most accurate indicator of historical fluctuations in water quality, and for Lake Alexandrina, the parameters of most concern are EC and pH. Changes in salinity over time are likely to be a reflection of marine incursion with times of low river flow resulting in higher salinities and higher riverine flow resulting in restricted marine inflows. pH reconstructions are also of paramount interest due to the current concern of the impact of acidic releases from exposed sulphate soils. It is obviously beneficial to examine whether this acidification process occurred in the past and the extent of system resiliency.

Radiocarbon dating of all three cores shows the age of Lake Alexandrina to be about 7000 years old (coinciding with maximum sea levels at the height of the last marine transgression). This is supported by ages of 6765 ± 76 (7600 cal. yr B.P.) at the base of core LA1 and 7000±300 (7800 cal. yr B.P.) at the base of LA2. Core LA1 yielded three similar C^{14} dates at differing depths and it is highly probable that the ^{14}C analysis was probably influenced by the hard - water effect (Shotton, 1972), where sediment is contaminated with older carbon. This process, which can occur when aquatic plants take up aqueous bicarbonate derived from old, inert sources, is common in wetlands set in calcareous environments (Roberts, 1998) such as the lower River Murray. Sedimentation rates increase rapidly post barrage construction, increasing from < 1mm / year pre barrages to more than 3cm / year accumulating behind the Goolwa Barrage (RS1) since the 1940s.

Core RS1

There is a distinct change in the composition of the diatom assemblage in this sediment core, which coincides with the construction of barrages (see solid line on Figure 2). Pre – barrages, *Cocconeis peltoides, Cyclotella striata* and *Tryblionella punctata* are abundant but occur infrequently post barrage. The post barrage sediments are dominated by *Staurosirella pinnata*, *Pseudostaurosira brevistriata, Paralia sulcata, Campylodiscus clypeus* and *Staurosira construens* var. *venter*. *Staurosira construens* var *construens* and *Staurosirella pinnata* are present throughout the record, with *Staurosirella pinnata* abundance fluctuating throughout (increasing to 90 % at 120cm, before steadily decreasing to 50 % at 32 cm).There was a distinct change in diatom species composition post-barrage construction when connectivity with the marine environment ceased. *Cocconeis peltoides* and *Cyclotella striata* dominated when there was open passage between Lake Alexandrina and the river mouth, but when the barrages restricted marine flow, the diatom community switched to one dominated by *Campylodiscus clypeus* and *Paralia sulcata*. Although these taxa are still salt tolerant diatoms, they indicate a change from marine / hypersaline waters to brackish waters post – barrage installation. The diatom results support those of the foraminifera, with a switch from marine species as a substantial percentage of the diatom assemblage below 130 -150 cm, to species indicative of brackish riverine environments after barrage emplacement.

Core LA2

The base of the core LA2 (Figure 3), which is ~7000 years old, is dominated by *Cocconeis placentula* and *Aulacoseira granulata*, and to a lesser extent, *Thalassiosira lacustris*. The presence of *Thalassiosira lacustris, Cyclotella striata* and *Paralia sulcata* indicate minor marine influence at this time. At 420 cm, *Staurosirella pinnata* increases abruptly to nearly 40% at the expense of littoral, rather than planktonic, taxa. High values of *Staurosirella pinnata* are sustained through to the top of the core, other than at 260-300 cm depth, where they are briefly replaced by littoral taxa. *Aulacoseira granulata* also decreases between 380 cm and 220 cm, in part replaced by *Stephanodiscus parvus*. *Paralia sulcata* is absent above 340 cm and *Thalassiosira lacustris* has lower values at 260 cm, replaced briefly by littoral taxa, although the thalassic planktonic taxon, *Cyclotella striata*, remains common. This change in diatom community is likely to represent a decrease in lake level and increased penetration of more brackish water, possibly associated with the variable, dry climate phase after the mid-Holocene wet phase as identified by Stanley & De Deckker (2003), Bowler (1981), and others. This would then lead to lower abundance of riverine / fresh lake planktonic diatoms and an increase in littoral taxa, particularly benthic taxa, and a mixing or incursion of more brackish to marine planktonic taxa from areas closer to the river mouth.

The planktonic taxa *Aulacoseira granulata* and *Thalassiosira lacustris* increase at 220 cm, at the expense of the estuarine diatom *Cyclotella striata*, marking a strong river input to the estuary. The decline in *Thalassiosira lacustris* above 160 cm marks a further increase in freshwater river input conditions, perhaps influenced by the increases in precipitation witnessed in lake records in western Victoria (Jones et al. 1998). The subsequent decrease in *Aulacoseira granulata* from 80 cm, combined with the increase in *Staurosira construens* var *venter*, indicates reduced river input and lower lake levels. The greatest change to the diatom flora is again near the surface, at 30 cm, mostly attributable to a strong increase in *Pseudostaurosira brevistriata* coinciding with the estimated time boundary for the onset of river regulation. This increase is associated with a small decrease in *Staurosirella pinnata* that may be attributable to the barrages controlling tidal flux to the Lake favouring *Pseudostaurosira brevistriata*, which has a lower salinity tolerance than *Staurosirella pinnata* (Gell, 1997; Fluin, 2002).

