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REPLY

Reply to the discussion by Gell and Finlayson (2023)

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The discussion by Gell and Finlayson (2023) contains incorrect assertions and fails to disprove the multi-faceted independent scientific evidence presented by Bourman *et al.* (2022), and the subsequent work of Tibby *et al*. (2022) supporting a predominantly freshwater condition of the Lower Murray and the Lower Lakes in South Australia throughout the Holocene. The paper by Bourman *et al.* (2022) represents the contributions of 16 specialist scientists whose independent research was combined and provided multiple line of evidence supporting these conditions. With these findings, it became evident that there was no scientific basis for claims such as those made by Helfensdorfer *et al.* (2020, 2021), Hubble *et al*. (2021) and Job *et al*. (2021) that the lakes were marine- and estuarine-dominated. There is no political necessity for Bourman *et al.* (2022) to promote a freshwater management strategy for the Lower Lakes, as this has already been achieved under the Murray–Darling Basin Plan developed with extensive community consultation (Murray–Darling Basin Authority, 2012). The scientific basis of this plan has also been recently reinforced by an independent study commissioned by the Murray–Darling Basin Authority, which concluded that the Lower Lakes were predominantly fresh during the 300 years before the arrival of Europeans (Chiew *et al*., 2020). This condition thus provides a reliable baseline for future management, as it best approximates the environmental condition of the lakes in the past and present.

We welcome the suggestion of Gell and Finlayson (2023) that discussion of the salinity history of the Lower Murray should define freshwater thresholds. In recent work (Tibby *et al*., 2020, 2022) and herein, a salinity threshold of <3000 mg/L (total dissolved solids) is applied to define freshwater conditions, as it has a strong ecological basis and is widely used in Australia (Nielsen *et al*., 2003). In this context, Gell and Finlayson (2023) are incorrect in implying that the environmental watering requirements for Lake Alexandrina have any basis in the definition of fresh. Rather, they are based on the environmental tolerances of freshwater taxa with important ecological and/or societal values (*e.g. Cycnogeton procerum* and *Nannoperca obscura*; Lester *et al*., 2011).

We agree with the need to recognise changes in boundary conditions and cognisance of the diversity of interests within the basin. However, we also argue that management decisions should be based on the best available science, the central tenet of the paper by Bourman *et al.* (2022). Under contemporary River Murray inflows, an open-barrage seawater future for the lakes based on incorrect paleohydrological assumptions would be highly likely to create an environmental disaster. A window into this type of future was evidenced by the extremely poor condition of the Lower Lakes when they salinised during the Millennium Drought (Kingsford *et al*., 2011). Gell and Finlayson (2023) express concern about the ongoing role of the barrages, which were constructed across the discharge channels of the River Murray during the Great Depression and completed in 1940, with a projected lifespan of 50 years. They support the view of Job *et al.* (2021) that the role of the barrages should be re-evaluated, particularly in light of 'the drying climate'. The key issue, which the barrages address, is not 'the drying climate' but the large diminution of historically quasi-annual winter

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freshwater flows, owing to water extraction and diversion, that previously flushed the Lower Lakes and the Murray Mouth even in years of average to below-average flows between flood years (Tibby *et al*., 2022).

The paper of Finlayson *et al*. (2022) does more than 'merely suggest the "reoperation of the barrages" to allow the inlet of tidal water, which may improve fish passage'. As was demonstrated and discussed extensively by Mosley *et al*. (2022), the management suggestion considered by Finlayson *et al*. (2022) would have deleterious consequences for the lakes on multiple freshwater fish species. However, we do favour the installation of more fish ladders at weirs and barrages, and the more nuanced operation of the barrages, which would be beneficial for estuarine-dependent fish: increased automation of the barrage system could facilitate micro-management of barrage operation depending on tidal cycles and river flows allowing the passage of fish through the barrage system, as also noted by Mosley *et al*. (2022).

