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Corrigendum

Watching the tide roll away – contested interpretations of the nature of the Lower Lakes of the Murray Darling Basin

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The author wishes to correct two points in this paper:

(1) On the third page of this paper (right column, line 31) the sentence: 'A core taken, but not analysed by Barnett (core LA 2), and another collected by Gell and Fluin in 1996 near the river entrance (core LA 1), formed the basis of analyses in the 2002 PhD thesis of Fluin (Fluin 2002)' should be replaced with: 'A core (LA 2) taken by Barnett (core 22 in Barnett 1994 as noted in Fluin *et al.* 2007), and another collected by Gell and Fluin in 1996 near the river entrance (core LA 1), formed the basis of analyses in the 2002 PhD thesis of Fluin (Fluin 2002).'

(2) Also on the third page of this paper (right column, lines 38–45) the sentences: 'The interpretation of the interactions between the River Murray, the Lower Lakes and the Coorong were presented at the Past Global Changes 'Salinity, Climate Change and Salinisation' workshop in Mildura in September 2004 (Gell *et al.* 2007). This conference paper was subsequently published as Fluin *et al.* (2007) on which I led the interpretation of the records from the Coorong' should be replaced with: 'The interpretation of the interactions between the River Murray, the Lower Lakes and the Coorong were presented at the Past Global Changes 'Salinity, Climate Change and Salinisation' workshop in Mildura in September 2004 (Gell *et al.* 2007). This conference paper was subsequently published as Fluin *et al.* (2007) on which I led the interpretation of the new diatom records from the Coorong collected in 2005.'

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Watching the tide roll away – contested interpretations of the nature of the Lower Lakes of the Murray Darling Basin

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Abstract. The Murray Darling Basin Plan (Murray Darling Basin Authority 2012) represents the largest investment by government in an Australian environmental management challenge and remains highly conflicted owing to the contested allocation of diminishing water resources. Central to the decision to reallocate consumptive water to environmental purposes in this Plan was the case made to maintain the freshwater character of two lakes at the terminus of the Murray Darling Basin, in South Australia. This freshwater state was identified as the natural condition on the basis of selected anecdotal evidence and was enshrined in the site's listing under the Ramsar Convention. The commitment to the freshwater state was challenged under drought when sea water was seen as a means of averting acidification when low river flows risked the exposure of sulfidic sediments. Independent evidence from water quality indicators (diatoms) preserved in lake sediment records, however, attested to an estuarine, albeit variable, condition before the commissioning of near-mouth barrages in 1940. This interpretation for a naturally estuarine history, published after peer review, was overlooked in a report to the South Australian government, which argued, without the provision of new evidence from the lakes, that they were fresh for their entire history. This revised interpretation is widely cited in the scientific literature, government reports and online discussion and underpins a watering strategy aimed at a freshwater future for the Lower Lakes. The allocation of large volumes of fresh water to achieve this condition presents significant difficulties owing to the highly contested nature of water use across the Basin.

Additional keywords: ecological condition, estuaries, Murray Darling Basin, palaeolimnology, Ramsar wetlands.

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Introduction

The Murray–Darling Basin (MDB) is one of Australia's largest drainage divisions, spanning more than one million square kilometres. It is also its most productive, supporting over 40% of the nation's agricultural domestic product. This productivity has been underpinned by an extremely high level of water abstraction to drive intensive irrigation agriculture at great cost to water-dependent ecosystems (Kingsford 2000). Originally to sustain navigation, but ultimately to guarantee water supplies, the rivers of the MDB became highly regulated after the commissioning of many dams and weirs, mostly after 1922.

The initial efforts at irrigation were limited and the greatest volumes of abstraction were focussed in the upper reaches of the Murray and Goulburn Rivers (Mallen-Cooper and Zampatti 2018). Nevertheless, concern about the impact of even this low level of abstraction on the flows entering South Australia was sufficient to warrant a presentation and debate within the colonial South Australian Parliament as early as 1886. For example, the Honorable Jon Rankine is quoted as saying in the House of Assembly in 1887 that 'Many people imagined that there would be nothing to fear from only flood waters being taken, but this was a great mistake. All the floodwaters were required to drive out the salt water so as to keep the lakes and a portion of the lower river fresh for a few months in the year' (Sim and Muller 2004, p. 26). This dispute intensified and became an important distraction to the nation's Federation signed in 1901. The Interstate Royal Commission on the River Murray (Davis *et al.* 1902) was to resolve this issue and, by 1915 the River Murray Commission was instituted to manage cross-state contests over water (Smith 1998).

The Coorong (~35 000 ha) and Lower Lakes, comprising Lake Alexandrina (65 000 ha) and Lake Albert (16 800 ha), lie at the mouth of the Basin, where the River Murray discharges into the Southern Ocean, and are a lagoon and estuarine complex (Fig. 1). Geomorphically, the Coorong estuary and the Lower Lakes are separated by the last interglacial shoreline, the Woakwine Range, but are connected hydrologically by a series of channels, of which the Goolwa Channel, the continuation of the River Murray, carried most of the river water to the sea. To preserve freshwater resources in Lake Alexandrina from the penetration of tidal waters entering through these channels, an array of barrages was commissioned and completed in 1940. These are situated near the mouth of the River Murray and acted to raise the level of the Lake and hold back incoming tides. They also slowed river flow, leading to the accumulation of salt-laden sediments within the lagoonal complex. This resulted in the gradual formation of Bird Island, a tidal delta south of Hindmarsh Island, and the northward migration and ultimate closure