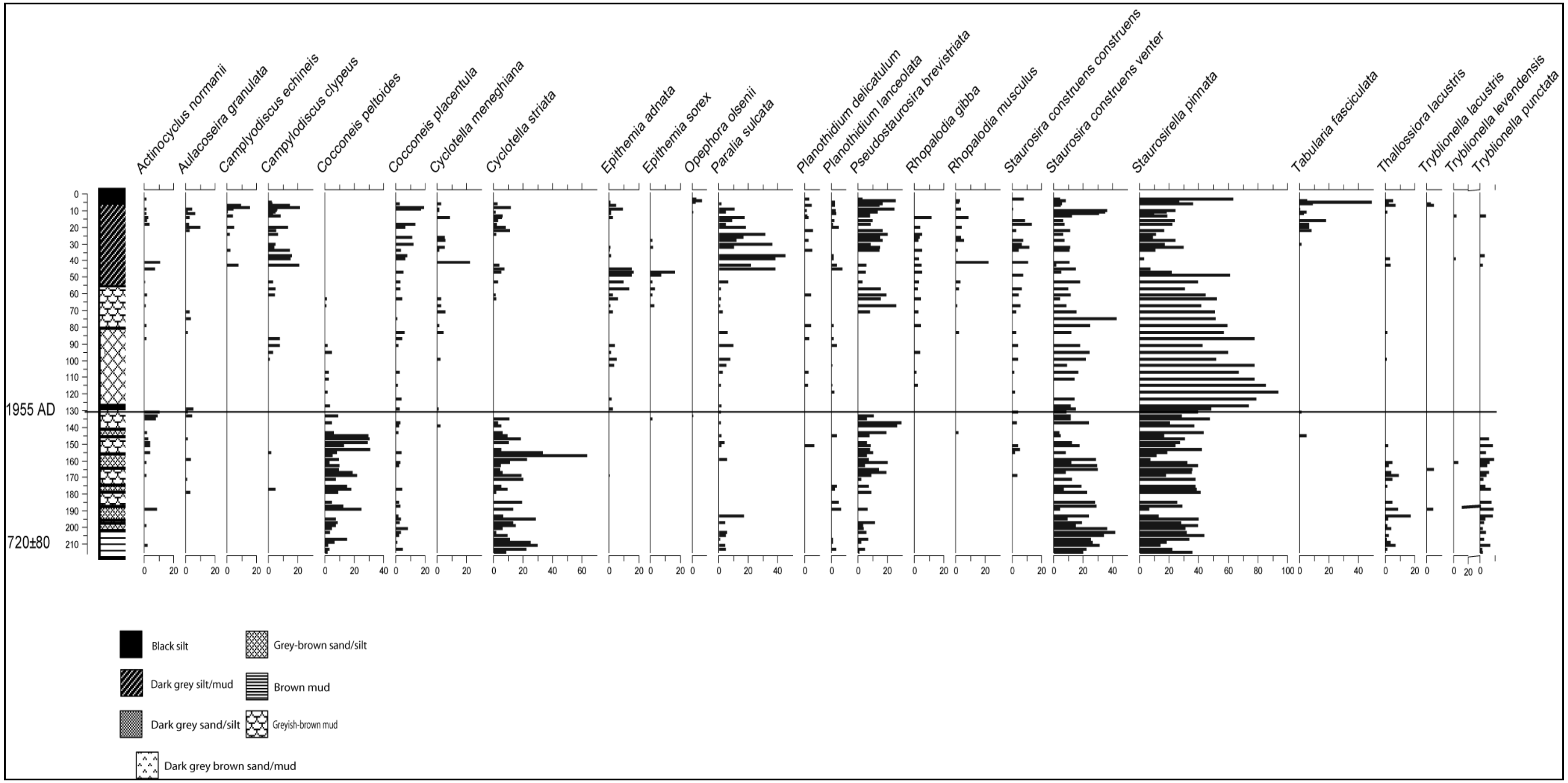

Figure 2: Summary diatom data from Lake Alexandrina core RS1

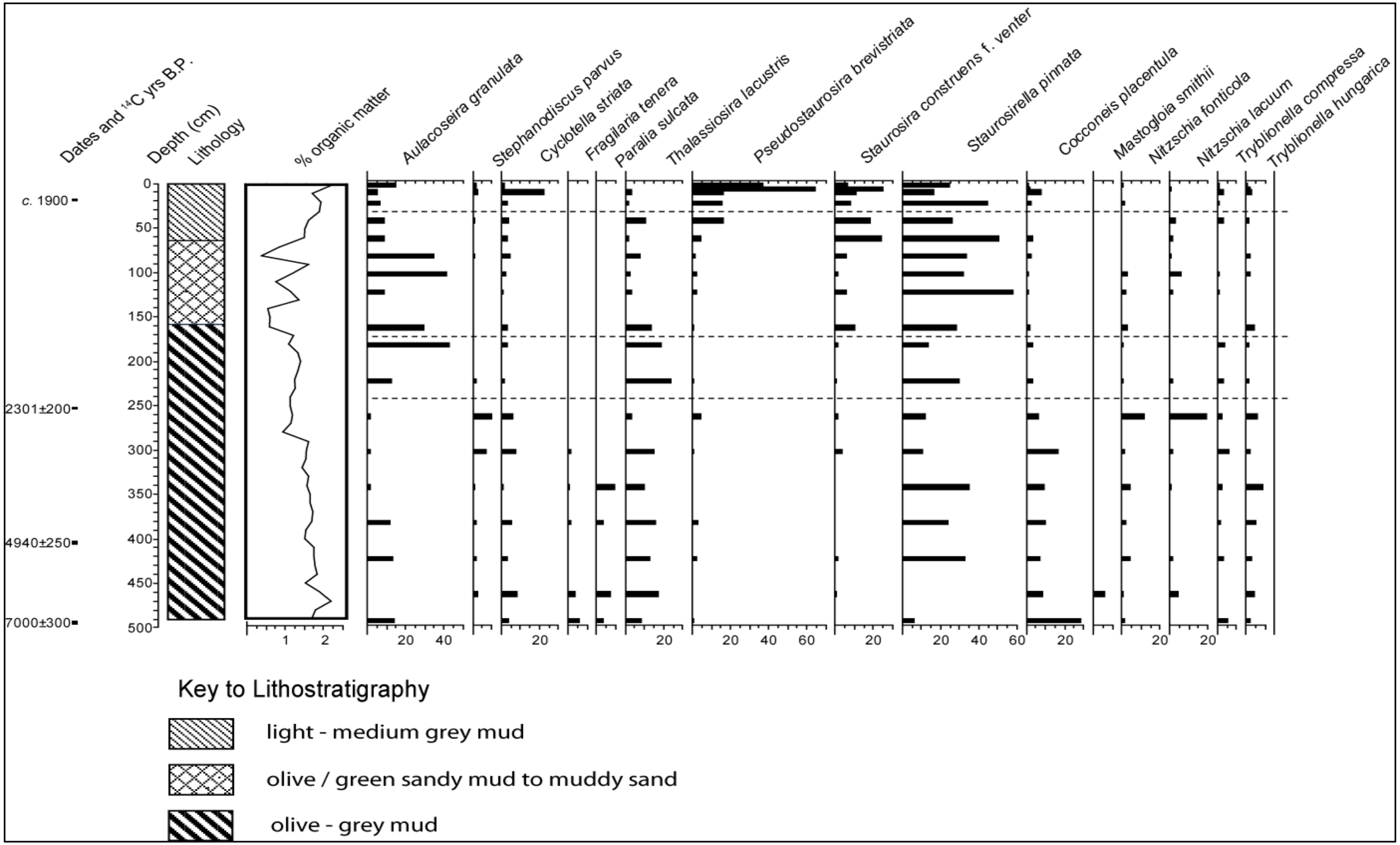

Figure 3: Summary diatom data from Lake Alexandrina core LA2

Core LA1

The base of core LA1 (Figure 4) is dominated by *Staurosirella pinnata*, *Epithemia adnata* and *Cocconeis placentula*, indicating a shallow, meso-eutrophic, reed fringed environment with fresh to brackish water in a pH range of 8.0 - 9.0. The diatom assemblage from 77 cm is dominated by *Staurosirella pinnata* that peaks at 70 cm (78%) and then decreases to < 10% at the top of the zone, being replaced by a range of benthic and epiphytic taxa. *Staurosirella pinnata* is gradually replaced by *Epithemia adnata* and *Rhopalodia gibba* - these two taxa accounting for > 70% of the total assemblage at 56 cm. This most likely reflects an increase in alkalinity and a reduction in water level. At 56 cm pH values probably exceeded 9.0, with high pH being conducive to valve dissolution, accounting for the diatom barren zone at 54 cm. Through this early phase the river plankton *Aulacoseira granulata* is regularly present, and, apart from a peak at 63 cm, thalassic forms (e.g. *Thalassiosira lacustris*) are absent.

Towards the middle of the core *Staurosirella pinnata* returns to dominance with *Melosira varians*, suggesting a deepening of lake waters. The peaks in *Aulacoseira granulata* suggest that this water is derived from river rather than tidal inflow. The flora is dominated by *Staurosirella pinnata* at 29 cm, after which this taxon declines to the top of the core. This decline marks a point of greatest change in the diatom community and represents the estimated time boundary of the onset of non-indigenous settlement. The epiphyte *Cocconeis placentula* replaces