Gell and Finlayson (2023) state that the 'always fresh future' for the lakes is constantly advocated by Bourman *et al*. (2022). This is not so, because the salinity of the Lower Lakes varies spatially and temporally depending on freshwater flows related to El Niño and La Niña drought and flood events, and tidal and wind conditions (Figure 1; Ryan, 2018). Bourman *et al*. (2022) state that the lakes were *predominantly* fresh, not always fresh. When Sturt entered Lake Alexandria from the River Murray in 1802, he commented that the water was sweet, but when he reached Point Sturt, the water had become brackish (Grenfell Price, 1928; Sturt, 1834). The position of the fresh/brackish transition zone, the 'meeting of the waters' (Bell, 1998), varied but predominantly extended south of Point Sturt, with the outflow of the river keeping the sea at bay. The position of the fresh/saltwater boundary would have varied moving to the north during drought, whereas during floods, the whole system would have been fresh with the main body of Lake Alexandrina being predominantly fresh throughout these changes. We note also that the Australian Drinking Water Guidelines consider that a salinity greater than 1200 mg/L is 'unacceptable (unpalatable)' for drinking (NHMRC & NRMMC, 2011), which is approximately 30 times less than seawater salinity. Hence Sturt's observations on water taste are consistent with the predominantly freshwater evidence presented in Bourman *et al*. (2022) and Tibby *et al*. (2022).

Gell and Finlayson (2023) have also incorrectly asserted that the natural salinity of the River Murray at Morgan 'regularly exceeds' 700 mg/L. From this, they suggest that waters flowing into Lake Alexandrina would have been predominantly oligosaline and not fresh. They cite Tibby and Reid (2004), whose River Murray salinity data were from 1991 to 1992, and a diatom paleolimnological record from Tareena Billabong (Gell, Bulpin *et al*., 2005), which is more than 5 km from the River Murray and more than 900 km from Lake Alexandrina. The Tareena Billabong record is therefore not relevant, although notably Gell, Bulpin *et al*. (2005) conclude that waters in the billabong were at times '∼600 mg/L' (*i.e.* fresh), as indicated by a variety of diatoms that included *Staurosira elliptica*. Salinity at Morgan exceeded 700 mg/L, particularly in the period of the mid-1960s to the mid-1990s (Hart *et al*., 2020) because this is

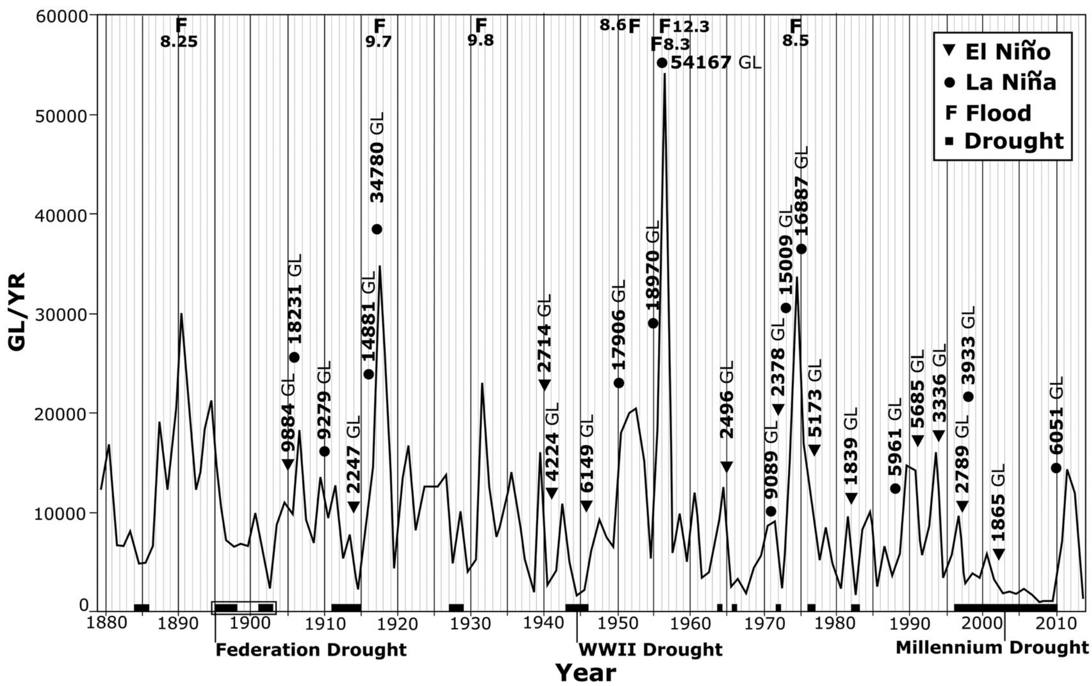

Figure 1. Record of annual flow into South Australia (in gigalitres/year) with the strongest El Niño and La Niña events and their corresponding flows (Source: Ryan, 2018). Note the record of severe droughts and floods in the Murray–Darling Basin and River Murray Floods with corresponding flood peak heights at Morgan in metres.