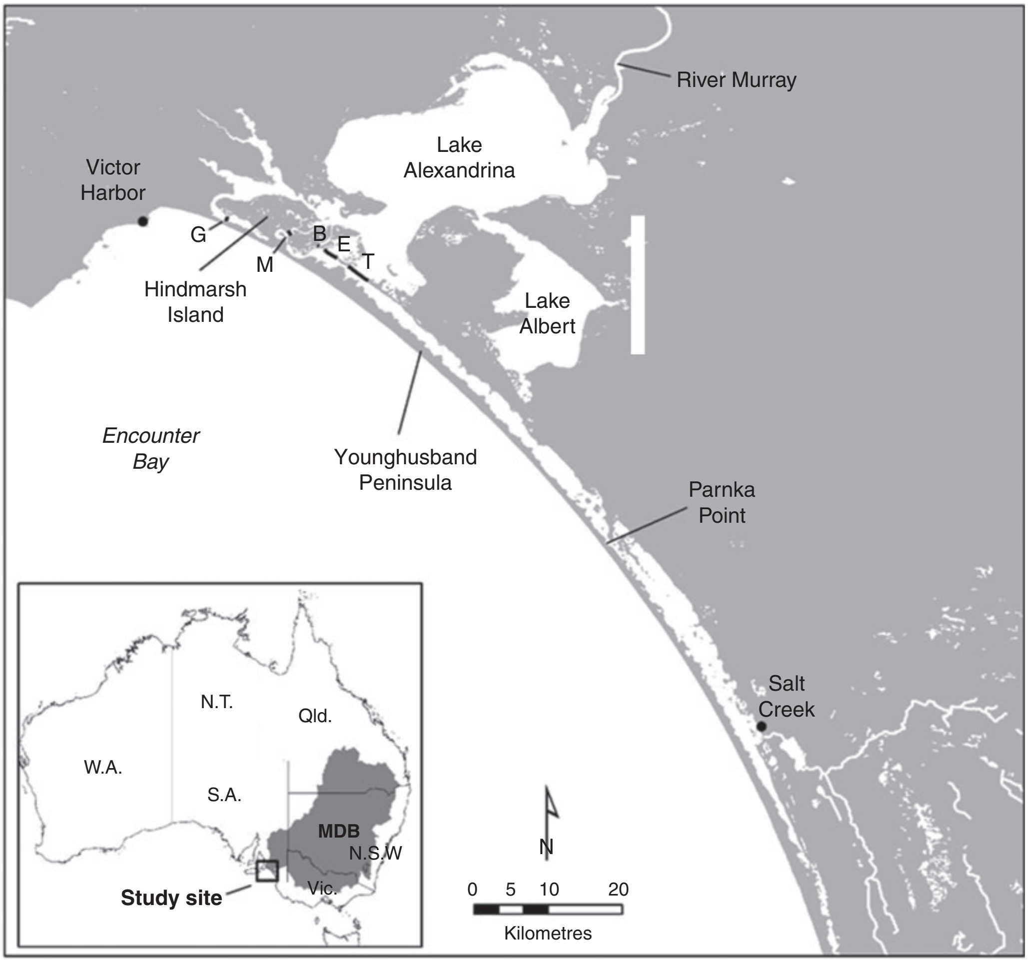

Fig. 1. Lake Alexandrina is a large terminal lake near the mouth of the River Murray, South Australia. Letters mark the locations of barrages.

of the river mouth (Bourman *et al.* 2000). The high evaporation rate typical of the region heightens the risk of the Lower Lakes drying. The commissioning of the barrages therefore left river water as the main source of water to maintain lake levels.

In 1985 the Coorong and Lower lakes were listed under the Ramsar Convention on the basis of, *inter alia*, their significant fish and waterbird populations and cultural (indigenous) significance. At the time the Lower Lakes were described as being mostly fresh (Department of Environment and Heritage 2000). Consistent with this, a report entitled *A Fresh History*, funded by a regional government agency, defined Lake Alexandrina as being predominantly fresh (Sim and Muller 2004). This report was largely based on documentary and anecdotal evidence and focussed particularly on the observation that, in 1901, the lake had become salty for the first time. This was attributed to abstraction upstream for irrigation in the eastern States, particularly in neighbouring Victoria.

Actions to restore the ecosystems of the MDB were in full swing by the late 20th century, with several reviews and audits conducted (Kingsford 2000). Among the outcomes include the identification of the volumes required to return the system to ecological health variously calculated at between 3200 and 7600 GL (e.g. Jones *et al.* 2002; Young *et al.* 2011; Williams 2017). By 2006 water levels in Lake Alexandrina had fallen due to drought and abstraction upstream and the Commonwealth Government had notified the Ramsar Secretariat of likely change in ecological character under Article 3.2 (Pittock *et al.* 2010). The risk of acidification through the oxidation of sulfidic sediments drew proposals for engineering solutions to protect to freshwater status of the lower lakes (Souter *et al.* 2013), but also drew calls for 700 GL of flow specifically to maintain a substantially freshwater and fluctuating lake system (Kingsford *et al.* 2009 cited in Pittock *et al.* 2010). The decision, made in the MDB Plan of 2012, to return 2750 GL year^{-1} to the river, through water buybacks, irrigation renewal and water transfer efficiencies, was made in no small part because it was effectively argued that Australia had an international commitment to restore Lake Alexandrina and retain it as a freshwater lake (Department of Environment and Heritage 2009) and to restore the Coorong lagoon by ensuring the river mouth remains open. Federal and State Governments agreed to allocate a further 450 GL where it could be demonstrated that this would accrue no socioeconomic hardship to communities in the Basin (Murray Darling Basin Authority 2012).

Today, the Basin-wide Environmental Watering Strategy (Murray Darling Basin Authority 2014), based on Lester *et al.* (2011), provides minimum expected outcomes for end-of-basin flows. These include:

- barrage flows of at least 2000 GL year^{-1} on a three-year rolling average of 95% of the time and a two-year minimum of 600 GL year^{-1};
- water levels in the lower lakes to be above sea-level and at +0.4 AHD (Australian height datum) 95% of the time;
- salinity in Lake Alexandrina to be less than 1000 µS cm^{-1} 95% of the time, and less than 1500 µS cm^{-1} all the time;
- the Murray River mouth to be open 90% of the time to an average depth of 1 m (Murray Darling Basin Authority 2014, pp. 23, 24).

These prescriptions essentially preclude the ingress of seawater from the Southern Ocean and oblige State and Commonwealth Governments to provide environmental flows of sufficient volume to the end of the MDB to maintain Lake Alexandrina in a predominantly freshwater state and to keep the river mouth open.

Two strands of evidence informed the decision to keep Lake Alexandrina fresh: (1) an interpretation based largely on historical and anecdotal evidence (Sim and Muller 2004) and (2) a new interpretation of palaeolimnological evidence by Fluin *et al.* (2009), which differs significantly from an earlier interpretation by Fluin (2002) and Fluin *et al.* (2007) that the lake was estuarine. In this paper I argue that the palaeolimnological evidence provides scientific evidence that may inform management decisions and that the best interpretation of that evidence is that Lake Alexandrina has an estuarine history, as presented by Fluin (2002) and Fluin *et al.* (2007), and now verified in Helfensdorfer *et al.* (2019). The crux of the matter, therefore is that the foundation for the claim in subsequent published literature that the Lower Lakes were always fresh relies on the findings of Fluin *et al.* (2007), which does not provide that interpretation. Further, the foundation for the claim for a freshwater history by various levels of government relies on Fluin *et al.* (2009), which neither addressed nor rebutted the findings of an estuarine history made in Fluin *et al.* (2007). The now generally accepted, but erroneous, position that Lake Alexandrina has been fresh for 7000 years provides an important foundation for the need for additional freshwater flows down the Murray River, as agreed in the MDB Plan.

