Review of the salinity optima of the diatom *Staurosirella pinnata*: implications for water reform in Australia

J. Marohasy & J. Abbot
School of Medical and Applied Sciences,
Central Queensland University, Noosa, Australia

Abstract

Water policy reform in Australia has been driven by a requirement to increase freshwater flows to Lake Alexandrina, part of a terminal near-coastal system at the end of Australia's longest river, the Murray. This water policy is based on the lake's listing in 1985 under The Convention on Wetlands of International Importance as freshwater, and analysis of a limited number of diatoms from one sediment core. The analysis classified *Staurosirella pinnata*, the dominant diatom species, as a freshwater species. However, a review of the literature suggests *S. pinnata* has a very broad salinity tolerance, and a recent study in an adjacent coastal lagoon, the Coorong, indicates *S. pinnata* has a salinity optimum of 29 ppt. If the natural state of Lake Alexandrina is estuarine, rather than freshwater, then water policy could focus on restoring connectivity with the Southern Ocean through removal of the barrages built in the 1930s to stop salt water intrusions, rather than increased freshwater flows from the Murray River.
Keywords: diatom, water reform, Staurosirella pinnata, Murray River, barrages.

1 Introduction

A key objective of water reform in Australia is the redistribution of water from irrigated agriculture back to the environment by way of increased environmental flows. This became a priority following the Millennium drought (2001 to 2009) that resulted in water levels receding at Lake Alexandrina, which is a vast and shallow terminal lake at the end of the Murray and Darling river-systems in south-eastern Australia, Figure 1.

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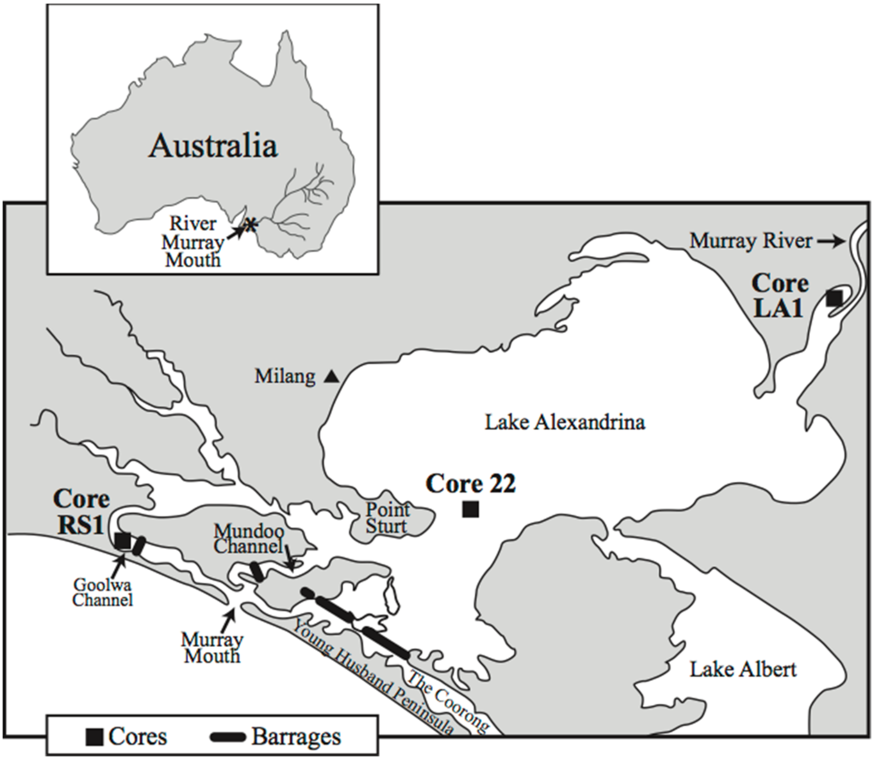

Figure 1: Lake Alexandrina is situated at the end of the Murray-Darling River system in south eastern Australia and was once connected to the Southern Ocean by a series of channels that are now blocked by barrages. The Coorong is a narrow body of water to the south east of Lake Alexandrina separated from the Southern Ocean by the Young Husband Peninsula.