the facultative planktonic *Staurosirella pinnata* reflecting modification of diatom habitat availability, most likely an increase in abundance of aquatic plants (submerged and / or fringing). Additionally, the increase in abundance of some of the minor littoral taxa indicative of eutrophic to hypertrophic conditions (*Cymbella cistula*, *Gomphonema parvulum*, *Melosira varians*, *Rhopalodia gibba* and *Tabularia fasciculata*) reveals an increase in nutrient concentrations within the lake, probably by the late 1800s, most likely arising from human settlement. *Tabularia fasciculata* also reflects high lake water salinities, perhaps reflecting seepage from elevated saline water tables that occurred due to extensive vegetation clearance soon after non-indigenous settlement (Menzies, 1983), The peak in *Tabularia fasciculata* and the absence of *Aulacoseira granulata* at 11 cm is dated by ^{210}Pb to possibly occur early as the 1900s and so may correlate with the severe drought in south eastern Australia between 1914 and 1915 where river salinity at Morgan measured 10 000 EC (Eastburn, 1990). The eutrophic, littoral taxa, which increased in abundance in the early 1900s, decrease in the upper – most sections of the core. The other major changes in the recent past are an increase in *Aulacoseira granulata* and *Pseudostaurosira brevistriata* numbers, which are both still indicative of high nutrient concentrations. The decrease in littoral taxa may represent an improvement in trophic status, but the concurrent increases in eutrophic planktonic and facultative planktonic taxa indicate that nutrient concentrations remain high. Without further information (i.e. comparison with other biological fossil indicators), interpretation of the recent past from this site remains speculative.