the apex of zones of enhanced saline groundwater expulsion, from Renmark to Morgan, and now subject to major salt interception schemes to alleviate this relatively recent issue (Barnett, 1989; Telfer *et al*., 2012). Saline groundwater inflows to the Murray floodplain have increased significantly over the past century, a result of extensive land clearances, poor irrigation practices and increased groundwater recharge, all acting to increase salt loads into the river at the same time as decreased river flow reduces its ability to dilute, transport and mitigate the salt load. This source of salt has nothing to do with whether the Lower Lakes were largely fresh or dominated by marine incursions during the Holocene. Similar inherited saline seepages occur on the margin of Lake Albert when water levels are low. The salt interception schemes between Renmark and Morgan have been successful in lowering saline water-table levels and reducing these saline water seepages into the river. Hence, salinity in the River Murray at Morgan over the past two decades has rarely, if ever, exceeded 800 μS cm^{-1} ($\ll$ 500 mg/L) (Hart *et al*., 2020). Hence, the claims of Gell and Finlayson (2023) about the salinity of the River Murray not being fresh (even using their stringent definition) have no basis.

The coincidence of upstream freshwater extractions along with the Federation Drought of 1895–1902, followed by increased diversions, led to more frequent seawater intrusions and the development of plans to construct the five barrages across the discharge channels linking Lake Alexandrina to the Goolwa Channel and the Coorong, primarily to maintain freshwater in the lakes.

Gell and Finlayson (2023) also discuss the low-resolution LA2 diatom record from central Lake Alexandrina. This record has been debated elsewhere but was not discussed at length in Bourman *et al.* (2022). In terms of diatom evidence, the LA2 record has largely been subsumed by the records in Tibby *et al*. (2022) and to a lesser extent by those in Haynes *et al*. (2019). These records are both more precisely dated than LA2 and at a much higher resolution. Hence, we briefly summarise them here. Furthermore, Tibby *et al*. (2022) include hydrodynamic modelling, which together with the diatom data, shows that even with a more open barrier system and with higher sea-levels, the Lower Lakes were fresh in more than 80% of years. Gell and Finlayson (2023) suggest that a post-colonisation shift to *Pseudostaurosira brevistriata* in, at most, four samples from the low-resolution LA2 record is evidence that Lake Alexandrina became fresher. However, this is the only core where such a change in observed, and previous work based on a higher-resolution diatom record drew the opposite conclusion (Gell, Tiddy *et al*., 2005, table 1). In other central basin Lake Alexandrina cores, namely Ax3 and Ax9 (Haynes *et al*., 2019) and Ax2 and Ax7 (Tibby *et al*., 2022; supplementary material), *Staurosirella pinnata* is the dominant post-colonisation diatom, represented by more than 60 samples. In Ax7, it shares this dominance with *Staurosira elliptica. Staurosirella pinnata* is also the dominant post-colonisation diatom in Lake Albert (Haynes *et al*., 2019; Tibby *et al*., 2022).

With respect to the freshwater mussel (*Velesunio ambiguus*) Gell and Finlayson (2023) argue that it has a preferred oligosaline range, as does the Southern Pygmy Perch. However, this does not demonstrate that these taxa did not live in freshwater. In addition to freshwater mussels (dominantly, but not exclusively the billabong mussel), other freshwater indicators included the otoliths of freshwater fish (Murray Cod, Golden Perch), freshwater crayfish and freshwater turtles (Wilson, 2017; Wilson *et al*., 2022). The freshwater mussels *V. ambiguous* and *A. jacksoni* are generally restricted to salinities <3000 mg/L (Walker *et al*., 2001). Although they can withstand salinities of 5000–10 000 mg/L for short periods, they are 'physiologically adapted to function best at considerably lower salinities' (Walker, 1981). On the other hand, the microscopic larval stage of *V. ambiguus* can only survive for half a day at 6000 mg/L and about 13 days at 400 mg/L (Walker, 1981), with self-maintaining populations unlikely to occur at salinities >3500 mg/L. The middens of the Lower Murray (Wilson *et al*., 2012, 2022) depict healthy, self-sustaining populations, not a population on the limits as demonstrated by shell densities and molluscan weights. Most importantly, no remains of estuarine and/or marine fossils were identified in the middens, in areas proposed as marine by Helfensdorfer *et al*. (2020).