A plan for the Murray Darling Basin, legislated in November 2012 under the *Commonwealth Water Act 2007*, will limit the quantity of water in the Basin that can be used for irrigated agriculture and result in the buyback of about one third of all the water previously used to produce food in non-drought years. An objective of this redistribution of water from agriculture to the environment is to give effect to The Convention on Wetlands of International Importance (The Ramsar Convention) [1]. This Ramsar Convention is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

In 1985, Lake Alexandrina became listed under the Ramsar Convention as a freshwater lake. The Australian government reporting to the Secretary General of the Ramsar Convention in Switzerland has stated that the key issue is a lack of adequate freshwater flowing into the lake from the Murray River (e.g. report with letter from C. Zammit, 13 December 2006). However, Lake Alexandrina is considered by many [2, 3] to have been in ecological decline since construction of sea dykes, known locally as barrages, across the channels that once connected the lake to the Southern Ocean, Figure 1. The barrages were constructed in the 1930s to stop salt water intrusions. Bourman *et al.* [3] states: “Originally a vibrant, highly productive estuarine ecosystem of 75,000 ha, characterized by mixing of brackish and fresh water with highly variable flows, barrage construction has transformed the lakes into freshwater bodies with permanently raised water levels”.

The Murray Darling Basin Authority, MDBA, and the South Australian Department of Environment, Water and Natural Resources are jointly responsible for management of Lake Alexandrina. These government agencies claim that analysis of diatoms in lakebed sediments shows that Lake Alexandrina has been predominantly freshwater for 7,000 years, and that this is therefore its natural ecological character [4, 5].

Diatoms are unicellular algae with ornate cell walls made of silica. As different species of diatom usually have different salinity tolerances, and preserve well in sediment, diatoms are often used in paleoliminology studies as indicators of past salinity. Reports to government [6], and published papers [7] that claim Lake Alexandrina has a 7,000-year freshwater history, rely on the qualitative assessment of the diatoms from a single sediment core taken from Lake Alexandrina in 1989 from a water depth of 3.7 m just to the northwest of Port Sturt, (Figure 1). This sediment core, measuring 8 cm in diameter and 494 cm in length, was first examined for diatoms by D.A. Penny as a contribution to a PhD study into the sedimentology of Lake Alexandrina by Barnett [8]. The study by Penny, detailed in Barnett [8], remains the most comprehensive investigation of the diatoms of Lake Alexandrina. Penny identified 113 species from Core 22 and Barnett [8, 9] stated that this core represented an approximate 7,000-year lower Murray history. Subsequent diatom studies refer to a subset of this original study, examining as few as 15 of the original 113 diatom species [6, 7].

Barnett [8, 9] and Fluin *et al.* [6, 7] make determinations about past salinities in Lake Alexandrina based on a qualitative assessment of the salinity tolerance of the diatom species found in Core 22, but without any explanation of how the diatoms were categorized with respect to salinity. For example, Fluin *et al.* [6, 7] concluded that over the 7,000-year record there are minimal numbers (generally <10 percent) of estuarine diatoms with *Thalassiosira lacustris* (Grunow) Hasle being the most numerous estuarine-indicator. Fluin *et al.* [7] also concluded that there is no evidence, based on the diatom species preserved in Core 22, for substantial marine incursions into Lake Alexandrina. However, it is unclear how Fluin *et al.* [6, 7] assigned diatom species to the categories of freshwater, estuarine and marine. They classify the dominant diatom species at almost all depths in all sediment cores, *Staurosirella pinnata* (Ehrenberg) (Williams and Round [10]), as freshwater.

The most recent government-commissioned report ‘An Environmental History of the Lower Lakes and Coorong’ [7] gives the impression that three new cores have been taken from Lake Alexandrina, but this is not the case. This report [7] is again based on Core 22 (relabeled LA2), and an additional core, LA1, that was collected in 1996 from the extreme north of Lake Alexandrina, behind the inlet of the Murray River, Figure 1. Analysis of the diatom fauna from LA1 has proved to be problematic, as detailed in Fluin *et al.* [6]. In particular, the core is only 85 cm in length with the top 6–7 cm being considered an "outlier" and the lower sections (40 to 85 cm) all yielding carbon dates as of "similar age" calibrated to 7,400 to 7,600 years BP. The third core, RS1, discussed in Fluin *et al.* [7], is acknowledged to contain predominantly marine diatom species and is not from Lake Alexandrina but rather the Goolwa channel situated immediately behind the Murray's sea mouth, Figure 1.

