Australian Journal of Earth Sciences

An International Geoscience Journal of the Geological Society of Australia

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/taje20

Holocene freshwater history of the Lower River Murray and its terminal lakes, Alexandrina and Albert, South Australia, and its relevance to contemporary environmental management

R. P. Bourman, C. V. Murray-Wallace, C. Wilson, L. Mosley, J. Tibby, D. D. Ryan, E. D. De Carli, A. Tulley, A. P. Belperio, D. Haynes, A. Roberts, C. Westell, E. J. Barnett, S. Dillenburg, L. B. Beheregaray & P. A. Hesp

AUSTRALIAN JOURNAL OF EARTH SCIENCES
https://doi.org/10.1080/08120099.2022.2019115

Holocene freshwater history of the Lower River Murray and its terminal lakes, Alexandrina and Albert, South Australia, and its relevance to contemporary environmental management

R. P. Bourman[a,b,c], C. V. Murray-Wallace[a], C. Wilson[d,e], L. Mosley[f], J. Tibby[b,g], D. D. Ryan[a], E. D. De Carli[a], A. Tulley[h], A. P. Belperio[i], D. Haynes[g,j], A. Roberts[d], C. Westell[d], E. J. Barnett[c,f], S. Dillenburg[k], L. B. Beheregaray[l] and P. A. Hesp[c]

[a]School of Earth, Atmospheric and Life Sciences, Faculty of Science, Medicine and Health, University of Wollongong, Wollongong, Australia; [b]Department of Geography, Environment and Population, University of Adelaide, Adelaide, Australia; [c]Beach and Dune Systems (BEADS) Laboratory, College of Science and Engineering, Flinders University, Bedford Park, Australia; [d]College of Humanities Arts and Social Sciences, Flinders University, Bedford Park, Australia; [e]Centre for Australian Biodiversity and Heritage (CABAH), Adelaide, Australia; [f]School of Biological Sciences, University of Adelaide, Adelaide, Australia; [g]Sprigg Geobiology Centre, University of Adelaide, Adelaide, Australia; [h]Department of Geography and Environmental Science, University of Southampton, Southampton, UK; [i]Minotaur Exploration, Norwood, Australia; [j]School of Physical Sciences, University of Adelaide, Adelaide, Australia; [k]Geosciences Institute, Federal University of Rio Grande do Sul, Porto Alegre, Brazil; [l]Molecular Ecology Laboratory (MELFU), College of Science and Engineering, Flinders University, Bedford Park, SA, Australia

ABSTRACT

Recent claims based on hydrodynamic modelling within a sequence stratigraphical perspective of incised valley fill sedimentation have argued that the Lower River Murray and its terminal lakes Alexandrina and Albert represented a marine–estuarine lake system, with marine salinities for some 200 km upstream from the Murray Mouth. These claims have encouraged proposals for the removal of barrages near the Murray Mouth to restore the 'original natural condition' of the lakes. It has also been suggested that fine-grained terrestrial sediments were trapped in this mega-lake, necessitating a re-assessment of the Holocene climatic history of southeastern Australia determined from the study of continental slope cores. We show that throughout Holocene time (the past 11.7 ka), the Lower River Murray remained a freshwater-dominated system, based on a range of mutually complementary sedimentary evidence. Radiocarbon dating of Aboriginal middens adjacent to the river and lakes comprising freshwater mussels (dominantly *Velesunio ambiguous*), crayfish (*Euastacus armatus*), turtles (*Emydura macquarii*) and otoliths of freshwater fish species, such as Murray cod (*Maccullochella peelii*), confirm freshwater riverine and lacustrine conditions throughout the Holocene. Lake Alexandrina also contains endemic obligate freshwater fishes, including a genetically divergent and locally adapted lineage of southern pygmy perch (*Nannorpeca australis*), revealing an evolutionary history linked to freshwater habitat in the lakes since the late Pleistocene. Freshwater diatoms from fine-grained fluvial clay successions at Riverglen Marina, and diatoms and lacustrine sediments, including sapropels in the lower lakes and their former embayments of Cooke Plains and Waltowa Swamp, also chronicle a history of freshwater deposition. Lakeshore ridges of terrestrially derived quartz sand formed during elevated freshwater lake levels 8.0 ± 1.2 ka ago, while consolidated masses of the freshwater clam *Corbicula australis,* radiocarbon dated at 2650 ± 90 year BP, also attest to long-term freshwater conditions. An open Murray Mouth is *prima facie* evidence for sustained river discharge, and the mouth remained open throughout the Holocene based on geomorphological evidence. The barrages that were built to retain freshwater within the lower lakes, in response to upstream water abstractions, which had reduced river flows, provide the closest analogue of the 'original' conditions of this environment. With increased automation, nuanced barrage operation could even better simulate the original environment, whereas removing the barrages and building a weir at Wellington would destroy the character of this internationally significant Ramsar Wetland, with detrimental impacts farther upstream.

KEY POINTS

1. Paleoclimatic, geomorphological and modelling reconstructions, together with sedimentary records based on freshwater diatoms, molluscs, fish, turtles and lacustrine systems and evidence of genetically divergent and locally adapted obligate freshwater fishes, demonstrate that predominantly freshwater conditions were present in the Lower River Murray and its terminal lakes throughout Holocene time (11.7 ka).

ARTICLE HISTORY
Received 8 September 2021
Accepted 8 December 2021

KEYWORDS
Lower River Murray; Lower Lakes; freshwater environments; mid-Holocene sea-level; archaeology; freshwater Aboriginal middens; diatoms; saprolite (Coorongite); lacustrine sediments; river management

CONTACT Colin Murray-Wallace cwallace@uow.edu.au School of Earth, Atmospheric and Life Sciences, Faculty of Science, Medicine and Health, University of Wollongong, Wollongong, NSW 2522, Australia
Editorial handling: Brian Jones

2. The empirical observations presented in this paper reveal that a large marine-dominated mid-Holocene estuary was not present in the Lower River Murray, Australia.
3. Proposals to remove the barrages near the Murray Mouth would destroy the long-term freshwater environment of this Internationally Significant Wetland Site with negative ecological impacts.

Introduction

The management of the Murray–Darling Basin remains an extremely contentious issue. Some researchers have called for the removal of the barrages near the Murray Mouth to allow marine waters to transform the current freshwater environment of the Lower Murray Lakes. Some protagonists believe that this was the 'natural' condition of the lakes in pre-European times and advocate for a vigorous examination of the long-term evolution of the geologically recent salinity regimes, especially in the light of maintaining economic production by irrigation under changing climatic conditions. For example, Job *et al.* (2021) argued that the Lower Murray Lakes display the morphology typical of a wave-dominated estuary and considered that the lakes had been in a persistent, mature estuarine state over the past 3500 years until construction of the barrages fundamentally changed their hydro-sedimentological functions.

One management proposal, involving the construction of a weir at Wellington and removal of the barrages, was discussed by Thom *et al.* (2020), who thought that this would 'recreate a more "natural" estuarine environment' (p. 9) by tidally flushing the lakes with seawater. They considered that simply removing the barrages would not restore the original tidal prism because of the extensive buildup of the flood-tidal delta at the site of the natural mouth and envisaged that it would require creation of a new entrance with training walls extending seawards to −15 m AHD (Australian Height Datum), beyond the inner shelf sand zone.