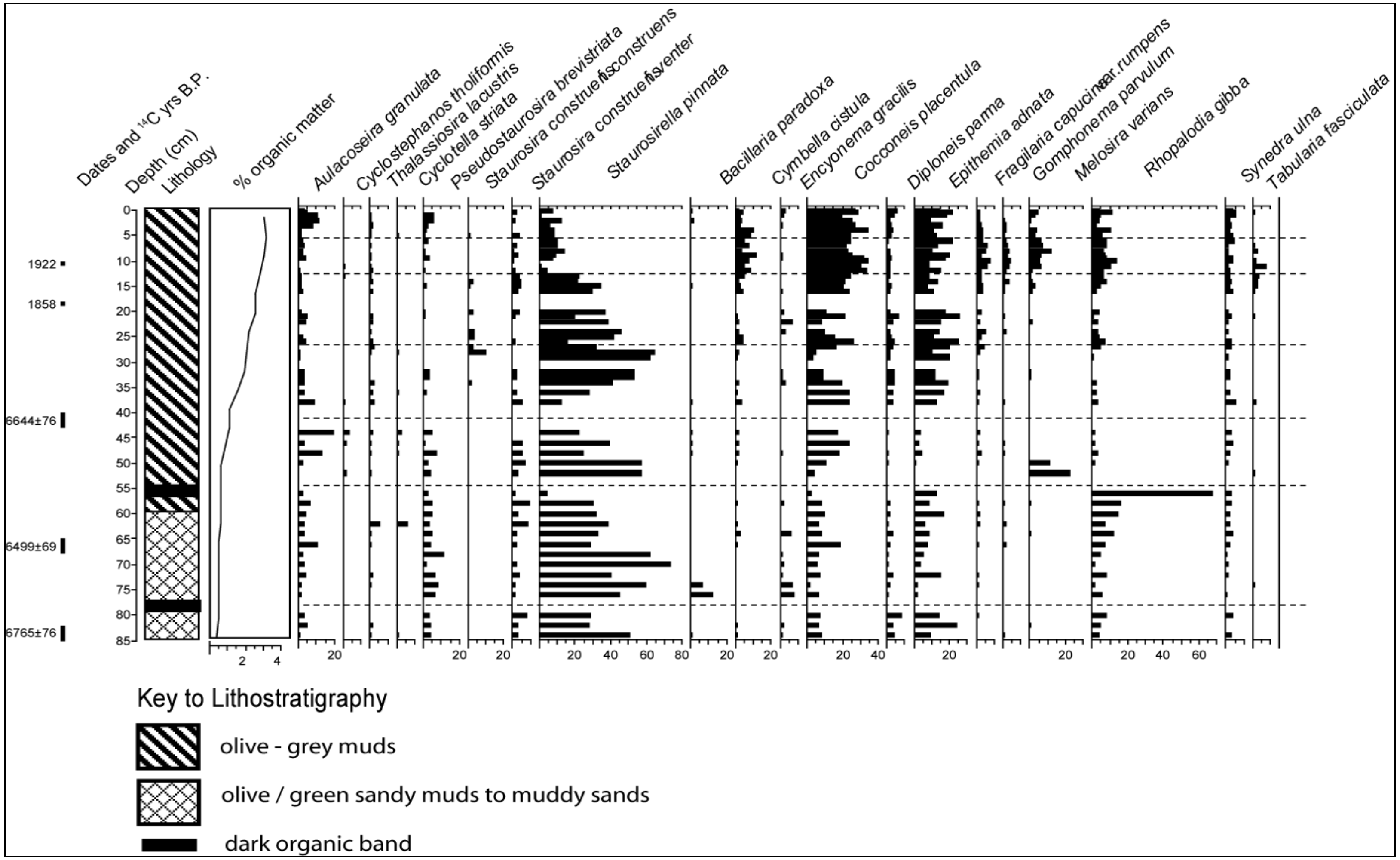

Figure 4: Summary diatom data from Lake Alexandrina core LA1

Lake Alexandrina summary

The three sediment cores show a clear continuum in both sedimentation rates and salinity levels in the lake over time. Core RS1 shows a very distinct change in diatom assemblages pre and post barrage. The pre – barrage diatoms are estuarine – marine, but with an absence of typical marine diatoms (such as are seen in The Coorong). Post – barrage, the diatom assemblages change completely, reflecting fresher, albeit still estuarine, conditions.

Moving up the Goolwa channel, to the location of core LA2, the change between pre and post – barrage conditions is not as marked. Over the 7000 year record, there are minimal numbers (generally < 10%) of estuarine diatoms, with *Thalassiosira lacustris* being the most numerous estuarine indicator. There is a marked change in the diatom community coincident with barrage construction, with an increase in *Pseudostaurosira brevistriata* post barrages. *Aulacoseira granulata*, a taxon common in the Murray River channel, shows a clear increase since *c*. 2000 years before present (BP), with numbers falling from about 500 BP to the present. If *Aulacoseira granulata* is used as a proxy for river flow, then it would seem that flow was greater between 2000 and 500 years BP. This assumption fits with the timeline of flow reconstruction data from Mundic and Tanyaka wetlands, further upstream, where river inflow was greater between 1500 and 500 years BP (Fluin unpublished data). These patterns warrant further investigation as they provide huge potential for reconstructing climate related flow events over the mid – late Holocene.

In core LA1, taken just south of Wellington, the impact of barrage construction is not as clearly demonstrated in the diatom community. The biggest change in diatom community is more related to non – Indigenous settlement from the late 1800s where there is an increase in epiphytic, eutrophic taxa such as *Cymbella cistula* and *Gomphonema parvulum*. *Thalassiosira lacustris* abundance is a lot lower in this core, suggesting that estuarine conditions have essentially been absent from this section of the lake (< 5%).

To summarise, in terms of salinity, it would seem that there was a salinity continuum in Lake Alexandrina prior to barrage construction. At the river mouth, close to the location of the Goolwa Barrage, there is strong evidence of estuarine conditions. Moving up the Goolwa Channel, into the centre of the lake, salinity diminishes to mostly fresh conditions with the occasionally salinity peak due likely to prevailing wind conditions or extended period of low river flow. Towards the north – eastern section of the lake, there is essentially no evidence for salinity elevated above fresh to slightly brackish conditions. These patterns exist for all the documented record (i.e. 7000 years).

In reference to pH, there is no evidence of pH conditions less than alkaline to highly alkaline over the past 7000 years at all sites. Diatoms are very sensitive to changes in pH and there are no diatoms present which indicate neutral – acidic conditions. This then suggests that releases from acidic sulphate soils are either a recent phenomenon or that the system showed great buffering resiliency in the past.