In this study, data from the original analysis of Core 22 is reanalysed confirming that *S. pinnata* is the dominant diatom species, and then the literature reviewed to establish the salinity range and optima of *S. pinnata*.

2 Review of data and literature

Barnett's PhD thesis [8] contains detailed information on the diatoms found in Core 22, which is the only sediment core taken from Lake Alexandrina proper that has ever been successfully analysed for diatoms. Appendix IV of the thesis contains a list of 113 species and their percentage abundance at depths of 1, 4, 8, 20, 40, 60, 80, 100, 120, 160, 180, 220, 260, 300, 340, 380, 411, 420, 460 and 490 cm. Carbon radiometric dating was used by Barnett [8, 9] to determine the chronology of the core, with the middle section (220–300 cm) corresponding to an age of 2,300 years before present, and the 460–490 cm section corresponding to 7,000 years before present [9].

Considering the 14 most common diatom species listed in Appendix IV, and defined here as species that occur as ≥ 5 percent of the total at any one depth, *Fragilaria pinnata* is overwhelmingly dominant at almost all depth, Figure 2. A revision of the genus *Fragilaria* [10] saw the species *F. pinnata* made synonymous with, and to be superseded by, *Staurosirella pinnata* (Ehrenberg) Williams & Round. *F. pinnata* will thus henceforth be referred to as *S. pinnata*.

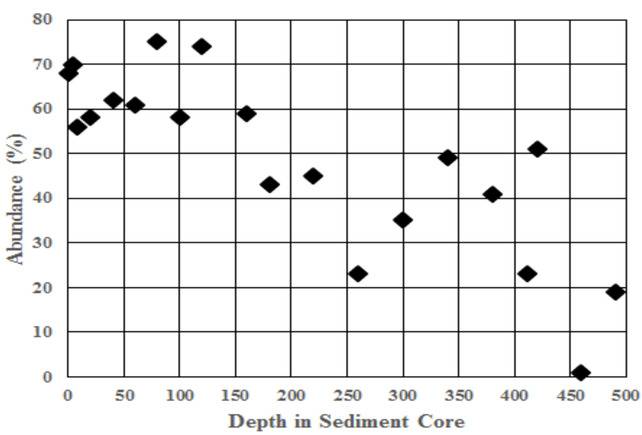

Figure 2: Percentage abundance of *Staurosirella pinnata* at each depth in Core 22 after Barnett 1993.

This species is particularly dominant at depths less than or equal to 220 cm where it comprises 45 percent or more of the diatom flora, Figure 2. Only at 460 cm is the species rare, comprising only 1 percent of the diatom flora, Figure 2. At this depth there is no single dominant species with *Thalassiosira lacustris*, *Navicula cincta* and *Nitzschia pusilla* the most abundant species but only comprising 12, 8 and 6 percent of the diatom flora respectively (Appendix IV, Barnett 1993). Considering the common diatom species except *S. pinnata* (i.e. excluding *S. pinnata* from the analysis), mean percentage abundance at the different depth various between 1.9 and 4.6 percent: that is no species dominants at any depth. A maximum percentage abundance of 24 and 23 percent, respectively, is recorded for *Fragilaria parasitica* at the top of the sediment core at the depths of 0 and 4 cm but this species is relatively rare at most other depths.

S. pinnata is listed in influential international reference works as a freshwater diatom [11–13]. This classification of freshwater is consistent with Barnett [9] where the species is described as oligohalibous to lower mesohalobous [9]. Oligohalibous refers to freshwater species, typically with a salinity range less than 2 parts per thousand (ppt). A mesohalobous species will typically tolerate a salinity range from 0.2 to 30 ppt with the lower mesohalobous species associated with "lower" brackish conditions typically defined as less than 10 ppt [11].