Recent studies by Helfensdorfer *et al.* (2019, 2020) and Power *et al.* (2020) contended that during the mid-Holocene (*ca* 8500–5000 cal yr BP), a huge estuarine–marine lake, 'Lake Mannum', occupied lakes Alexandrina and Albert, and the Lower River Murray across the full width of the Murray Gorge for up to 200 river kilometres upstream. Furthermore, they argued that vast quantities of terrestrially derived sediments were sequestered in this lake, primarily in a central basin, largely preventing their transfer to the ocean.

In this paper, we demonstrate that throughout Holocene time (11.7 ka), not only was the Lower River Murray a freshwater system, but also the Lower Lakes (Alexandrina and Albert) were predominantly fresh. This conclusion is supported by evidence from paleo-environmental studies including geomorphological reconstructions, sedimentary records, the biota of the riverine and lacustrine systems, and the archaeological record. Thus, this paper highlights the long-term freshwater character of the Lower River Murray and its terminal lakes Alexandrina and Albert, emphasising the need to maintain freshwater flows not only to sustain the current environment, which has evolved over the past 11.7 ka, but also to conserve the wetland as a Ramsar Wetland of International Importance.

Regional setting and geomorphological history

The Murray–Darling Basin, the largest exoreic drainage basin in Australia of 1 062 530 km^2 (1/7th of the Australian continent), discharges to the Southern Indian Ocean in Encounter Bay, South Australia via the Lower River Murray, lakes Alexandrina and Albert (the Lower Lakes) and the Murray Mouth (Figure 1). The tectonically formed setting between the uplifting Mount Lofty Ranges and the south-eastern Coorong Coastal Plain has influenced the location of the Lower River Murray from Morgan to the coast, while progressive and ongoing tectonic subsidence has determined the location of the Lower Lakes area. Superimposed upon this tectonic background, astronomically driven sea-level fluctuations accompanied by the progressive uplift of the Coorong Coastal Plain to the southeast have given rise to an outstanding succession of stranded shorelines separated by interdune corridors (Murray-Wallace, 2018). A detailed account of the geological and geomorphological setting of the study site is presented in Bourman *et al.* (Bourman, Murray-Wallace, Ryan, & Belperio, 2018; Bourman, Murray-Wallace, Ryan, Belperio, & Harvey, 2018).

Damming of the River Murray near Swan Reach by tectonic activity or by a barrier shoreline formed a 50 000 km^2 freshwater mega-lake, Lake Bungunnia, about 2.4 Ma ago when outflow to the ocean was diverted to the Glenelg River in Victoria *via* the Douglas Depression (Bowler *et al.*, 2006; McLaren *et al.*, 2009). The current courses of the Lower River Murray and its gorge were established from about 800 ka ago following breaching of the dam; the associated high discharge at this time helps to explain the underfit character of the present River Murray Gorge.

Lower sea-levels accompanying the Last Glacial Maximum saw the course of the River Murray extend south from its current position onto the Lacepede Shelf (Hill *et al.*, 2009). This course eroded calcrete-capped Pleistocene eolianite dunes, enlarged interdunal areas and developed the essential framework for the Lower Lakes (Murray-Wallace, 2018; Murray-Wallace *et al.*, 2010). Subsequently, the lakes formed in response to ongoing tectonic subsidence and sea-level rise following the Last Glacial Maximum, culminating in the development of the

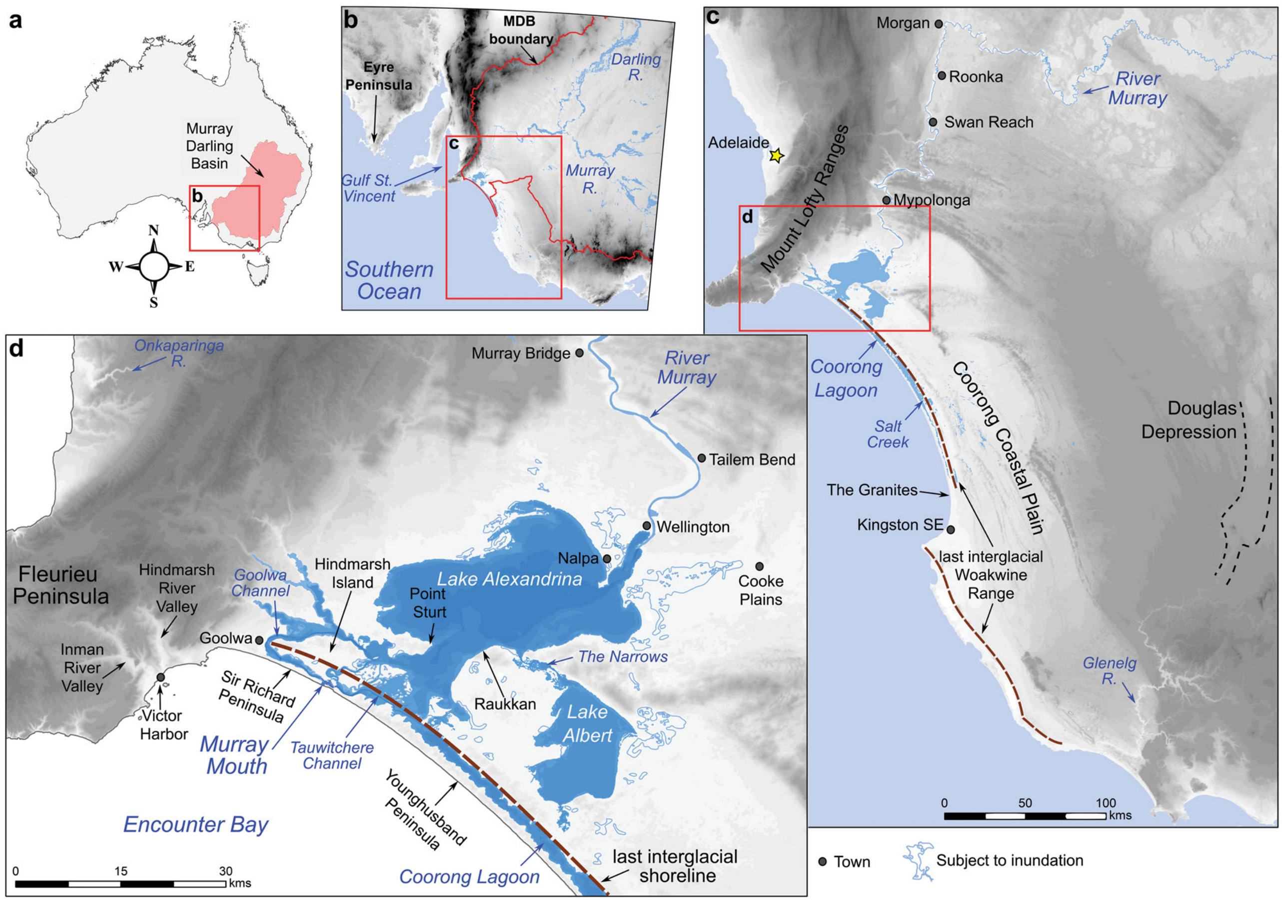

Figure 1. Location of Murray Estuary and Lower River Murray showing the influences of the Mount Lofty Ranges and the Pleistocene coastal barriers of the Coorong Coastal Plain on the configuration of lakes Alexandrina and Albert, the Goolwa Channel and the Coorong Lagoon. Background is 1 second SRTM (Copyright Commonwealth of Australia [Geoscience Australia), 2011]. Lower lakes and Coorong bathymetry data supplied by South Australia Department for Environment and Water (SA DEW).