The Coorong

Prior to the current research, palaeoenvironmental investigations in The Coorong were limited to one undertaken in 1995, at the behest of the USE Dryland and Flood Management Board. The work concentrated on investigating the frequency and magnitude of freshwater flows into the South Coorong Lagoon, by taking a number of cores from around the Salt Creek area, and used ostracods and dating to reconstruct water conditions. Results provided strong evidence that the hypersalinity in the South Lagoon (SL) was a recent development (post-European settlement), 'a result of changes to the land' (Thomlinson, 1996, p. 2), and that regular freshwater inflows would have occurred prior to that time (Thomlinson, 1996). Other sediment investigations were aimed at characterising the mineral and gross organic composition of The Coorong sediments (Brown, 1965); or the sedimentology of The Coorong as part of a larger investigation of the Murray Basin geology (Brown and Stephenson, 1989). Holocene dolomitic formations in the ephemeral lakes to the south of The Coorong on the Coorong Coastal Plain were described by von der Borch (1976) and Warren (1990); the origin of organic-rich (sapropel) layers were investigated by McKirdy et al. (1995; 2009(a)); regional environmental conditions were reconstructed by (Mee et al., 2004; 2007); and Edwards et al. (2006) reconstructed water conditions using diatoms and ostracods in the sapropels.

In the current study, the combination of dating techniques from 12 cores provided a 1900 AD horizon for all cores (see Figure 5).[1] Calibrated ages indicate that basal sediments in the South Lagoon (*c*. 8400 yrs) are slightly older than those in the North Lagoon (*c*. 7300 yrs). Median sedimentation rates pre – 1955 AD were 0.28 mm/yr in the North Lagoon (NL) compared with 0.71 mm/yr in the South Lagoon (SL), suggesting higher overall sedimentation rates in the SL during the Holocene. Post – 1955 rates show exponential increases at all sites; the lowest rates were in the SL sites (1.6 mm/yr at both sites 18 and 19); the highest rates (9.8 mm/yr) occur at both site 5 in the NL and site 27 in the SL; and NL sedimentation rates range from 2.6 mm/yr at site 12 to 7.2 mm/yr at site 7 (Gell and Haynes, 2005; Fluin et al., 2007).

Inferences about Coorong salinity and water sources

Though more than 400 diatom species were recorded overall, for the sake of comparison, 12 diatom species or genus groups were selected based on either (significant) relative abundance (RA), well understood ecological niches, or occurrence in all cores (see Figure 5). The most salient feature of the cores is that marine / euryhaline diatoms comprise the bulk of the assemblages down the bottom ~2/3rds of each core. There is also a clear divide between the relative proportions and types of taxa or groups in the NL from those in the SL. In addition, there is a significant change in all assemblages above the line representing 1900 AD, more often than not followed by another, albeit more subtle change, after 1955 AD.

The dominant species in the NL cores prior to 1900 AD is *Paralia sulcata,* a chain-forming, centric diatom typically a major component of benthic communities in coastal, estuarine or lagoonal environments, susceptible to tidal or wind disturbance, and may thus be prone to redistribution in shallow water. *Paralia sulcata* has been found in environments with salinities ranging from estuarine to >marine (Zong, 1997), and the species is thought to be capable of non-sexual reproduction (McQuoid and Nordberg, 2003), which gives it a competitive advantage over many other marine / estuarine species. Other species or groups include epiphytic G*rammatophora* and

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[1] Coorong ages mentioned in this text are normalised to the year of collection (2005 or 2006), and expressed either as yrs AD, or years before present.

Cocconeis varieties commonly associated with seagrasses (Vos and De Wolf, 1993; De Stefano et al., 2000), which co-appear with epipelic (sediment-dwelling) *Campylodiscus* varieties, and with planktonic *Cyclotella striata* and *Chaetoceros* resting spores. *Aulacoseira* spp., the diatoms typically found in the Murray River, are absent from all cores south of site 7, and in the 5 cores (C1 and 5 not shown) where they are present, RAs average <5% of the assemblages, and peaks do not exceed 20% in any core (Haynes, unpublished data). After 1900 AD, there was a significant shift to assemblages that are dominated by members of the Fragilariaceae family. These include *Fragilaria* varieties, facultative planktonic *Staurosira*, *Staurosirella* and *Pseudostaurosira* varieties, and species of the *Opephora* genus, the latter of sand and mud dwelling habit. Facultative planktonics are able to move through the water column to increase exposure to light, and thus have a competitive advantage in low light environments.

These data suggest that prior to 1900 AD, the water for all of the NL was clear, deep enough to support a variety of aquatic macrophytes, and salinities were unlikely to have exceeded that of marine water. Water from the Murray River periodically penetrated to about halfway down the NL, but residence time is unlikely to have been extended. Flows from the river would appear to have been important for scouring the Murray Mouth channel, and allowing the ingress of marine water to The Coorong. This process may have been important in the maintenance of water levels, in driving water circulation and mixing in the NL, thus maintaining salinities at or below those of seawater most of the time. The dominance of Fragilariaceae at the expense of virtually all the other varieties after 1900 AD is an unambiguous signal of disturbance. This is most likely a consequence of reduced water exchange through the Mouth following upstream regulation, possibly indicates that light penetration is insufficient to support aquatic plants and their symbionts, and may signal an elevation in salinity levels, perhaps with concurrent lowering of water levels.

The South Lagoon offers a more complex picture of fluctuating water conditions throughout its history spanning the early Holocene. Though diatom varieties at site 18 are similar to those in the NL, the RAs in the assemblage are significantly different. In addition, for most of the site 27 core, the percentage of non – marine diatoms is significantly higher compared with the other five cores. Though *Paralia sulcata* is an important component of both SL cores prior to 1900 AD, by comparison *Grammatophora* and *Cocconeis* (marine and non-marine) varieties are frequently present in greater RAs, along with substantial proportions of planktonic (non-marine) *Cyclotella* spp. and (marine / estuarine) *Cyclotella striata* varieties. More interestingly, the changes associated with the post – 1900 AD conditions that are fairly uniform in C3, 4, 7, 12 and 18, appear to have taken a different character at site 27, commencing *c.* 570 yrs ago, and well before European arrival. The top ~100 cm the core from site 27 has significant RAs of *Fragilaria sp. 10*, a variety present at the base of the core, 8000+ years earlier, and periodically upcore. This trend is mirrored by the (marine) *Opephora* group, some of which have a tolerance for elevated salinity (Haynes, unpublished data).