Barnett [9] while acknowledging a marine origin for the lake, states that the dominance of *S. pinnata* since 6,000 years before present, suggests "a greater freshwater influence" for most of the history of Lake Alexandrina. Fluin *et al.* [6] state that the presence of *S. pinnata* is indicative of a "meso-eutrophic reed fringed environment with fresh to brackish water in a pH range of 8.0–9.0" but without citing a reference. Fluin *et al.* [6] cite Gell [14] later in that paper with reference to the salinity tolerance of *S. pinnata* relative to other diatom species. Gell [14] in their study of diatoms in wetlands upstream of Lake Alexandrina, place *S. pinnata* in a Group 6, which has a designated salinity of more than 5 ppt, yet later in the same paper Gell [14] indicate that *S. pinnata* has a salinity optimum of 0.59 ppt. Meanwhile, Gell *et al.* [15] suggests a salinity optimum of 0.84 to 35.63 ppt for *S. pinnata*, Table 1.

This broader range of 0.84-35.63 ppt is similar to that reported by Saunders *et al.* [16] of 1.5–43.4 ppt based on 34 sampling sites in 19 lagoons along the east coast of Tasmania, south eastern Australia. Saunders *et al.* [16] used this data to determine that *S. pinnata* had a summer salinity optima of 9.5 ppt and a winter optima of 12.1 ppt, Table 1. Quantitative studies similar to Saunders *et al.* [16], based on comprehensive sampling regimes in estuaries in China and Argentina, have found that *S. pinnata* has optima of 6.34 ppt and 17.3 ppt, respectively [17–19], Table 1.

In the Coorong, a coastal lagoon adjacent to Lake Alexandrina, Figure 1, *S. pinnata* dominated during a period from 1997 to 2002 when average salinity was 35 ppt [20]. Based on a salinity transfer model developed for the Coorong, the salinity optima for this species is 29 ppt [20].

This very high salinity optima, close to seawater, is consistent with Finkel *et al.* [21] description of *S. pinnata* as a marine, chain-forming pennate species.

Table 1: Summary of the ecological characteristics of *Staurosirella pinnata* based on previous literatures. Salinity is measured in parts per thousand, ppt. When the ppt value has been derived from a weighted average optimum, or tolerances it is designated by WA Opt & WA Tol, respectively. Brackets designate salinity inferred from habitat and/or locality.

Salinity (ppt)	**Environment**	**Locations**	**Authors**
(>25)	Estuary	Baker Bay, Columbia River, USA	McIntire & Amspoker 1984
(>25)	Estuary	Youngs Bay, Columbia River	McIntire & Amspoker 1984
	Tidal mud flats	Mar Chiquita, Argentina	Espinosa *et al.* 2006
	Estuary	Itupanema Beach, Brazil	Ribeiro *et al.* 2010
	No coastal records, found inland creeks and rivers	Queensland, NSW, Victoria	Foged 1978
(33–40)	Mangrove forest in coastal lagoon	Bahia Magdalena, Mexico	Fuerte *et al.* 2010
0.21–2.34	Wetland	Hattah Lake, Murray Darling, Australia	Gell *et al.* 2002
0.84–35.63	Wetland	Psyche Bend, Murray Darling	Gell *et al.* 2002
0.66–21.43	Estuary	Quequen Grande River, Argentina	Hassan *et al.* 2006
1.05–25.2	Estuary	Mar Chiquita, Argentina	Hassan et al. 2006
6.34 WA Opt	Estuaries	Buenos Aires province	Hassan *et al.* 2009
6.42 WA Tol	Estuaries	Buenos Aires province	Hassan *et al.* 2009
150	Saline lake	Mono Lake, California	Herbst & Blinn 1998
38	Tidal estuary	Chesapeake Bay, USA	Marshall *et al.* 2005
	Intertidal marsh	Masonboro Island, North Carolina	McGee 2005
9.5–12.2 WA Opt	Coastal lagoons	Tasmania, Australia	Saunders *et al.* 2007
1.5–43.4 WA Tol	Coastal lagoons	Tasmania	Saunders *et al.* 2007
	Estuaries and coastal lakes	South East Australia	Saunders 2011
42–65	Hypersaline coastal lagoon	Arauama Lake, Brazil	Sylvestre *et al.* 2001
	Estuary	Pearl River, China	Zong *et al.* 2010

Table 1 Continued.