Gell and Finlayson (2023) also questioned the interpretation of the Riverglen RG2 diatom record as fresh. They argue that the presence of taxa with broad-ranging salinity tolerances (*e.g. Staurosira elliptica*, *Staurosirella pinnata* and *Cocconeis placentula)* suggests that the salinity of the site was variable. However, as argued elsewhere (Tibby *et al*., 2020), the presence of taxa with broad tolerances, which, critically, are often abundant in freshwaters, must be considered in the context of the other parts of the assemblages. Specifically, Tibby *et al*. (2020, p. 145) highlight that *S. pinnata* 'has been reported from hundreds, if not thousands, of freshwater lakes and streams around the world' and note a similar situation for *Cocconeis placentula*. The overwhelming dominance of freshwater diatoms in the RG2 record, in the absence of taxa that are restricted to saline waters, indicates that the water was fresh *even in* the presence of taxa that have a broad tolerance. Similarly, Gell, Bulpin *et al*. (2005, p. 446) interpret the salinity of Tareena Billabong as '$\sim$600 mg/L' based on an assemblage that includes *Staurosirella elliptica* and *Staurosirella pinnata* in similar if not higher proportions to those in the Riverglen record. Accordingly, there is no evidence to suggest the Riverglen site was anything other than fresh.

Gell and Finlayson (2023) ignore the genetic and the ecological niche modelling evidence demonstrating the prevalence of the freshwater Southern Pygmy Perch throughout the Pleistocene in Lake Alexandrina and the lower River Murray (Buckley *et al*., 2021, 2022). Instead, they imply that the state-level listing of this species as endangered (Hammer *et al*., 2013; Marshall *et al*., 2022) is not a cause of concern, and that water management should target the nationally listed Murray hardyhead, a species with higher salinity tolerance than most native freshwater fishes of the Murray–Darling Basin (Wedderburn *et al*., 2007). These two species are part of a group of five threatened small-bodied freshwater fish species that are of critical conservation status in the Lower Lakes because of altered river regulation, including local and catchment-wide water abstraction, and other threats such as habitat degradation and alien species (Hammer *et al*., 2013). Management strategies in the Lower Lakes should focus on all five threatened species (see Hammer *et al*., 2013 for details about conservation status and multi-species management), including restoring connectivity between the genetically isolated Lower Lakes populations of Southern Pygmy Perch (Cole *et al*., 2016) and Murray hardyhead (Thiele *et al*., 2020) with their upstream riverine populations.

We do not accept that Bird (1962, p. 204) was 'misguided' when he wrote: 'After winter rains, and particularly after flooding in the Murray valley, the lakes became almost fresh, but in drought periods the reduction in freshwater inflow led to invasion of the lakes by sea water, and high levels of salinity were attained.' However, Bird does not mention the added influence of irrigation water abstractions upstream, which increased the impacts of droughts. Furthermore, Bird wrote 60 years ago and did not have available the vast amount of scientific data acquired since that time, which indicates a predominantly freshwater history of the Lower Lakes during the Holocene as summarised by Bourman *et al*. (2022).

There is no doubt that there have been many changes to the natural ecological character of the Murray Estuary: the reduction in freshwater flows as irrigation schemes have developed upstream, and the construction of a barrage system across the lower reaches of the estuary. The barrages were built to retain freshwater in Lake Alexandrina and Lake Albert, a status that most closely replicates the original system 300 years before colonisation, as concluded by the independent study of Chiew *et al*. (2020). An open-barrage seawater option for the Lower Lakes, under contemporary River Murray inflows, could have many unintended and negative ecological and socio-economic consequences.

In conclusion, we refute the claim by Gell and Finlayson (2023) that we advocate a politically motivated, 'always fresh', terminal region of the River Murray. Based upon the best available science, it is clear that the system was variable but that the Lower Lakes and the Lower River Murray were predominantly fresh. The current salinity closely replicates the natural status of the Lower Lakes with the main change being the absence of the dynamic 'meeting of the waters', the brackish zone between fresh river water and the saline oceanic water.

Disclosure statement

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