Holocene coastal barrier systems of Sir Richard and Younghusband peninsulas from *ca* 7000 years ago (Bourman & Murray-Wallace, 1991; Harvey *et al*., 2006; Short & Hesp, 1984). Before the formation of the Holocene barrier shorelines of Sir Richard and Younghusband peninsulas, the River Murray drained directly to the ocean at the site of the Goolwa Barrage, having done so since the Last Interglacial (Bourman *et al*., 2000; de Mooy, 1959). There was no gap in Sir Richard Peninsula at this site during the Holocene as figured by Helfensdorfer *et al*. (2019, figure 1), having been closed off by the growth of Sir Richard Peninsula; nor is there any evidence verifying the size of the gaps depicted elsewhere along the Holocene barrier.

In pre-European contact times, the Lower Lakes were occupied by a classic estuary, a vibrant, highly productive estuarine ecosystem of ∼75 000 hectares (Chiew *et al*., 2020; Paton, 2010; Wood, 2008), becoming increasingly fresh inland from the coast. There were sufficient freshwater flows to flush the river and maintain the mouth (James, 2004b). Lakes Alexandrina and Albert, which receives water from Lake Alexandrina, were predominantly occupied by freshwater upstream of the headlands of Point Sturt and Raukkan (Point McLeay), whereas the Goolwa Channel and the Coorong were saline, with a mixing zone of fluctuating salinities at the 'Meeting of the Waters' (Bell, 1998, pp. 562–570). The position of the mixing zone varied depending on interactions between freshwater river flows from the River Murray, streams draining from the south-eastern slopes of the Mount Lofty Ranges, and tidal and storm events. Except during extreme droughts, flows were sufficient to maintain freshwater conditions along the entire reach of the Lower River Murray and in the Lower Lakes. In contrast, in the inverse estuary of the Coorong Lagoon, a vast linear waterbody bounded landward by the last interglacial shoreline and the Younghusband Peninsula, salinities generally increased away from the Murray Mouth, although there were considerable freshwater inputs from the South East wetlands south via Salt Creek.

Evidence for freshwater conditions in the Lower River Murray and Lower Lakes throughout the Holocene

Various lines of evidence, including the preservation of freshwater riverine biota in Aboriginal middens, freshwater diatoms in terrestrially derived fine-grained sediments, sapropels associated with freshwater lacustrine sediments, sedimentary indicators of high freshwater lake levels and a long-term open Murray Mouth, together demonstrate the predominant freshwater conditions in the Lower River Murray and the Lower Lakes over the entire Holocene.

Archaeological evidence: freshwater molluscs and middens

The freshwater ecology of the Lower River Murray and its terminal lakes is manifested in the broader cultural landscape. Freshwater mussel, dominantly *Velesunio ambiguus* (Philippi, 1847), shell middens provide the most compelling physical evidence for a Holocene freshwater history in the Lower River Murray and the Lower Lakes. Not only are freshwater mussels currently extant in the waters of the Lower River Murray and lakes Alexandrina and Albert (Walker *et al*., 2018), but the size and spatial distribution of the middens demonstrate that they were an important food source for Aboriginal peoples in the Murray–Darling Basin for millennia (*e.g.* Bowler *et al*., 2003; Westell et al., 2020). Aboriginal names are privileged in this paper for several cultural places, followed by European place names in parentheses.

Archaeological investigations conducted along the Lower River Murray at locations including Murrawong (Glen Lossie), Pomberuk (Hume Reserve) (Ngarrindjeri Regional Authority Inc., 2009) and Kangerung (Swanport) between 2007 and 2021 (see Wilson, 2017; Wilson *et al*., 2012, 2021) have demonstrated Aboriginal occupation throughout the Holocene, at the same time that Helfensdorfer *et al*. (2019, 2020) and Power *et al*. (2020) have claimed the presence of a marine influence in this river tract extending upstream to Blanchetown (Figure 2). Specifically, Wilson (2017) and Wilson *et al*. (2012, 2021) conducted archaeological investigations of midden sites along the River Murray between the current settlements of Monteith (the site of the 2019 and 2020 investigations of Helfensdorfer *et al*., 2019, 2020), and Mypolonga (Figure 2). A radiocarbon age of 8367–8053 cal yr BP (ANU-3120) was obtained on *V. ambiguus* (*sensu* Walker, 1981) from a Murrawong Site (GLMBS) located about 10 km upstream of Murray Bridge (Wilson, 2017; Wilson *et al*., 2012, 2021). In total, Wilson *et al*. (2012) obtained radiocarbon ages on 59 *V. ambiguous* shells and charcoal samples ranging from *ca* 8200 cal yr BP at the above-mentioned site to the middle of the last millennium at Pomberuk (Hume Reserve at Murray Bridge), attesting to the