The location of site 18 is in the main channel, which connects the North and South Lagoons. If water from the Murray River penetrated into the SL, this is the most likely flow path, and frustules of *Aulacoseira* species should be easily detectable in the sediments. As there is no evidence for this, it appears that the water didn’t penetrate as far south as this site. Alternatively, the evidence may not have been preserved, though given the excellent preservation of all other diatom varieties in this core, poor preservation is difficult to invoke as a plausible reason for absence of *Aulacoseira* valves. The diatom assemblage from site 27 in particular seems to suggest an alternative scenario; one with regular contributions of ‘fresher’ water, which probably originated at the southern end of the system, emanating from Salt Creek. This would explain a pre – European diatom assemblage composed of varieties suggestive of salinities being periodically <35‰ but without Murray River diatoms. The impact of drainage construction in the South East of the state, and the reduction of surface (and probably groundwater) flows into the SL appears to have manifested as heightened salinity levels in conjunction with reduced water clarity. Though the significance of *Fragilaria sp. 10* can only be speculated at present, its dominance at the top of the core from site 27 invites further investigation as a potential indicator for Salt Creek flow regimes and late – Holocene climate reconstructions for this region.

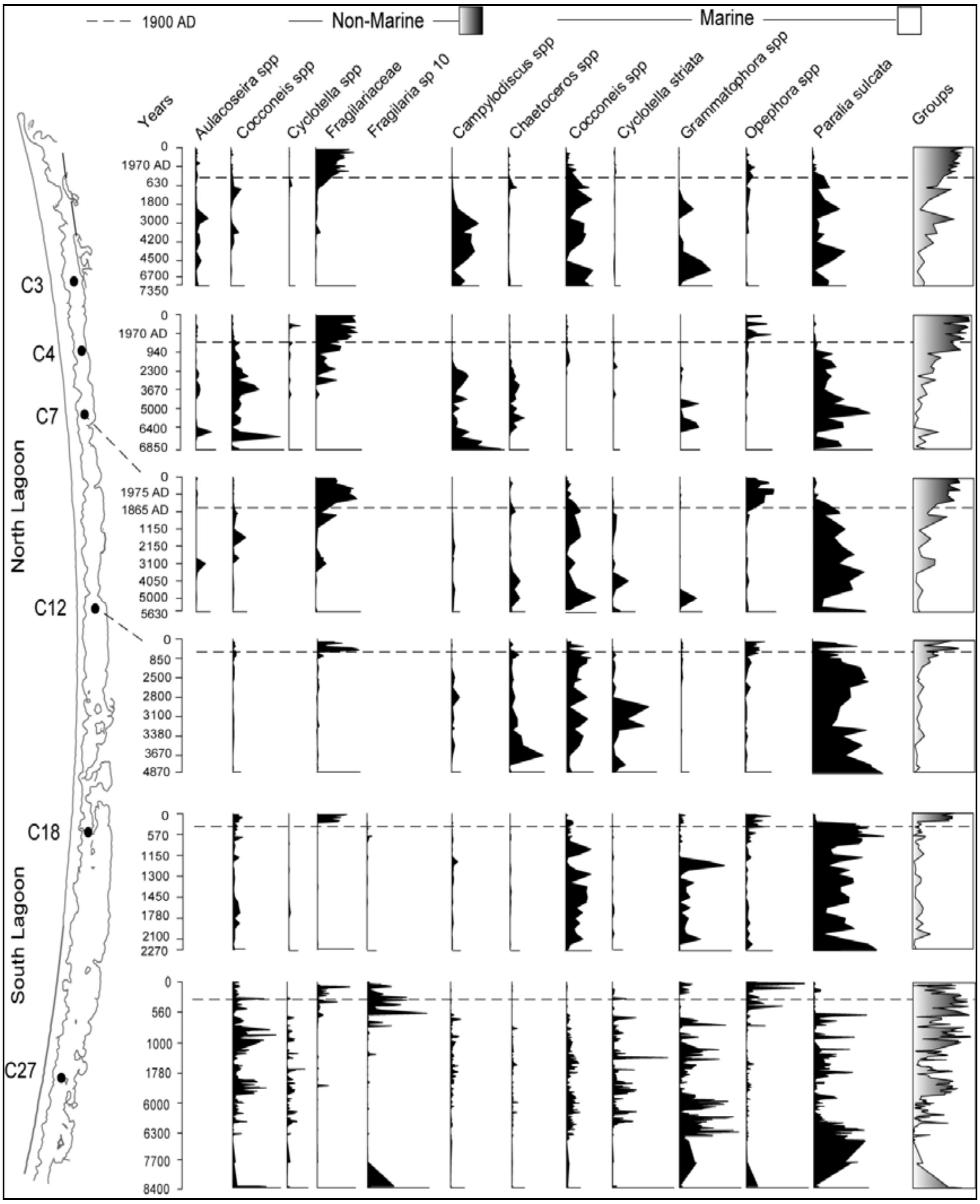

Figure 5: Summary diatom data from the Coorong Lagoon (Data – D. Haynes, permission required before reproducing). Piston cores – (NL) C3, C4, C7, C12 and (SL) C18, Livingston core – C27(2). See methodology for taxa classification.

Webster (2005) has documented the hydrodynamics of The Coorong and his conclusions are as follows:

The hydrodynamics of The Coorong, that is its currents, water levels and salinity regime, are driven by freshwater flows through the barrages and from the Upper Southeast drainage area, wind blowing over the water surface, evaporation and precipitation, and by sea level fluctuations propagating through the Mouth channel. Sea level fluctuations are due to the tides, the passage of storms and weather systems, and to a seasonal cycle of water level variation in the Southern Ocean. Significant barrage flows serve three main functions from the hydrodynamic perspective. They ensure that the Mouth channel is scoured out for at least part of the year allowing sea level fluctuations to penetrate into The Coorong to cause currents and mixing which are essential for removing accumulated salt. Barrage flows introduce fresh water into The Coorong which is eventually drawn and mixed into the South Lagoon thereby lowering salinities. Thirdly, large barrage flows elevate the water level and ensure that mixing exchange through the narrow, shallow channel between the two lagoons is more effective (Webster, 2005).