Palaeolimnological research on the Coorong and Lower Lakes

Inferring salinity and haloecology from diatom frustules

Lakes and estuaries contain sediments that accumulate more or less continuously over time (Weckstrom *et al.* 2017). Buried within these sediments are chemical and biological remains that reflect the nature of the wetland at the time of sediment deposition. The collection of sediment cores, the subsampling of sediments and the identification of these remains allows for the condition of the wetland to be inferred. In estuaries this usually allows for a ~7000-year history to be outlined as this was the point in geological history that sea levels last stabilised and geomorphic evolution of present-day coastal wetlands commenced. Diatoms are particularly useful fossil bioindicators of estuarine condition (Taffs *et al.* 2017) owing to their abundance, diversity and close association with, and widespread calibration to, water chemistry (e.g. Gell 1997). Importantly also, owing to their preference for waters of particular salinities and ionic compositions, they can be used to diagnose the influence of salinity of marine origin (thalassic) compared with that from non-marine (athalassic) sources.

Prior palaeolimnological research

Barnett (1994) analysed sediment cores from Lake Alexandrina and concluded that the lake was estuarine from 7000 years ago, but despite being variable on account of climate variability, overall was fresher in the modern period as the barrages, commissioned in 1940, had restricted previous marine incursions. Bourman and Barnett (1995) observed that before barrage construction in the 1930s saline water was present sporadically far upstream and that the estuarine Lakes Albert and Alexandrina became fresh after the barrages were in place. Further, Bourman *et al.* (2000, p. 141) stated that 'barrage construction on the beach facies of the last interglacial shoreline transformed the estuary into freshwater lakes with permanently raised water levels and reduced the tidal prism by 90%'. The observations for an estuarine history, and even the intrusion of saline water 'far upstream', are now vindicated by the hydrodynamic modelling of Helfensdorfer *et al.* (2019), which suggests that estuarine conditions extended 200 km north of Lake Alexandrina during the Holocene high sea-level conditions (7000–5500 years BP) and, even under lower sea levels, Lake Alexandrina remained estuarine throughout the 7000 years before the local hydrology being altered through barrage construction in the mid 20th century.

A core taken, but not analysed by Barnett (core LA 2), and another collected by Gell and Fluin in 1996 near the river entrance (core LA 1), formed the basis of analyses in the 2002 PhD thesis of Fluin (Fluin 2002). The evidence derived from six of the 30 cores collected from the Coorong by Gell and colleagues was reported to the South Australian Department of Water, Land and Biodiversity Conservation in Gell and Haynes (2005) and is detailed in a book chapter by Gell (2017). The interpretation of the interactions between the River Murray, the Lower Lakes and the Coorong were presented at the Past Global Changes 'Salinity, Climate Change and Salinisation' workshop in Mildura in September 2004 (Gell *et al.* 2007). This conference paper was subsequently published as Fluin *et al.* (2007) on which I led the interpretation of the records from the Coorong. The published records of fossilised diatoms in the two Lake Alexandrina cores reveal changes in key indicator taxa over the last 7000 years. Non-contiguous subsampling leaves out much of the record but the data reveal gradual changes, attributed to long-term changes in regional rainfall, until the commissioning of the barrages, as discussed below.

Critical to the interpretation of the fossil record is the understanding of the ecological preferences of the taxa preserved in the sediments. This is largely achieved through the collection of modern diatom specimens and the calibration of the relative abundance of these to measured water quality parameters. This was achieved for diatoms from inland salt lakes (Gell 1997) and was completed for some Australian estuaries (Haynes *et al.* 2011; Saunders 2011; Logan and Taffs 2013). As diatoms

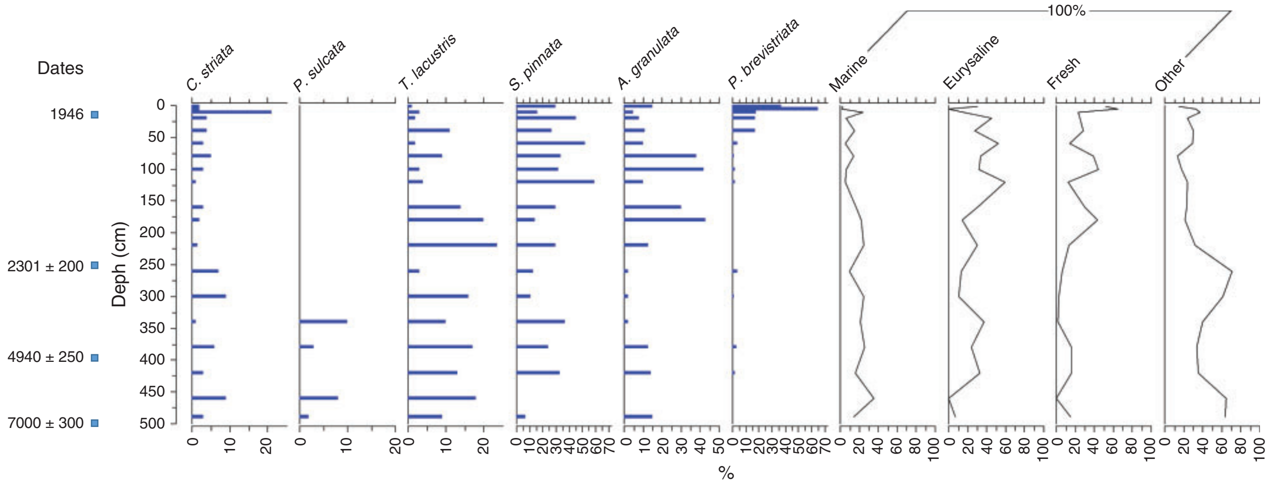

Fig. 2. Summary diagram of the diatom stratigraphy of core LA 2 (based on Fluin *et al.* 2007). The '% marine' curve = $\sum$% *C. striata*, *P. sulcata* and *T. lacustris*; '% eurysaline' = *S. pinnata*; '% fresh' = $\sum$ *P. brevistriata*, *A. granulata*; '% other' = $\sum$all other taxa on Fig. 2) (Fluin *et al.* 2007). Note variable scales in species plots.

are ecologically conservative and largely cosmopolitan, interpretation of Australian fossil sequences can benefit from the ecological preferences identified from databases developed elsewhere across the world. In summary, the salinity preferences, for example, of most widespread species of diatoms, are well known internationally, and the information is readily available in a series of papers by a range of different authors.