Salinity (ppt)	Environment	Locations	Authors
(35)	Coastal waters	British coast	Hendey 1964
(35)	Open ocean	Sargasso Sea, North Atlantic, USA	Finkel *et al.* 2010
	Brackish water	Oyster Pond, Martha's Vineyard, USA	Finkel *et al.* 2010
	Ocean	Provasoli-Guillard National Center for the Culture of Marine Phytoplankton	Finkel *et al.* 2010
0.25 WA Opt	Lakes	British Columbia, Canada	Wilson *et al.* 1996
0.01–4.84 WA Tol	Lakes	British Columbia	Wilson *et al.* 1996
29 WA Opt	Coastal lagoon	Coorong, South Australia	Haynes *et al.* 2011

Similarly, Hendey [22] described the species as common along the British coastline. *S. pinnata* also been found at Itupanema Beach, Brazil [23] and tidal estuaries and marshes in North America [24–27]. *S. pinnata* has been found in hypersaline coastal lagoon in Brazil [28] and California [29] and in a mangrove forests in Mexico [30] and tidal mudflat in Argentina [31], Table 1. In contrast, Foged [32] only found the species in land creeks and rivers in eastern Australia, while Wilson *et al.* [33] report the species as present in the freshwater lakes of British Columbia.

What could be considered inconsistent classifications concerning salinity ranges, that is the freshwater [11–13] versus the salt water listings [26–28], suggest either *S. pinnata* has an exceptionally broad salinity tolerance, or that there is taxonomic confusion. Indeed the taxon could be represented by a species-complex. Some samples collected from North America exhibit several morphological variants that are often included under the name *S. pinnata* [34].

3 Discussion

Five barrages block the channels that converge on the Murray River's sea mouth preventing salt water intrusions. It is argued that these barrages are necessary because the growth of upstream irrigation industry during the 20th century reduced river flows which previously maintained a freshwater environment in Lake Alexandrina for most of its 7,000 year history. The diatoms preserved in the lake's sediment are routinely cited as supporting evidence [4–7]. There has been no discussion, or acknowledgement, however, in this government-sponsored literature concerned with this water policy reform of discrepancies and inconsistencies in the characterisation of *S. pinnata*, or the limited data on which this freshwater determination has been made, in particular that it is based on a single sediment core.

Generally determinations of historical salinity are based on many more samples, followed by the construction of diatom-salinity inference models. Zong *et al.* [19], for example, created a transfer function based on 77 modern surface sediment samples taken from across the Pearl River estuary in China to quantitatively establish the salinity optima of the modern diatom assemblages. A training set was then used to reconstruct paleo-salinities for four sediment cores that correspond to the past 9,000 years of record for the Pearl River estuary. Hassan *et al.* [18] used a similar methodology to reconstruct changes in salinity along the northeastern coast of Argentina, developing the training set from sampling at 40 sites in three different estuaries. At the Orielton Lagoon in south-east Tasmania, Australia, there is no natural salinity gradient because of the construction of a causeway, so Saunders *et al.* [16] sampled 19 lagoons around the Tasmanian east coast to develop a training set which could then be applied to reconstruct the history of Orielton lagoon.

A comprehensive review of the literature, Table 1, shows that *S. pinnata* has been characterised as both a freshwater and also marine species, Table 1. This could be indicative of a confused taxonomy. However, where detailed quantitative ecological studies have been undertake, for example in the Coorong, Tasmania, Argentina and China [16, 17, 19, 20], the species is unambiguously estuarine. This would also be consistent with geomorphological studies of Lake Alexandrina, which suggest it was originally the central basin of a wave-dominated estuary [35, 36] before construction of the barrages in the 1930s [2, 3].

The political implications are significant with the freshwater classification of Lake Alexandrina driving the redistribution of water allocations in the Murray Darling Basin, and assisting the allocation of more than US$10 billion dollars of government funding to different interest groups since 2009 [37]. However, if the natural environment of Lake Alexandrina is estuarine, and the objective of the water reform restoration of natural environments, then the policy would be very different. In particular, it might be focused on reconnecting Lake Alexandrina with the Southern Ocean to facilitate the inflow of salt water [38].

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