The diatom data summarised herein are not inconsistent with such a model.

Supporting information from other data sources

Support for these interpretations can be found in recent investigations of the biogeochemical status of The Coorong Lagoons utilising a consortium of elemental, isotopic and biomarker analyses of 9 cores (by Krull et al. (2009) from 7 sites, and by McKirdy et al. (2009(b)) from 2 sites). Results suggest that the North and South Lagoons have evolved as two separate biogeochemical systems, and that the current condition of the lagoons is in marked contrast with those prior to the 1950s. ^{13}C-NMR spectra confirm that the organic matter is largely algal – derived throughout all cores, but with significant contributions from the aquatic macrophyte *Ruppia megacarpa* (and possibly other aquatic macrophytes) in pre – 1955 AD sediments for the whole of The Coorong (Krull et al., 2009; McKirdy et al., 2009(b)).

The historical record indicates that while the perennial *Ruppia megacarpa* variety was once abundant in the NL, it is today confined to the northern reaches and remnant estuary around the Murray Mouth. In addition, *Ruppia megacarpa* is being progressively replaced by *Ruppia tuberosa*, an annual, salt – tolerant variety that dominated in the SL until recently (Nicol, 2005), but is now largely absent in that basin. In addition, an examination of *Ruppia* remains from a SL core (VDY1) show that the salt-tolerant *Ruppia tuberosa* has in fact only been dominant at this site in recent times, possibly from as late as *c.* 1950 AD. By contrast, seeds of *Ruppia megacarpa*, which has limited tolerance to elevated salinity, were the only *Ruppia* variety found in the lower section of the core, indicating that it has flourished with regular periodicity for several millennia, but declined more recently (Dick et al., in Prep).

The biogeochemical data has highlighted the functional differences between the North and South Lagoons, rather than the similarities, and identified the dominant role that macrophytes played in the food-web. That salinity levels were at or below 35‰ often enough to allow *Ruppia megacarpa* to reproduce and persist in both lagoons prior to European modifications, are persuasive data supporting the diatom – inferred salinity regime.

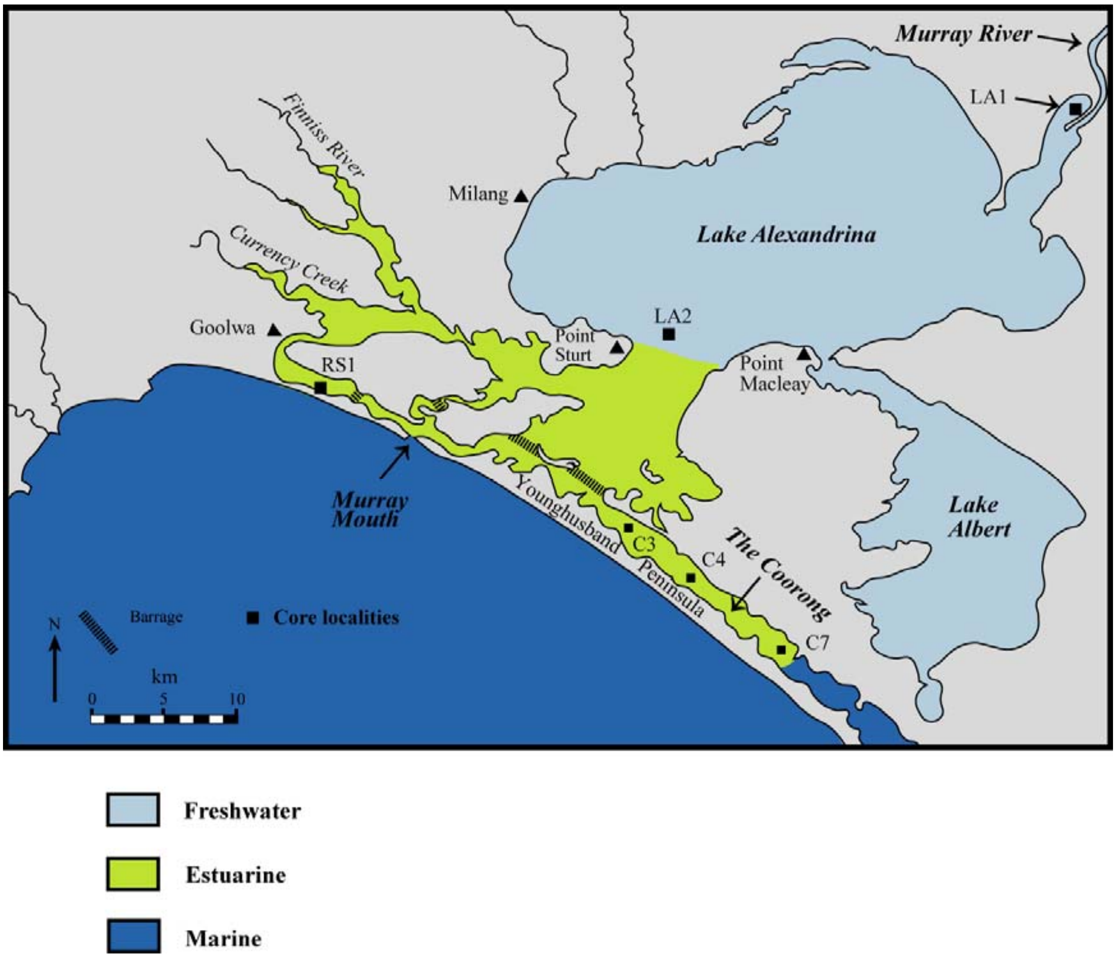

Figure 6: Summary diagram of information from Figures 2-5 showing the extent of the Murray River estuary before barrage construction as inferred from diatom-based evidence.