It is clear from this international and Australian evidence that the taxa considered marine or estuarine in Fluin *et al.* (2007), *Cyclotella striata*, *Paralia sulcata* and *Thalassiosira lacustris*, are indeed reflective of marine conditions (see Appendix 1 for detailed review of the known ecology of these taxa). None were recorded from inland salt lakes (Gell 1997) and so their presence reflects saline or subsaline conditions influenced by waters of marine (thalassic) origin. Other key taxa in the LA 2 record were *Staurosirella* (syn. *Fragilaria*) *pinnata* and *Pseudostaurosira* (syn. *Fragilaria*) *brevistriata*. Both were recorded in inland lakes with weighted average salinity optima of 3.9 g L^{-1} and 1.9 g L^{-1} respectively. Gell and Haynes (2005) and Fluin *et al.* (2007) reported *Staurosirella pinnata* to be abundant in the upper sediments of both the north and south lagoons of the Coorong, which is, and has been in historic times, saline to hypersaline. It was also recorded to be abundant in lakes of 6.3 g L^{-1} and above in Gell (1997). On the basis of this evidence *S. pinnata* appears to be highly salt tolerant (eurysaline); *P. brevistriata*, on the other hand, is regarded as an obligate freshwater taxon. While these diatoms are broadly tolerant, these inferred preferences are used to summarise the change in condition of Lake Alexandrina, as revealed from core LA 2, and presented in Fig. 2.

The interpretation by Fluin et al. (2007)

In reference to the high incidence of thalassic (marine) taxa in the early part (~5000–7000 years BP) of the Lake Alexandrina record, Fluin *et al.* (2007, p. 130) stated 'The presence of *Thalassiosira lacustris*, *Cyclotella striata* and *Paralia sulcata* indicate marine influence at this time' and 'the change in diatom community [after 5000 years BP] is likely to represent a decrease in lake level and increased penetration of seawater, possibly associated with the variable, dry climate phase after the mid-Holocene wet phase'.

The return to regional wet conditions is reflected in the passage 'The decline in *Thalassiosira lacustris* above 160 cm [~2200 years BP] marks a further increase in freshwater river input conditions, perhaps influenced by the increases in precipitation' (Fluin *et al.* 2007, p. 130).

Acknowledging the prevalence of athalassic (non-marine) taxa, Fluin *et al.* (2007, p. 132) stated: 'The Holocene diatom assemblages of Lake Alexandrina reflect relatively freshwater conditions with longstanding and major inputs from the River Murray. Marine water indicators were never dominant in Lake Alexandrina'.

The 2007 paper did, however, clearly enunciate the post-barrage change to freshwater conditions when it stated that: 'The barrages completely separate both lakes from the Coorong, with infrequent fresh water flowing through the barrage gates. As a result, Lake Alexandrina is *presently* [my emphasis] a large, predominantly fresh water system with no salt water input', and '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. Further 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*' (Fluin *et al.* 2007, p. 130).

In summary, Fluin *et al.* (2007) concluded that water column salinity in the large terminal Lake Alexandrina was only moderately influenced by tidal inflow of seawater, particularly over the past ~2000 years. It is now (i.e. today) largely fresh as a result of isolation by a series of barriers completed by 1940. Unequivocally, Fluin *et al.* (2007) stated that, before regulation, Lake Alexandrina was tidal, with the balance between marine and river influence attributable to the regional hydroclimate as revealed in the water balance records of the 'rain gauge' lakes of western Victoria. So, although it was more influenced by fresh water over the last 2000 years, Lake Alexandrina continued to be influenced by seawater and was therefore, by definition, an estuary (see Tagliapietra *et al.* 2009). The greatest change in the entire record, as revealed by the CONISS dendrogram, was *after* the commissioning of the barrages whereupon the diatom flora reflected unprecedented, freshwater conditions. Not unexpectedly, the interpretation of Fluin *et al.* (2007) is consistent with that presented in Fluin (2002).

The freshwater history expounded by Sim and Muller (2004)

Coincident with the compilation of the palaeolimnological research of Fluin and coworkers on Lake Alexandrina, the River Murray Catchment Water Management Board published the document 'A Fresh History of the Lakes: Wellington to Murray Mouth, 1800s to 1935' (Sim and Muller 2004, p. 1) that concluded that 'Prior to European settlement, Lakes Alexandrina and Albert at the terminus of the River Murray were *predominately* [my emphasis] fresh …'. Further, this document (Sim and Muller 2004, p. 1) stated that 'Contrary to what many believe today, saltwater intrusions into the Lake environment were not common until after 1900 when significant water resource development had occurred in the River Murray system'. Clearly, this conclusion is in stark contrast to that made from palaeolimnological data produced in Fluin (2002) and published in Fluin *et al.* (2007).

The interpretations of Sim and Muller (2004) are founded mostly on anecdotes, particularly those coming from the time of the Federation Drought at the turn of the 19th to 20th centuries, but more generally across the years ~1820–1935. As such, it provides a synthesis of the commentary within South Australia as to the changing nature of Lake Alexandrina and the lower reaches of the River Murray as perceived by local residents. Sim and Muller (2004, p. 1) noted that 'Short-lived intrusions of saltwater would occur during periods of low flow down river resulting in a lowered level of water in the lakes. Even in times of these low flows, it would appear that only small areas of the Lakes were affected' and that 'Saline invasions were more common after 1900 and the development of irrigation works because reduced river flows could not hold back the sea' (Sim and Muller 2004, p. 1).

The years around 1900 were characterised by one of the more significant droughts in documented history, and the reconstruction of hydroclimate since 1788 (Gergis *et al.* 2012) reveals it to have coincided with a substantial shift in the Pacific Decadal Oscillation relative to 230 years of variability. This was conceded thus: 'Irrigation schemes began at the same time as a long lasting, widespread drought that further diminished the amount of water in the river system' (Sim and Muller 2004, p. 1).

What Sim and Muller (2004) neglected to report were the findings of the 1902 Interstate Royal Commission that were contrary to their position. The Commissioners represented three States (Victoria, New South Wales and South Australia) and sought counsel from across the MDB, and not just from South Australia. Davis *et al.* (1902) reported many observations, including one which stated that 'One effect of a deep entrance channel would be to increase the saltness of the lakes, which, after a strong north-west or westerly gale, are brackish; the salt water being forced up channels as far as Wellington' (Davis *et al.* 1902, p. 33). Further, they reported the observations that 'When the winds shift to the south-east it is again blown out of the lake, a greater quantity running out under these circumstances than during any river flood' (Davis *et al.* 1902, pp. 33, 34) and that of the master of a trading boat who is quoted as saying 'he had known the water of the lakes as salt in past years' (Davis *et al.* 1902: p. 34). Ultimately, the Commissioners concluded that 'Apart from verbal statements, the evidence of facts is against the hypothesis that there has been any increase in saltness in the Murray Lakes by reason of diversion of water from the river channel' (Davis *et al.* 1902, p. 34).