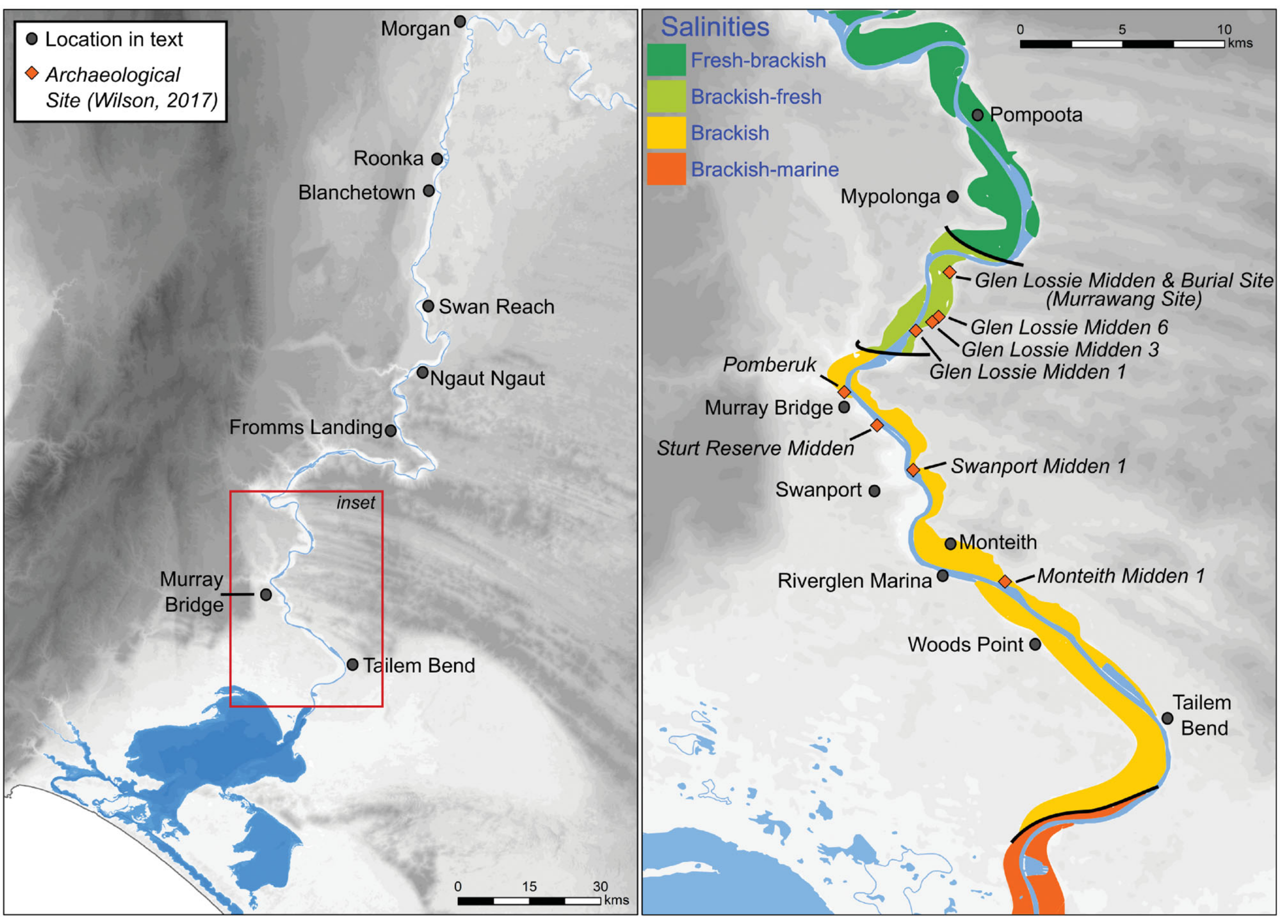

Figure 2. Locations of midden sites investigated along the Lower River Murray (Source: Wilson, 2017). The salinity zones, which we reject, are those of Helfensdorfer *et al*. (2020, figure 2). Background is 1 s SRTM (Copyright Commonwealth of Australia [Geoscience Australia], 2011). Bathymetry data supplied by SA DEW.

continuous Aboriginal occupation of the area involving the extensive exploitation of freshwater resources over this period (Wilson, 2017; Wilson *et al*., 2012, 2021).

Hubble *et al*. (2021) state that middens and burial sites are located adjacent to, but not within, the present-day floodplain. However, Wilson (2017, p. 143) clearly recorded that surface *V. ambiguous* samples were collected from shell middens located on floodplains 0–4 cm in depth from the surface ($n = 26$). Occupation sites occur both on floodplains and on higher ground above flood levels adjacent to the river. The Murrawong archaeological complex (Wilson *et al.,* 2021) extends along the highwater line of the 1956 flood, which, at 341 000 megalitres per day (ML/day), was the largest recorded in South Australia, with an estimated return interval of 170 years. The second highest flood, estimated at 319 000 ML/day, occurred in 1870 (McCarthy *et al*., 2006). A flood of similar dimensions to the 1956 flood, or perhaps slightly larger, is thought to have occurred at approximately 3000 years BP and impacted on the occupation site at Tungawa Rockshelter No. 6 (Fromms Landing). Mulvaney *et al*. (1964, p. 486) reported a 5 cm-thick layer of stratified riverine sand at the base of a buried bluff cut into occupational debris at this site, and this was interpreted as resulting from a single major flood event (see Roberts & the Mannum Aboriginal Community Association Inc., 2012 for revised site nomenclature in the region). The sand layer was wedged between two middens, dated at 3170 ± 94 years BP (3564–3076 cal yr BP [NPL29]) and 2950 ± 91 years BP (3336–2800 cal yr BP [NPL28]), respectively, at an elevation exceeding the height of the 1956 flood. There are likely to have been several floods of this dimension over the past 3000 years, while a flood twice the volume of the 1956 flood occurred in approximately 1760 CE (Snowball *et al*., 2006) based on the elevation of lines of ancient black box (*Eucalyptus largiflorens*), which germinates at flood peaks. There is also some anecdotal evidence for such a flood before European settlement that far exceeded the 1870 CE event, and which may relate to the 1760 event. Charlie Trussell of Cobdogla, who died in 1955 and hence did not witness the 1956 flood, reported that Aboriginal people in the nineteenth century were told of a flood by their ancestors that made the 1870 flood look like a 'piccaninny flood' (Mortimer, 1985). Furthermore, we note that even if some Aboriginal shell middens were located above the current floodplain, it is more likely that the mussels were collected in the freshwater conditions in the vicinity rather than transported for tens of kilometres.

Hubble *et al*. (2021) acknowledged the presence of freshwater mussel shells in middens along the lower river but considered that their presence did not disprove high water salinities during the mid-Holocene, as *V. ambiguus* can tolerate salinities up to 3000 mg L^{-1} (*i.e.* <1/10 salinity of seawater). However, Walker *et al*. (2018) noted that the salt tolerance of *V. ambiguus* is quite low, probably well below 3000 mg L^{-1}, while higher water salinities generated during low-flow conditions invariably impact deleteriously upon mussel populations. The mussel shoals in Lake Alexandrina, for instance, were 'obliterated' during the Millennium Drought and have been slow to recolonise (Walker, 2017, p. 42). Estuarine and marine shells are noticeably absent in the Lower River Murray middens, which comprise predominantly, but not exclusively, the lagoon mussel *V. ambiguous.* Other indicators of freshwater ecology in the Lower River Murray middens include the otoliths of freshwater fish species such as Murray cod (*Maccullochella peelii*), freshwater crayfish or yabbies (*Cherax destructor*) and freshwater turtles (Wilson, 2017), of which there are three extant species (Murray short-necked turtle [*Emydura macquarii*], Eastern long-necked turtle [*Chelodina longicollis*] and broad-shelled turtle [*Chelodina expansa*]) (Thompson & Spencer, 2021).

Other occupation sites, farther upstream at Tungawa Rockshelter No. 2 (Fromms Landing), were dated at 4850 ± 100 years BP (5839–5311 cal yr BP [R456/1]) on shell and 3240 ± 80 BP (3611–3215 cal yr BP [R456/2]) on ash/charcoal in a layer associated with freshwater mussels. At Ngaut Ngaut (Devon Downs) (Roberts & the Mannum Aboriginal Community Association Inc., 2012), 18 km farther upstream, archaeological investigations, together with radiocarbon dating of freshwater mussel shells at 6180–5655 cal BP (GaK-1024), established ongoing occupation of the site since that time, with the freshwater mollusc, *Corbicula angasi*, also present in the midden deposits (Hale & Tindale, 1930; Smith, 1977, 1982).

About 6 km upstream of Blanchetown, the extensively researched archaeological site at Roonka was possibly occupied as an open-air camp during the annual flooding of the River Murray, over a period of occupation extending back to 20 000 BP and used as a cemetery from 7 ka (Littleton *et al*., 2017; Pretty, 1977; Rogers, 1990). Wilson (2017) summarising work by Pate (2000) argued that people at this site obtained at least 30% of their dietary protein from freshwater fish, mussels and crustaceans.

Figure 3 provides a summary of the $n = 75$ calibrated radiocarbon ages recovered from archaeological materials along the Lower River Murray within the three modelled salinity zones of Brackish, Brackish–Fresh and Fresh–Brackish, identified by Helfensdorfer *et al*. (2020, figure 2) on the basis of modelling. Calibrated age ranges have been produced using the OxCal program (Bronk-Ramsey, 2010) and are based on the SHCal20 calibration curve (after Hogg *et al*., 2020). The radiocarbon ages are identified as either relating to freshwater mussel or some other material (*e.g.* charcoal). When assessing these ages, it is important to recognise that ages from archaeological sites seldom encapsulate the full-time depth or resolution of a deposit but rather encapsulate a set of points that provide a framework to the chronology. In most instances, it can be reasonably expected that the 'gaps' in dating would be filled to some extent by additional archaeological material, and some level of interpolation and extrapolation could be applied. As above, freshwater mussels are ubiquitous elements of all stratigraphic layers, and where 'other