Potential limitations to the inferences from Lake Alexandrina and The Coorong

Sampling resolution

10 cm of sediment in our cores can represent as little as 10 years and as much as 1000 yrs. Clearly, finer sampling resolution will increase the likelihood of capturing a more accurate picture of the magnitude and periodicity of any changes.

Preservation of silica in high pH and saline water

Diatom cells are susceptible to dissolution in high pH and saline environments (Ryves *et al*. 2001), but due to the differing silica content of diatom species, some species are more vulnerable than others. The well-silicified varieties i.e. *P. sulcata*, *Grammatophora*, *Cyclotella,* are likely to be more resistant to dissolution, and may thus be statistically over-represented in fossil assemblages at the expense of less robust varieties. For example, Volkman et al. (2008) found *Cylindrotheca closterium* to be the predominant planktonic diatom in the modern Coorong, and modern sampling by Haynes (unpublished data) found seasonally high proportions of this species in the SL, but evidence for it was not found in the fossil record. Given that the current condition of the lagoon is unprecedented, *C. closterium* may not have been present in the recent past. However, even if it was present during the last 100−500 years, its weakly silicified frustules render its long-term preservation in the alkaline sediments of The Coorong unlikely (e.g. Dickman and Glenwright, 1997).

Ecology of the species discussed

There is a very well established literature describing the ecology of freshwater diatoms (Stoermer and Smol, 1999). However the literature for coastal and marine diatom ecology, though large, is less well established. Hence, while we are highly confident that we can unambiguously identify freshwater phases, the precise salinity of phases dominated by estuarine and marine taxa (particularly in The Coorong) is not so well established. This observation is particularly pertinent to those taxa that have a broad tolerance to salinity (euryhalinity) such *Staurosirella pinnata, Paralia sulcata, Cyclotella striata* and *Cocconies placentula.*

Implications of the findings for future management of the site

There are a number of proposals about how to manage The Coorong, Lower Lakes and Murray Mouth (CLLMM) region given the current, degraded state of these ecosystems. Our findings demonstrate that the current state of The Coorong and Lower Lakes is without precedent and that the ecosystems are very different to those which existed prior to European settlement of the region.

Many proposals in regard to the management of the CLLMM region draw upon inferences about their pre-impact condition. In particular, some calls to allow sea water into Lake Alexandrina have been justified by an assumption that sea water would have penetrated into the Basin in the past. However, as is summarised in Figure 6, this is not the case and the majority of the Lake has been fresh for its entire history.

It is clear from research on The Coorong that substantial amounts of fresher water entered The Coorong Lagoon from the Upper South East region. Hence, proposals to provide increased discharges from this region to alleviate the heightened salinity in the South Lagoon can be justified in terms of the natural history of the region.Given the degraded state of the freshwater systems of Lakes Albert and Alexandrina, there is an increased emphasis on preserving the wetland ecosystems at the bottom of the Finniss and Currency Creek systems. Research such as that outlined above, but focussed on these systems, could provide useful insights into the age of, and extent of natural variability in, these key ecosystems.

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Table 1: Summary of analyses undertaken in The Coorong

Site No.	Site Name & UTS Co-ordinates	Col. Date	Water Depth (m)	Core Type	Core length (cm)	M/S	*Pinus* pollen	Dating+	Diatoms	Forams Ostracods Charophytes	Biomarkers / Isotopes	*Ruppia*	Pollen
	NORTH LAGOON												
C1	*Pelican Point*: 0320499 6058500	21.03.05	2.2	50mm	**51**	*	*		*		*		
C3	03224531 6055674	21.03.05	1.8	50mm	**145**	*	*	1,2,3	*	*			*
C4	*Fiddle Head*: 0329617 6051672	22.03.05	2.0	50mm	**143**	*	*	2	*		*		
C5	*Mubin-Yerok Point*: 0329989 6050875	22.03.05	1.6	D-sect	**594**	*	*	2	*	*	*		
C7	*Long Point*: 0332646 6048511	22.03.05	1.6	50mm	**154**	*	*	1,2,3	*	*			*
C9	*Lambert Point*: 0338931 6043868	23.03.05	1.0	50mm	**133**	*	*	2	*		*		
C12	*Mt. Anderson*: 0346261 6036094	23.03.05	1.4	50mm	**138**	*	*	1,2,3	*	*			*
C13	0349128 6033736	23.03.05	1.3	50mm	**144**	*	*	2	*		*		
	SOUTH LAGOON												
VDY1	*Villa Dei Yumpa:* 0361194 6024451	3.05.06	0.5	80mm	**70**	*	*	1,2	*	*		*	
C18	*Cow Island*: 0359514 6022399	24.03.05	0.6	50mm	**130**	*	*	2	*	*	*		
C19	*Braeside*: 0362089 6022040	24.03.05	0.5	50mm	**46**	*	*	1,2,3	*				*
C23	0364771 6017181	24.03.05	1.2	50mm	**77**	*	*	1,2,3	*	*			*
C26(2)	*Nth Pelican Island*: 0369597 6010254	25.03.05	1.4	50mm	**50**	*	*		*		*		
C27	*Mellor Island:* *0371011 6007440*	25.03.05	1.7	50mm	**106**	*	*	1,2,3	*	*			*
C27(1)	*Mellor Island:* *0371037 6007471*	1.05.06	2.5	Liv: 2 drives	**153**	*			*		*		
C27(2)	*Mellor Island:* *0371037 6007471*	1.05.06	2.5	Liv: 8 drives	**684**	*	*	2	*	*	*		

+ 1 = Pb-210 & Cs-137, 2 = C14 AMS, 3 = OSL; MS=magnetic susceptibility