Sim and Muller (2004) do not report on these contrary views expressed in Davis *et al.* (1902). Given that the 1902 Interstate Royal Commission would have been regarded, less parochially, as the authoritative document of the time, it is clear that Sim and Muller (2004) represents a small subset of the views available. For Davis *et al.* (1902) to come to a conclusion, on balance, that is so markedly different to that given in Sim and Muller (2004) suggests that the reporting in the latter is not reflective of the full range of views held at the time. We now see that the conclusions reached by Sim and Muller (2004) are not only in disagreement with the palaeolimnological evidence, but are also not consistent with the wide-ranging conclusions of the 1902 Interstate Royal Commission.

The new interpretation from Fluin et al. (2009)

From 2010 a new report (Fluin *et al.* 2009) was posted on the South Australian Government website. Entitled 'An Environmental History of the Lower Lakes and The Coorong', this 22-page report on the palaeolimnology of Lake Alexandrina and the Coorong lagoon was produced by three of the five authors of the 2007 publication. Neither Gell nor Hancock, coauthors on the 2007 publication, were authors of the 2009 report.

Using the same diagrams and descriptions as Fluin *et al.* (2007), Fluin *et al.* (2009) concluded: 'There is no evidence in the 7000 year record of substantial marine incursions into Lake Alexandrina', yet they also stated that 'There were substantial alterations to the diatom community in Lake Alexandrina following European settlement and particularly after barrage installation'. In contradiction to the evidence presented in Fluin *et al.* (2007), they asserted that: 'Over the 7000 year record, there are minimal numbers (generally <10%) of estuarine diatoms' and that '… estuarine conditions have essentially been absent from this section (LA 1) of the lake (<5%)'.

The interpretation of the LA 2 record in Fluin *et al.* (2009) can be found in the 2007 paper but with two significant changes (Table 1). Specifically, the words 'marine influence' (Fluin *et al.* 2007, p. 130) are altered to 'minor marine influence', and 'increased penetration of seawater' (Fluin *et al.* 2007, p. 130) are altered to 'increased penetration of more brackish water'. Both alterations diminish the interpretation of a tidal influence on the ecological character of Lake Alexandrina mounted in Fluin *et al.* (2007). The second alteration creates confusion as the term brackish cannot be qualified, it meaning salty waters, usually the result of freshwater mixing with seawater (e.g. Bayly 1967). So, the use of the terms 'minor' and 'brackish' serve to diminish the role of the ocean as a source of lake water salinity.

Table 1. Alterations to passages found in Fluin *et al.* (2007) and Fluin *et al.* (2009)

Passage in Fluin *et al.* (2007, p. 130)	Passage in Fluin *et al.* (2009)
The presence of *Thalassiosira lacustris*, *Cyclotella striata* and *Paralia sulcata* **indicate marine influence** at this time	The presence of *Thalassiosira lacustris*, *Cyclotella striata* and *Paralia sulcata* indicate **minor** marine influence at this time.
… the change in diatom community [after 5000 years BP] is likely to represent a decrease in lake level and increased penetration of **seawater**, possibly associated with the variable, dry climate.	… the 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.

Fluin *et al.* (2009) does not present, nor review, the interpretation made in Fluin *et al.* (2007) and merely cites it as previous work. Second, it offers no new palaeolimnological evidence from Lake Alexandrina that qualifies the record from core LA 2, nor does it provide new knowledge of the preferences of the key species that would support a new interpretation. Fluin *et al.* (2009) does, however, provide supplementary evidence in the form of an additional record of core RS 1. Although they include it under the results for Lake Alexandrina, the core was actually taken downstream from Goolwa, ~28 km from the lake and only ~7 km from the river mouth. It was taken in the Goolwa Channel, a section of the River Murray that typically carried 70% of the total flow to the mouth. This core reflects a mix of thalassic (*Cyclotella striata*, *Paralia sulcata* and *Thalassiosira lacustris*) and freshwater (*Pseudostaurosira brevistriata*) taxa before weir construction, and an increase in freshwater species (*Epithemia* spp., *Rhopalodia gibba*) after. The authors conclude that these shifts represent a change from 'marine/hypersaline waters to brackish post-barrage installation', at one point, yet that 'pre-barrage diatoms are estuarine – marine – but with an absence of typical marine diatoms' in the summary. Therefore, the LS 1 record throws no more light onto the interpretation of LA 2 other that to reinforce the conclusions that the taxa considered as indicative of marine influence in Fluin (2002) and Fluin *et al.* (2007) were so, as they were also common in sediments closer to the ocean.

Third, in their summary of Lake Alexandrina Fluin *et al.* (2009) suggest that 'in terms of salinity, it would seem that there was a continuum in Lake Alexandrina prior to barrage construction'. This represents the typical nature of estuaries where there is a gradient from seawater near the mouth to fresh inland. However, their map of the distribution of 'estuarine' and 'freshwater' states (their fig. 6) identifies clearly delineated zones and no 'continuum'. Here, the freshwater zone lies north of a line that commences just seaward of core LA 2, a site which, elsewhere in the report, they concede was 'estuarine' and 'slightly brackish' before the barrages.

Fourth, the new interpretation has a political context. It is apparent that Fluin *et al.* (2009) recognise the management context of their account when they observe in the project background that the national media have reported that many people have justified opening the barrier between the systems on the basis of a past estuarine baseline. Fluin *et al.* (2009) appear to give support to those resisting this particular management approach when they conclude '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 [their] fig. 6, this is not the case and the majority of the Lake has been fresh for its entire history'. This position, which is at odds with the conclusions reached by Fluin (2002) and Fluin *et al.* (2007), comes with no new evidence, other than that provided by core RS 1, which was taken from the Goolwa Channel, a site that was clearly estuarine. The sum of marine taxa presented in Fig. 2 here is derived from the Fluin *et al.* (2007) data and shows thalassic diatoms accounting for 5–35% of the total for ~7000 years, up until the commissioning of the barrages in 1940. As diatom productivity has been observed to be greater in the upper reaches of an estuary (Arndt *et al.* 2007), it is possible that these relative abundance values under-represent the influence of tidal waters on the salinity regime operating in Lake Alexandrina. Further, the remaining diatoms are mostly composed of valves of a euryhaline taxon, which suggests variable, saline conditions. By justifying the preclusion of the inflow of seawater as a means of managing lake acidification, which involves invoking an entirely fresh history for the lower lakes, the position posited by Fluin *et al.* (2009) lends weight to the calls for increased river flows as the management solution as proposed by Kingsford *et al.* (2009) and adopted in the environmental watering strategy (Murray Darling Basin Authority 2014). Further insight into the significance of the new interpretation may be gained from a quote from a local resident from the region cited in Gross *et al.* (2012, p. 59): 'The incentive for returning large volumes of water as environmental flows is reduced in an 'estuarine' perspective of the lakes'. It is to these water resources management issues that I now turn.