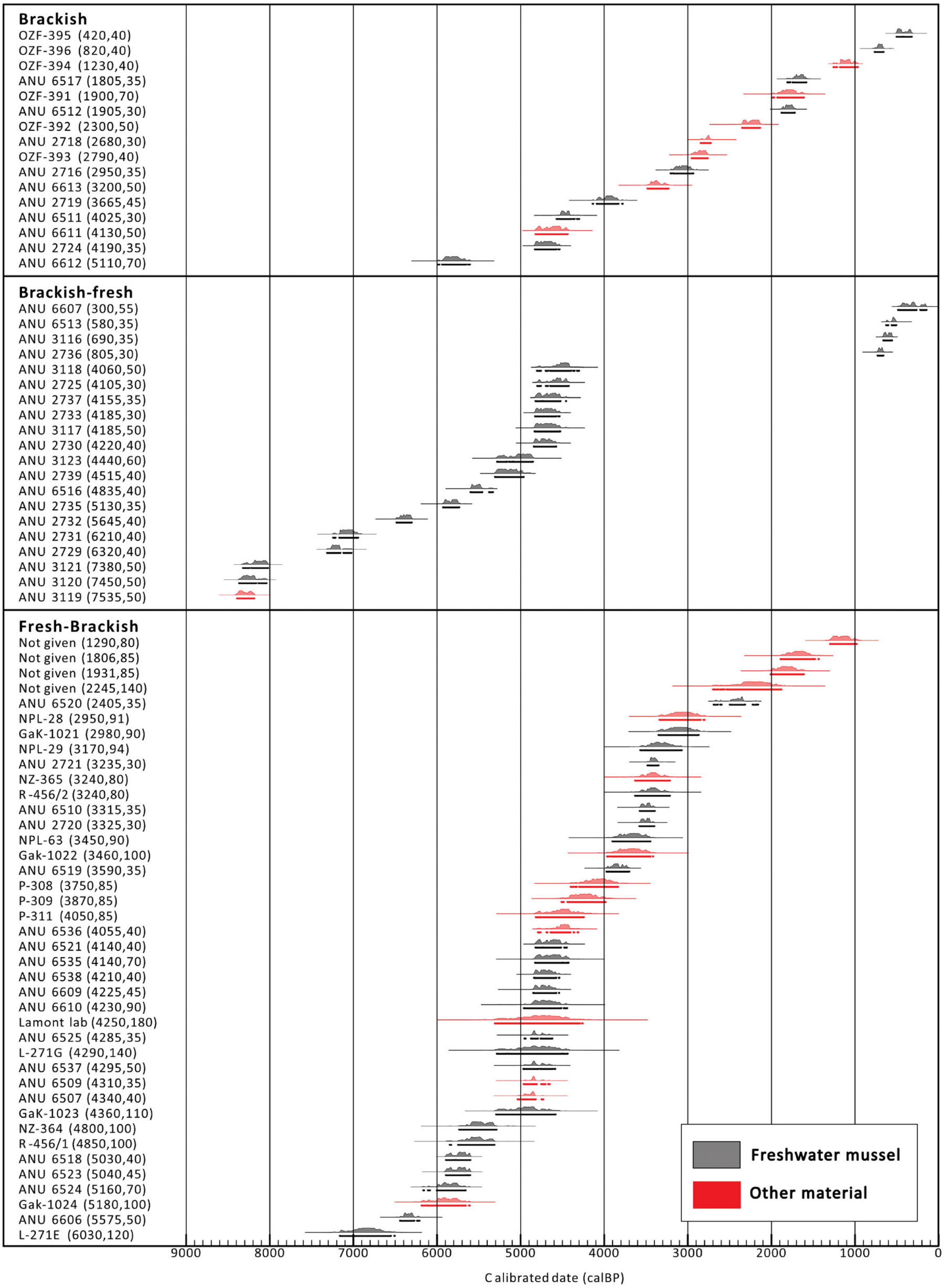

Figure 3. Graph of calibrated radiocarbon ages from archaeological materials along the Lower River Murray within the three modelled salinity zones of Brackish, Brackish–Fresh, and Fresh–Brackish, identified by Helfensdorfer *et al*. (2020, figure 2).

materials' have been dated, this does not necessarily negate the presence of mussel shells.

These observations of freshwater species inhabiting the Lower River Murray during and before the Holocene support the interpretation for a freshwater environment along the river, rather than a marine/estuarine one as contended by Helfensdorfer *et al*. (2019, 2020) and Hubble *et al*. (2021). It seems that their interpretations were predicated on modelling of purported saline incursions from the sea, while they ignored the impacts of elevated water levels and freshwater environments resulting from climatically increased river flows.

This scenario is reminiscent of one played out in the nineteenth century by Pollitzer (1883) and Tate (1884). According to Tate (1884, p. 29), Pollitzer insisted that the river alluvium 'actually is a marine deposit', 'that the gorge was made by a salt-laden stream formed by the receding sea', and 'that if you bore a hole in these deposits you will meet with brackish water, in spite of having fresh Murray water within a few inches'. Tate (1884) responded, saying that Pollitzer (1883) ignored the evidence of its freshwater origin in the form of numerous shells still living in the river, while the brackish water is locally derived from surface flow of water through talus of calciferous sand-rock (marine limestone of the Murray Gorge) from which it derives salt. Contemporary evidence also shows that much of the regional groundwater entering the river channel is saline (Barnett, 2018).

Tate (1884) observed that the water in the River Murray carries a remarkably low quantity of saline matter in solution and is notably soft. He also noted that the water of the River Murray is always thick with suspended matter, with its white opacity increasing with the rise of the river. However, after floods, he observed that water in the fringing creeks and lagoons became clear after the suspended sediments were deposited and reduced the muddiness of the river water when discharged back into the stream.

Lacustrine sediments

Other strong evidence for mid-Holocene freshwater conditions in the Lower Lakes and hence the Lower River Murray comes from the studies of Barnett (1994, 1995), Bourman and Barnett (1995), Fluin (2002), Fluin *et al*. (2007, 2009), Gloster (1998), Littleton *et al*. (2017), Murdoch (2009), Tibby *et al*. (2020), and von der Borch and Altmann (1979), all of whom investigated the sedimentary history of lakes Alexandria, Albert and the Coorong Lagoon.

Lake Alexandrina

Cooke Plains Embayment. von der Borch and Altmann (1979) undertook extensive coring and analyses of sediments from the Cooke Plains Embayment, a low-lying, elongate east–west former extension of Lake Alexandrina (Figures 4 and 5) during the mid-Holocene. They reported indicators of freshwater conditions in Lake Alexandrina during and since the mid-Holocene. Distinctive stratigraphic successions beneath the embayment recorded the expansion of the lake, a still-stand and regression of the lakeshore, marked by the identification of two distinct phases of transgression and regression (von der Borch & Altmann, 1979).

The transgressive phase is represented by basal sand and clay, sapropel (also called 'Coorongite' locally) and diatomite units, which overlie yellow clay and arkosic sand deposits. von der Borch and Altmann (1979) equated this succession with expansion of Lake Alexandrina at the peak of the Holocene *ca* 6500 years BP marine transgression at about 1 m APSL (above present sea-level), coinciding with a mid-Holocene humid period 8000–5000 years ago. Such a climatic episode, recorded in other southern Australian lakes as increased lake levels (*e.g.* Bowler, 1981; Bowler *et al*., 1976; Bowler & Hamada, 1971; Wilkins *et al*., 2013), resulted in an increased discharge of the River Murray, augmenting expansion of the Lower Lakes. This phase is also represented by river terrace formation in the nearby river valleys of Fleurieu Peninsula (Bourman, 2006).