Implications of the revised interpretation on the management of the Lower Lakes

By 2010 there were available two different interpretations from palaeolimnological evidence of the prebarrage state of Lake Alexandrina, one published in *Hydrobiologia* stating that it was an estuary with the relative influence of sea and river water mediated by climate (Fluin *et al.* 2007, based on Fluin 2002 and consistent with Barnett 1994), and the other on the South Australian Government website stating that most of the lake was fresh for its entire history (Fluin *et al.* 2009). This has paved the way for considerable confusion in the scientific literature and is revealing of the way that scientific conclusions are reported, even recycled, among users of that information.

A brief exploration of the Scopus website (www.scopus.com) on 10 September 2017 showed that Fluin *et al.* (2007) had been cited on 44 occasions. Of these, 17 were self cites; two were in outputs too obscure to retrieve, eight were on matters of diatom ecology or related to determinations of sedimentation

Table 2. Details of seven papers that have used Fluin *et al.* (2007) to argue for a fresh history of the Lower Lakes

Authorship	Publication	Quote
Mosley, L.M., Zammit, B., Leyden, E., Heneker, T.M., Hipsey, M.R., Skinner, D. and Aldridge, K.T. (2012), p. 3925.	The impact of extreme low flows on the water quality of the Lower Murray River and Lakes (South Australia). *Water Resources Management* **26**, 3923–3946.	'The river channel discharges into the large (821.7 km^2 total surface area) and shallow Lower Lakes, which are freshwater, eutrophic, and highly turbid (Geddes 1984; Fluin *et al.* 2007; Cook *et al.* 2009)'
Mahon, H.C., Hammer, M.P. and Harris, J.O. (2015), p. 1491.	Effect of salinity on growth of juvenile Yarra pygmy perch (*Nannoperca obscura*: Percichthyidae). *Environmental Biology of Fishes* **98**, 1491–1500.	'The installation of tidal barrages and weirs near the mouth of the system (~1940–50s) to prevent incursion of marine water resulting from upstream hydrological abstraction, modified the hydrology and ecology of extensive freshwater lakes known as the Lower Lakes (LL) and the Coorong estuary (Fluin *et al.* 2007; Wedderburn *et al.* 2002)'
Hammer, M.P., Bice, C.M., Hall, A., Frears, A., Watt, A., Whiterod, N.S., Beheregaray, L.B., Harris, J.O. and Zampatti, B.P. (2013), p. 807.	Freshwater fish conservation in the face of critical water shortages in the southern Murray–Darling Basin, Australia. *Marine and Freshwater Research* **64**, 807–821.	'This [regulation; flow reductions] has jeopardised the future of a long-term freshwater refuge and biodiversity hotspot (Phillips and Muller 2006; Fluin *et al.* 2007; Kingsford *et al.* 2011)'
Wedderburn, S.D., Hammer, M.P. and Bice, C.M. (2012), p. 36.	Shifts in small-bodied fish assemblages resulting from drought-induced water level recession in terminating lakes of the Murray–Darling Basin, Australia. *Hydrobiologia* **692**, 35–46.	'… barrages were constructed in ~1940 in response to river regulation and water abstraction that was causing periodic marine incursion in an otherwise predominately freshwater environment (Fluin *et al.* 2007)'
Kingsford, R.T., Walker, K.F., Lester, R.E., Young, W.J., Fairweather, P.G., Sammut, J. and Geddes, M.C. (2011), p. 257.	A Ramsar wetland in crisis – the Coorong, Lower Lakes and Murray Mouth, Australia. *Marine and Freshwater Research* **62**, 255–265.	'Historically, the water in the lake was mainly fresh, indicated by freshwater diatom tests (95%) accumulated in the sediments over the past 7000 years (Barnett 1994; Fluin *et al.* 2007)'
Brookes, J.D., Aldridge, K.T., Bice, C.M., Deegan, B., Ferguson, G.J., Paton, D.C., Sheaves, M., Ye, Q. and Zampatti, B. (2015), p. 192.	Fish productivity in the lower lakes and Coorong, Australia, during severe drought. *Transactions of the Royal Society of South Australia* **139**, 189–215.	'Lake Alexandrina was estuarine prior to construction of the barrages, although paleolimnological evidence suggests it was predominantly fresh (Fluin *et al.* 2007) as river flows restricted the tidal ingress proximal to the Murray Mouth'
Hammer, M.P., Unmack, P.J., Adams, M., Johnson, J.B. and Walker, K.W. (2010), p. 221.	Phylogeographic structure in the threatened Yarra pigmy perch *Nannoperca obscura* (Teleostei: Percichthyidae) has major implications for declining populations. *Conservation Genetics* **11**, 213–223.	'In addition, the occurrence of *N. obscura* within MDB only in Lake Alexandrina supports information that this water body has been a predominantly fresh habitat over thousands of years (Sim and Muller 2004; Fluin *et al.* 2007)'

rate and eight pertained specifically to the Coorong and not the two Lower Lakes. Of the remaining nine citations, seven clearly misrepresented the findings reported in Fluin *et al.* (2007). Of these, Brookes *et al.* (2015) note the lake to have been estuarine before the barrages, but erroneously stated that the palaeolimnological evidence (i.e. Fluin *et al.* 2007) revealed it to be 'predominantly fresh'. As Table 2 reveals, most of these publications used the evidence from the palaeolimnological record to attest to a permanent freshwater history, even though the original 2007 paper, while suggesting a fresher condition under wetter climates, and a freshwater state after regulation in 1940, never stated that Lake Alexandrina was either 'predominantly fresh' or 'a freshwater refuge'. The continuous presence of marine species and the dominance of the euryhaline *Staurosirella pinnata* indicate that, at the LA 2 site, Lake Alexandrina was always an estuary and could not be defined as predominantly fresh until the construction of the barrages.

As the debate pertaining to the restoration of the Murray–Darling Basin has intensified, a composition was submitted to *The Conversation*, an independent Australian online media outlet whereby scientists can air controversial topics for the wider public to read (Finlayson *et al.* 2017). *The Conversation* encourages feedback via a Comments section, and the article drew a particularly misguided post (https://theconversation.com/we-need-more-than-just-extra-water-to-save-the-murray-darling-basin-80188):

'This has been studied using remains of diatoms, which neatly signal whether environments are saline, brackish or fresh, and *they show unambiguously that for the last 7000 years Lake Alexandrina was a freshwater environment* with only a few brief incursions of saltwater during extreme drought events (which over a 7000 time-span, you will have a few of). So yes, the lakes were indeed *predominately fresh* [my emphasis] before white man modification/water extraction. A dry read but one such paper detailing this evidence is: Fluin J, Gell P, Haynes D, Tibby J, Hancock, G. (2007). Paleolimnological evidence for the independent evolution of neighbouring terminal lakes, the Murray Darling Basin, Australia. Hydrobiologia 591: 117–134'.

Remarkably, the person posting the comment concluded that the Lower Lakes were predominantly fresh, which was not the actual conclusion of the paper he/she cited.

In summary, the discussion above shows that a range of writers, including scientists and members of the wider public, appear to have used Fluin *et al.* (2007) to lend authority to a position they themselves had surmised existed in the lower lakes over the past ~7000 years. While members of the wider public may find website reports easily accessible, most authors of scientific papers have ready access to peer-reviewed journals and *Hydrobiologia* is a well recognised means of disseminating such work. So, how did they get it so wrong? There are several possible explanations:

- They read Fluin *et al.* (2007) and concluded that the authors said, or intended to say, that Lake Alexandrina was 'predominantly fresh' thereby exhibiting 'confirmation bias' (*sensu* Berger and Johnston 2015);
- They assumed that the condition of the lake was 'predominantly fresh' and used Fluin *et al.* (2007) as an authority without checking it first to confirm that interpretation;
- They took the opinion of Sim and Muller (2004) that the lake was 'predominantly fresh' but sought, or were required under review, to cite peer-reviewed evidence to that effect, and failed to check the original 2007 article;
- They had read Fluin *et al.* (2009) which provided them with the conclusion that the lake was 'predominantly fresh', but cited Fluin *et al.* (2007) as the authority anyway.

Irrespective of the means by which 'predominantly fresh' became the accepted natural condition of the Lower Lakes, it seems that the science community has, perhaps inadvertently, presented a conclusion that is at odds with the original representation of the published palaeolimnological evidence, whether that be from Fluin *et al.* (2007) or even from previous interpretations from Barnett (1994), Bourman and Barnett (1995) or Bourman *et al.* (2000).

Despite the published paper by Fluin *et al.* (2007) clearly observing a variable, estuarine state before the barrages and the onset of fresh conditions after their commissioning, government agencies have used and cited, exclusively, the conclusions of the unpublished Fluin *et al.* (2009) in considerations on the natural state of Lake Alexandrina. For example, the South Australian Department of Environment and Heritage (2009, p. 4) stated: 'The diatom record in lakebed sediments provides strong evidence that the Lower Lakes have been predominantly freshwater for the last 7000 years and that seawater ingressions, when they did occur, did not extend northwards of Point Sturt', which is seaward of core site LA 2. This position was released in a fact sheet (Government of South Australia 2010) which stated that 'Diatoms found in 7000 years of sediments indicate the majority of Lake Alexandrina was freshwater in all years'. These documents were consolidated in Lester *et al.* (2011), which identified the water requirements for Lake Alexandrina. None of these documents cited or addressed the observations of an estuarine history as described in Fluin *et al.* (2007), nor the observations of Barnett (1994); Bourman and Barnett (1995) and Bourman *et al.* (2000). The permanently fresh interpretation from Fluin *et al.* (2009) was then adopted in the environmental watering strategy (Murray Darling Basin Authority 2014) that set targets for Lake Alexandrina as being 'full' and 'fresh' ($<$1000 EC) 95% of the time, maintained by the release of at least 2000 GL year^{-1} over the barrages. In conclusion, the new interpretation and its widespread adoption have acted to obfuscate the original conclusions of several earlier, published palaeolimnological studies and have appeared to strongly influence the socio-political decision-making process that has laid down an outcome of great ecological, social and economic consequence for water management in Australia.

It is odd that the grey-literature report (Fluin *et al.* 2009), which occurred only on a potentially transient webpage, was the preferred reference upon which to base these decisions, compared with a series of peer-reviewed papers in international journals with full archiving information and access. Now, this decision to set water quality targets, based on a new interpretation of a fresh history, and so to prioritise allocation of scarce environmental water to Lake Alexandrina, is challenged in the literature by Helfensdorfer *et al.* (2019). This new published paper not only affirms Lake Alexandrina to have been estuarine for the last 7000 years (i.e. prebarrages) but provides evidence for the tidal influence reaching more than 200 km inland before 5500 years BP. The interpretations found in the reports of Sim and Muller (2004) and Fluin *et al.* (2009) are at odds with the published, peer-reviewed observations of Barnett (1994), Bourman and Barnett (1995), Bourman *et al.* (2000), Fluin *et al.* (2007) and now Helfensdorfer *et al.* (2019). Despite this, it is the interpretations from the former alone that have been adopted by government to derive a highly significant water allocation decision.

Wider implications for science and conservation advocacy

In the acute national contest under the allocation of water under the MDB Plan of 2012, we have evidence for peer-reviewed, published science being supplanted by multiple reports in the grey literature (e.g. Sim and Muller 2004; Fluin *et al.* 2009) without the provision of new evidence, valid reinterpretation or the establishment of any shortcomings of the original scientific research. Although Fluin *et al.* (2009) included new data from core RS 1 in the Goolwa channel, some 28 km downstream, as part of new evidence of the salinity history of Lake Alexandrina, it provided a revised interpretation of Lake Alexandrina, and core LA 2 specifically, without providing any new evidence from Lake Alexandrina *sensu stricto*. This opened a contest of interpretations that continues on internet posts and blogs today, and likely influenced decisions made under the MDB Plan, the largest investment by government into the rehabilitation of a degraded river system in Australia.

Postmodern deconstruction of scientific evidence dispels the myth that science is ever entirely objective. Head (1995), for example, neatly portrayed the likely inherent biases in the condition of the author of the well known and highly influential book 'The Future Eaters' (Flannery 1994), the celebrated version of the coevolution of the Australian landscape and its people. Being human, it is nigh impossible for a scientist to remain absolutely objective, and society always ought to contextualise the author or speaker when absorbing the evidence put forward by scientists, particularly when a given management position is advocated. However, while a single position may be advocated, even based on strong epistemic values, for many practitioners it remains that conservation biologists may have licence, and even a duty, to advocate from non-epistemic evidence (Boon 2019) given the 'crisis' nature of the discipline. The wider community, however, might be justified in seeking to know when a scientist is drawing exclusively on empirical evidence, albeit from a personal context, and when he/she is advocating a position to counter the forces leading to 'the current state and trajectory of the natural world' (Boon 2019).

The warning for us in this story about water management and pre-European ecological states in the MDB is that it is critical that published interpretations be revised only in association with either (1) evidence of important errors of fact or interpretation in the original papers, or (2) the provision of new evidence that supplants earlier findings. Both are valid grounds for the taking of a new or revised position, and indeed the very progress of scientific understanding requires that this type of revision takes place. When it comes to presenting scientific evidence, however, scientists should realise that the political process has no conscience. Because of this reality, we must preserve the reputation of our science by reporting it objectively and making clear when we are advocating from non-epistemic evidence. Then, as members of a civil society, we may apply our right to participate in the challenging processes that make decisions that affect people, their places and the environment.