The basal sand, a consistent and ubiquitous unit throughout most of the embayment, was regarded as a diachronous, transgressive sand reworked from regolith during expansion of Lake Alexandrina. The overlying greenish-black, rubbery, sapropel unit, which is limited to the deepest areas of the paleo-embayment, is up to 40 cm thick and contains pollen of bluebush, saltbush, ti-tree and casuarinas, along with pollen of the freshwater plants, *Myriophyllum* and *Haloragis*. These observations indicate the existence of aquatic plants, characteristic of essentially freshwater swamps. The sapropel was radiocarbon-dated at 6930 ± 150 years BP (GaK-6718). Evidence from diatoms also revealed deposition in freshwater at the Lake Alexandrina end of the embayment.

Carbonate, black mud and evaporite units represent the regressive phase within the Cooke Plains Embayment from *ca* 5000 years ago. The carbonate unit is up to 90 cm thick, comprises white clay, gypsum, halite, minor quartz and illite, and contains the halobiont gastropod *Coxiella striata*. This unit was associated with fringing ephemeral carbonate lakes formed by evaporation as the lakeshore retreated. Diatoms within the black mud unit reveal that the unit formed in areas of permanent freshwater (von der Borch & Altmann, 1979, p. 75).

Although Job *et al*. (2021) found evidence of transgressive and regressive phases in the history of Lake Albert, they argued that the specific timing of sapropel deposition overlying transgressive sands has not been well established. Furthermore, they claimed that the sapropel deposits were not formed under highstand surface water levels, because in their model, the estuary would have been hydrologically well connected, making it unlikely that there would be the sustained eutrophy and the negligible sedimentation required for sapropel formation. Instead, Job *et al*. (2021) proposed that the sapropels were formed during the early stages of estuary formation (*ca* 7.5–7.0 cal kyr BP), before highstand levels, in a transitional phase wetland environment proximal to, but not connected to, the river in restricted perennial lakes.

The perspective adopted by Job *et al*. (2021) was followed by Hubble *et al*. (2021), who stated that sapropels

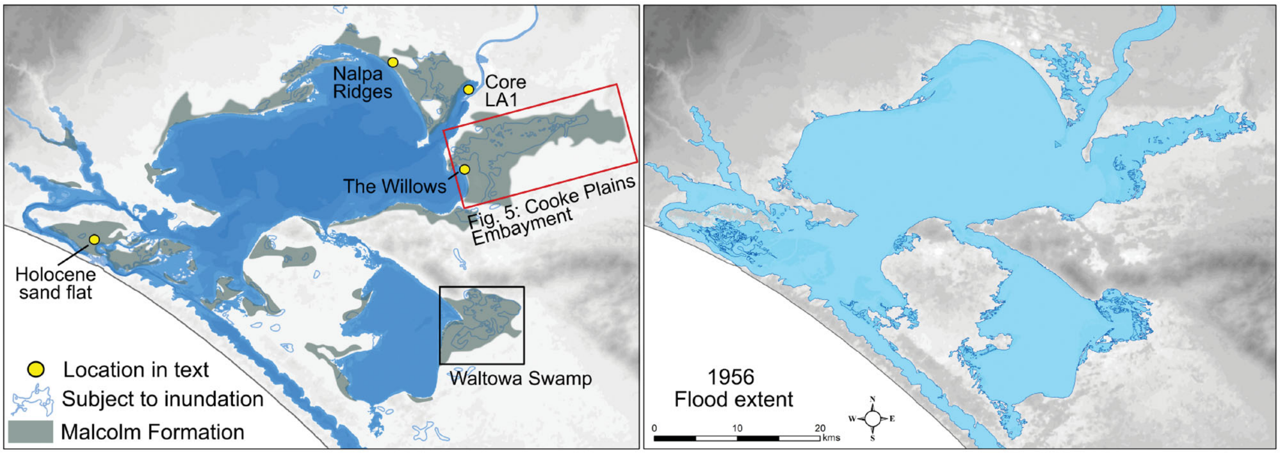

Figure 4. Lower Lakes of the River Murray showing the location of the Cooke Plains Embayment, Waltowa Swamp, and the former extents of the lakes during the mid-Holocene (modified after von der Borch & Altmann, 1979). Background is 1 second SRTM (Copyright Commonwealth of Australia [Geoscience Australia], 2011). Malcolm Formation, 1956 Flood extent and bathymetry data supplied by SA DEW.

derived from the accumulation of freshwater algae 'were *likely deposited* in freshwater lakes not connected to the primary fluvio-estuarine system during the mid-Holocene and therefore cannot be used to assert freshwater conditions in the estuary'. However, the Cooke Plains Embayment is a former backwater extension of Lake Alexandrina where sedimentation was restricted, and sustained eutrophic conditions could be achieved. Olliver Geological Services (1995) replicated the findings of von der Borch and Altmann (1979), both in the Cooke Plains Embayment and in Waltowa Swamp, a similar backwater embayment of Lake Albert, neither of which is a former restricted perennial lake close to the river, and both of which were directly connected to the lakes during the flood of 1956 CE, which peaked at 1.43 m AHD at the Murray Mouth. According to Olliver Geological Services (1995), the diatoms in the Cooke Plains Embayment ranged from essentially fresh to a little less than normal marine. The freshwater diatoms occurred in the west, closest to Lake Alexandrina, with more saline diatoms in the east, where evaporation from shallow areas and groundwater input increased salinity (Olliver Geological Services, 1995).

There is no need to invoke the *ad hoc* hypothesis of a former transitional phase wetland environment in a restricted perennial lake proximal to the river, during the early stages of estuary formation (*ca* 7.5–7.0 cal kyr BP), and prior to highstand levels. There is no direct local evidence to support such a proposal. In contrast, the extensiveness and regularity of the stratigraphy and timing of deposition in the former embayment of Cooke Plains are in harmony with a higher sea-level accompanied by increased river discharge to elevate water levels around the lakes. These higher levels were accompanied by the development of saprolites in the backwaters of the enlarged lakes.

Finally, as the lake levels dropped, littoral transport along the lakeshore formed two recent barriers of siliceous sand across the mouth of the embayment (von der Borch & Altmann, 1979). It is also noteworthy that during the 1956 flood, when the stage height of the river at the mouth was 1.43 AHD, both the Cooke Plains Embayment and the Waltowa Swamp Embayment were inundated (Figure 4).

Lake Alexandrina diatoms. Numerous investigations have been undertaken of diatoms as indicators of salinity conditions in the Lower Murray and Lower Lakes (*e.g.* Barnett, 1990, 1993, 1994, 1995; Bourman & Barnett, 1995; Fluin, 2002; Fluin *et al*., 2007, 2009; Haynes *et al*., 2018). These detailed studies have demonstrated no evidence for substantial marine incursions into Lake Alexandrina over the past 7000 years. An alternative interpretation of these data was provided in the commentary of Gell (2020), whose claims have been rebuffed by Tibby *et al*. (2020), who noted that the diatoms argued to be marine indicators by Gell (2020) can occur within a range of salinities, including freshwater. Notable in terms of the conclusions of Helfensdorfer *et al*. (2020) is that in core LA1, located close to where the River Murray enters Lake Alexandrina (Figure 4), diatoms classified as marine by Gell (2020) make up less than 5% of the assemblage in all but one sample (Fluin *et al*., 2007). The above diatom data are unequivocally in contrast to the regime of marine salinity inferred by Helfensdorfer *et al*. (2020).

Diatoms from the Riverglen Marina in the Lower River Murray. New diatom data, derived from Core RG2 retrieved at the site of the Riverglen Marina on the right bank of the river and opposite the alluvial Monteith site of Helfensdorfer *et al*. (2020), are critical in demonstrating the freshwater status of the Lower River Murray during the Holocene (Figures 6 and 7). Core RG2, which is 1.5 m long with the top of the core located at −6 m AHD, provides a record of environmental change from *ca* 7400 to 5800 years ago, separated from samples at *ca* 3600 and 3500 cal yr BP by an erosional hiatus (Table 1). Methods are described in Appendix 1.

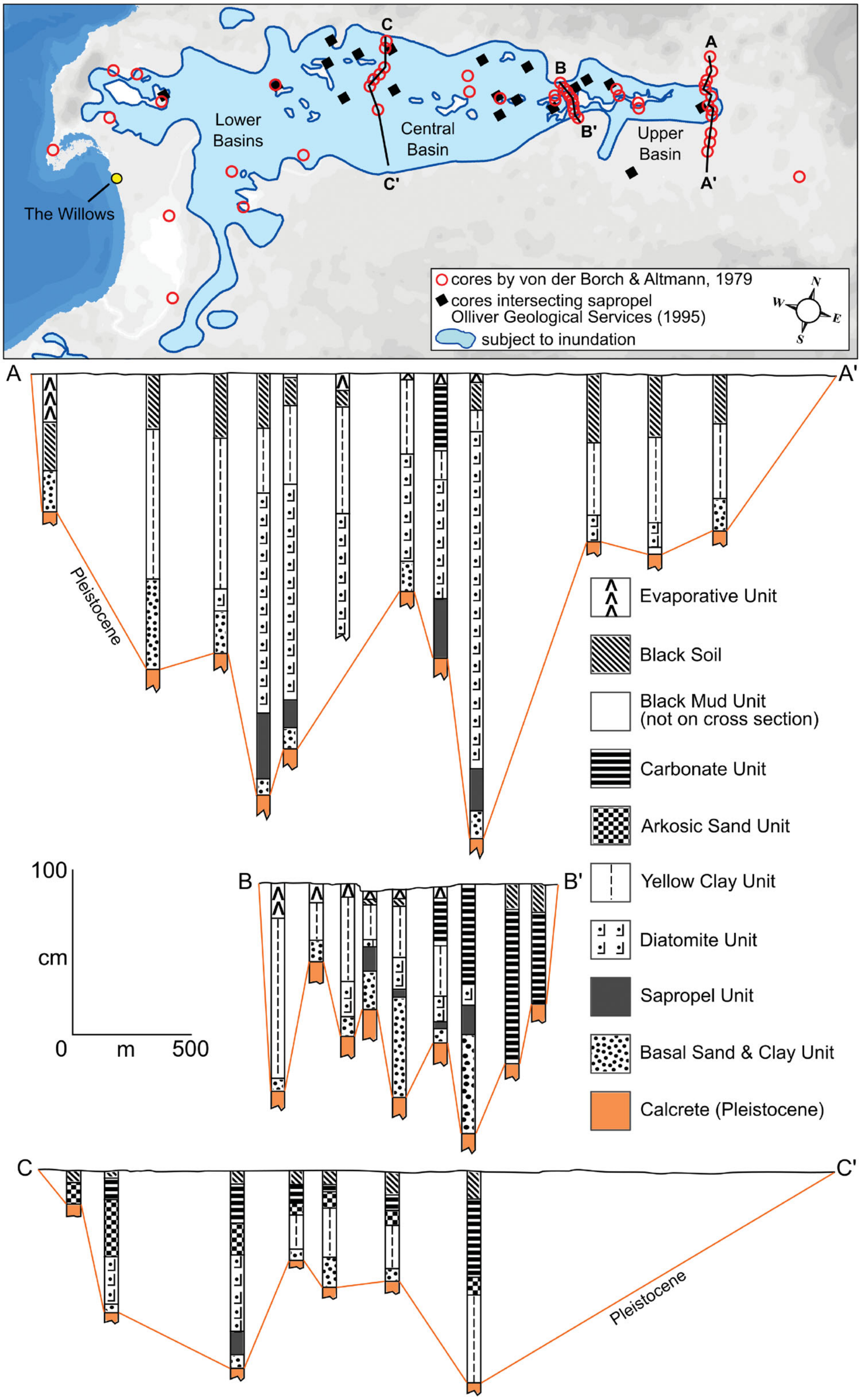

Figure 5. Top: Cooke Plains Embayment showing core localities in Lower, Central and Upper Basins (modified after von der Borch & Altmann, 1979 and Olliver Geological Services, 1995). Bottom: Stratigraphy of Cooke Plains Embayment established from core-hole records of von der Borch and Altmann (1979) Background is 1 s SRTM (Copyright Commonwealth of Australia [Geoscience Australia], 2011). Bathymetry data supplied by SA DEW.

The diatom record from Core RG2 is dominated either by taxa that are exclusively found in freshwater environments or by polyhalobionts that are found in a wide range of environments spanning from freshwater to marine salinities. The dominant taxon for most of the record (covering the period from 7400 to 6200 years ago) is *Aulacoseira granulata*. This species is the dominant diatom in the River Murray at present (Hötzel & Croome, 1996;