In the case of water allocations in the MDB, this case-study shows the values of maintaining the correct and transparent use of scientific information in a complex aquatic/terrestrial system in which the following conditions hold:

(1) There is considerable competition for fresh water in the MDB and this had led to political conflict. Essentially, there is not enough water to meet irrigation demand, much less maintain a biodiverse and functional ecosystem.
(2) This conflict led to a program of national regulation of water flows to maintain the river's natural environment and provide for human use, the 2012 MDB Plan. This approach is, however, merely the most recent manifestation of a debate that has gone on for well over a century and has included several Royal Commissions.
(3) The compromises reached in the 2012 MDB Plan do not satisfy all users and there is a national debate on just how much water should be allowed to flow to the mouth of the river for both environmental needs and use by South Australians.
(4) The amount of data available to inform management decisions about water use and availability is very restricted and is subject to a certain degree of interpretation.
(5) Considerably more research is needed before any resolution of the likely state of the MDB prior to European settlement, or even before the implementation of large-scale river diversions and irrigation schemes in the early parts of the 20th century, can be understood. Even then it is possible that any such state would differ today regardless of human uses of the river.
(6) The consistent and transparent use of scientific information, subject to peer-review and published in the scientific literature, is critical to the resolution of these problems.

Conflicts of interest

The author declares no conflict of interest.

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Appendix 1. Ecological preferences of key fossil indicator taxa

Cyclotella striata

The *Cyclotella striata* species complex includes numerous species and subspecies with similar morphology (Håkansson 1996). Problems exist surrounding the identification of these centric species in part because, in saline inland lakes, estuaries and lakes with high conductivities, there is a mix of marine and freshwater species and often the nomenclature has been guided by the ecology of the species being named (Håkansson 1996). The *Cyclotella* group has a wide environmental tolerance, but only eight species have been found in saline waters (Olvia *et al.* 2008) including those in the *C. striata* complex. *C. striata sensu* stricto has been described as being prevalent in brackish, marine, estuarine and inland saline lakes (Bradbury *et al.* 1981; Jiang *et al.* 1997; Saunders *et al.* 2008; Cook *et al.* 2016). It was regarded by Roetzel *et al.* (2006) as being allochthonous euryhaline (able to adapt to a wide range of salinities). Jiang *et al.* (1997) attributed a rapid increase in *C. striata* in a core from the north-eastern Atlantic margin to a decrease in sea salinity as a result of strong coastal currents and global sea level rise. They also observed it commonly in the spring plankton in estuaries along the North Sea coast. While Pokras (1991) reported *C. striata* as a brackish water species from the Zaire River, Africa, Marshall and Alden (1990) referred to it as being a freshwater species abundant in the estuarine rivers of the Lower Chesapeake Bay, USA. Declining abundance of *C. striata* in Chesapeake Bay cores was associated with increasing turbidity and eutrophic conditions following European settlement in the 18th century (Marshall *et al.* 2005).

Paralia sulcata

Paralia sulcata has been reported in waters of varying salinities, from brackish to marine (McQuoid and Norberg 2003); however, it is widely accepted as being predominantly marine (Westerman and Andrèn 1994) where it inhabits the benthos and plankton zones. It has a widespread cosmopolitan preference for marine littoral zones of the Baltic (Westerman and Andrèn 1994) and has been recorded from the Arctic to the tropics. It preserves well in the sediments of water bodies and can be useful as a palaeoindicator species (McQuoid and Norberg 2003) but can be resuspended into the water column from the benthos by tidal mixing and wind. This, and its broad tolerance, means that detailed interpretation of the presence of this species can be difficult (McQuoid and Norberg 2003). Commonly, the occurrence of *P. sulcata* in the sediment record has been interpreted as being an indication of high primary production caused by coastal upwelling (McQuoid and Norberg 2003). McQuoid and Norberg (2003) suggest that *P. sulcata* may have a competitive advantage in low light conditions as it is often recorded in increased abundances in winter (Gebühr *et al.* 2009) but this may also indicate an increase in the mixing of the benthos. It has also been found to have a negative correlation with salinity levels in the Inlets of British Columbia, showing its preference for estuarine, rather than marine, conditions and Gebühr *et al.* (2009) suggested that high salinity may be a limiting factor for this species. The interpretation of declining abundances of *P. sulcata* have been attributed to an increase in deposition of fine, organic sediment (Mills *et al.* 2009), and freshwater or increased sediment flux in Chesapeake Bay (Cooper 1995). However, in contrast to the above studies, Zong (1997) reported *P. sulcata* in greater numbers in areas of fine-grained organic rich sediments.

Thalassiosira lacustris

The Thalassiosirales (from thalassic, meaning of marine origin) are known to include marine, planktonic, diatom genera, although there are ~12 fresh or brackish-water species recognised (Alverson *et al.* 2011; Hasle 1978). Because of the diversity in valve morphology there is much confusion surrounding the taxonomy of the genus *Thalassiosira* (Smucker *et al.* 2008). *Thalassiosira lacustris* was first described in 1856 as being a freshwater species (Hasle and Lange 1989) but this species has since been recorded from both marine and freshwater environments (Hasle and Lange 1989), as reported by Hustedt as early as 1928. Smucker *et al.* (2006) reported the species primarily in marine coastal regions but also from large rivers around the world. It was reported as spreading in North America, first being noted in environments such as coastal areas and large brackish rivers, but Smucker *et al.* (2008) collected it from several inland streams, although it was not recorded in any great abundance, except where moderate to high stream conductivities were also recorded. They concluded that *T. lacustris* can tolerate a wide range of habitats but is most likely to occur in brackish water as opposed to freshwater environs and was found in large numbers only in waters where moderately high conductivity also existed. Kasperoviciene and Olenina (1994) described it as a freshwater species with a brackish water affinity while Soons *et al.* (1997) used it to infer a freshwater zone above brackish sediment sequence collected in Canterbury, New Zealand. John (1983) observed it in rivers in Western Australia where he described its habitat preference to be brackish with a salinity range of between 2.5 and 15%, although he found it in the lower part of the Swan River estuary, where salinity levels were 15–35%. The optimum electrical conductivity of *T. lacustris* collected from mostly freshwater samples in the Murray River was found to be 936 $\mu S\ cm^{-1}$ (Tibby and Reid 2004) yet Smucker *et al.* (2008) reported that *T. lacustris* did not reach high numbers when the conductivity was <400 or $>2000\ \mu S\ cm^{-1}$.