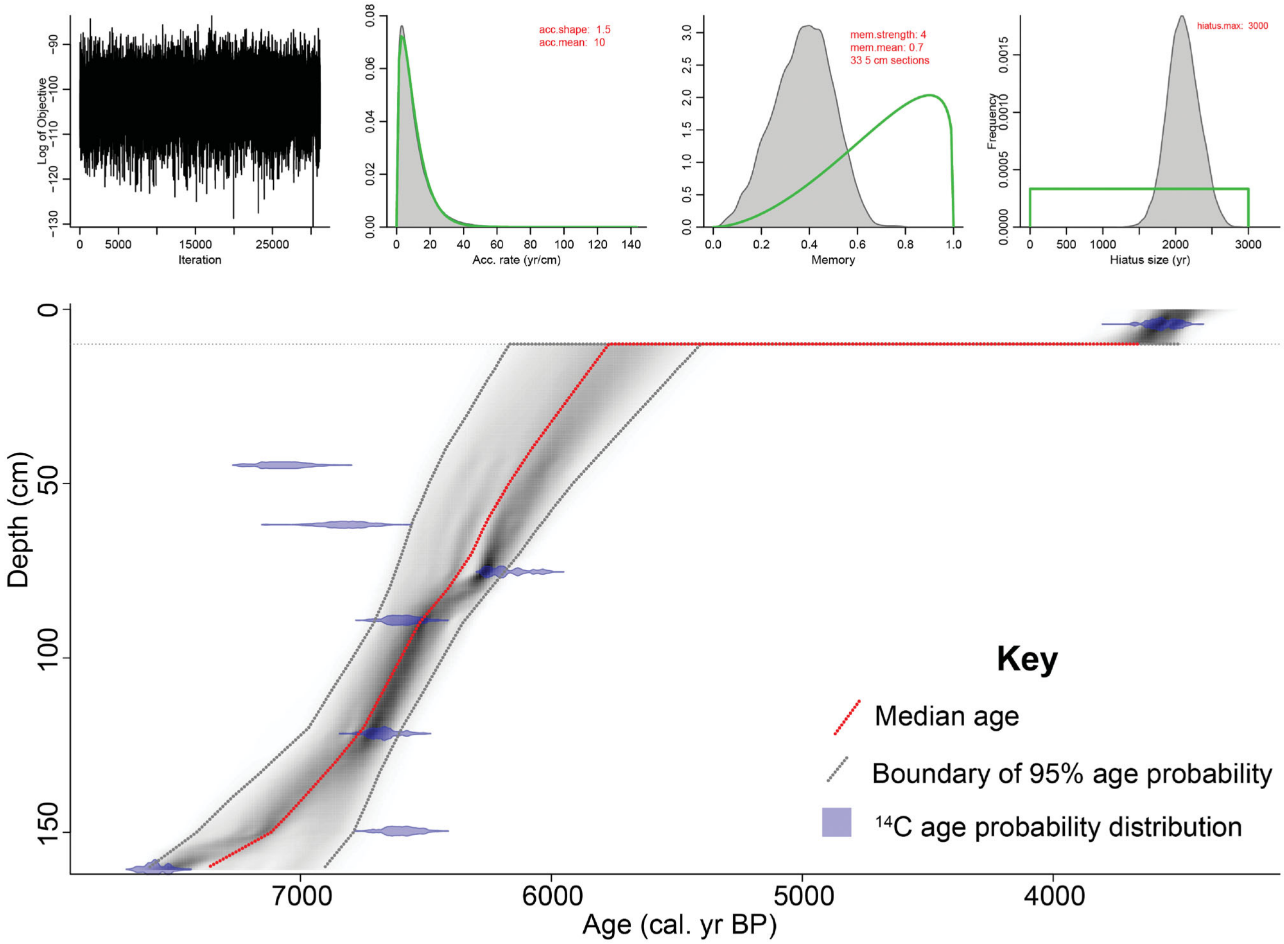

Figure 6. Age–depth relationship in Core RG2 record, Riverglen, Lower River Murray, South Australia. Probability distributions for the ^{14}C ages are shown in blue. The median age is shown by the red line and the 95% probability distribution of the ages is encapsulated by the grey lines.

Tibby & Reid, 2004). Its dominant representation through this period indicates the continual presence of freshwater at the site (Figure 7). *Aulacoseira granulata* is succeeded, to some extent, after 6700 years ago by a variety of taxa that are mainly epiphytic (*i.e.* they grow on plants and indeed other surfaces). Some of these species, including *Epithemia adnata*, are found exclusively in freshwater environments, whereas others, particularly *Cocconeis placentula*, can be found in freshwater but also in higher salinities. Importantly, no taxa that are restricted to marine or estuarine water sources (*i.e.* thalassic waters) occur in the record, nor were any marine/estuarine shells encountered in the core.

Collectively, the diatom evidence from Core RG2 indicates that at no time between 7400 and 5800 years were elevated salinities found at this location. It appears that after 6200 years, there was a decrease in the discharge of the River Murray and/or the site became increasingly 'swampy' with a cover of aquatic plants. Although we cannot interpret the period of time represented by the disconformity (*i.e.* 5800–3800 cal yr BP), the diatom flora, before and after the hiatus, provide evidence of freshwater conditions over these periods. Given that the site of the core is adjacent to the Monteith alluvium site of Helfensdorfer *et al.* (2019, 2020), the diatom data from the core tell an unambiguous story of persistent freshwater conditions, providing a diametrically opposed interpretation based on biological data compared with that generated by the modelling of Helfensdorfer *et al.* (2019, 2020).

Lake Albert

Investigations of Lake Albert by Gloster (1998) and Murdoch (2009) produced similar findings to those of von der Borch and Altmann (1979); radiocarbon ages between *ca* 6.8 and 5.3 ka were derived from organic-rich freshwater sapropels obtained from cores sunk into the bed of Lake Albert (Gloster, 1998). Sapropel formation was associated with a mid-Holocene humid period when lake levels were at their highest. Additional work on Lake Albert supported this interpretation, as Murdoch (2009) obtained radiocarbon ages of 7195 ± 35 years BP and 7305 ± 35 years BP on plant macrofossils representing freshwater conditions from the base of Lake Albert cores. Fitzpatrick *et al.* (2018) also reported calibrated radiocarbon ages from 6230 ± 40 to 5840 ± 40 years BP for a rubbery sediment deposit called 'Coorongite' that is formed by a freshwater algal species (*Botryococcus braunii*) from two locations in Lake Albert.

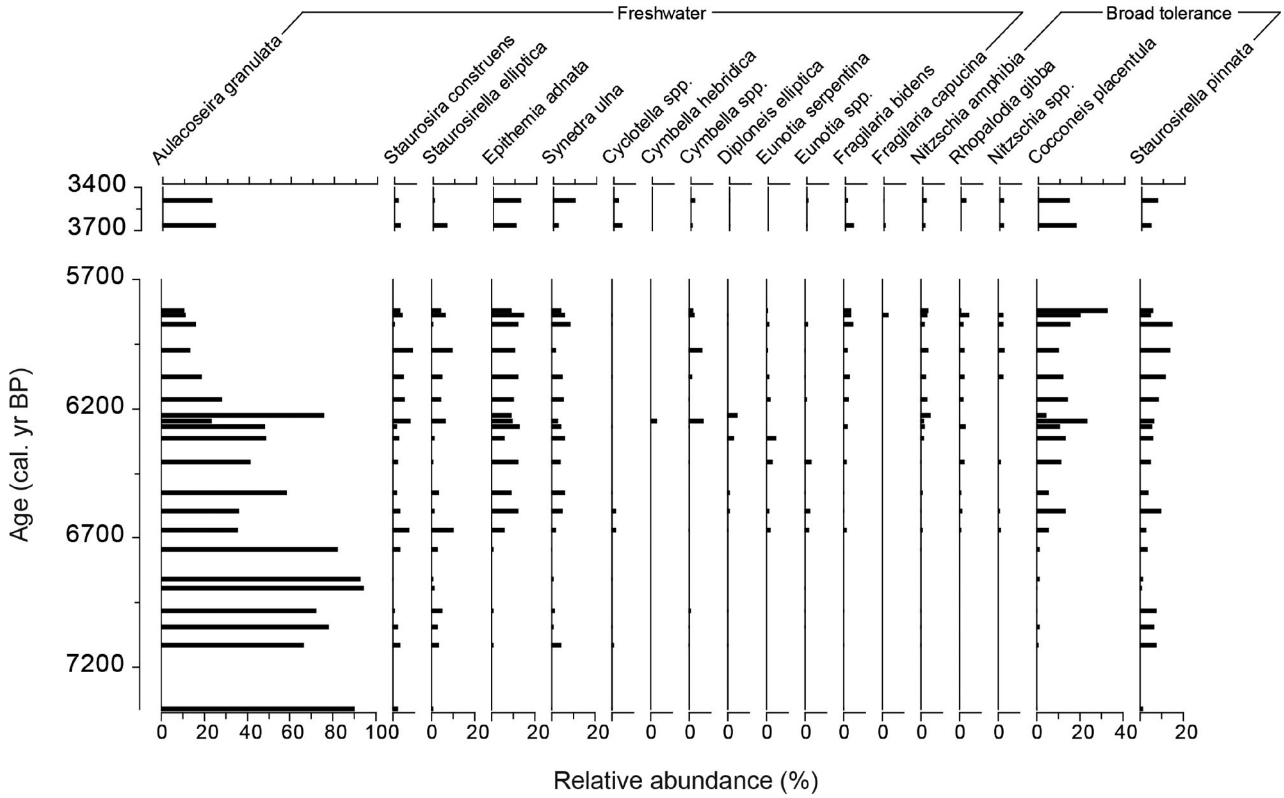

Figure 7. Diatom stratigraphy from the Core RG2 record. Only taxa >3% in any sample are shown.

Table 1. Radiocarbon ages on organics and charcoal from sediment Core RG2, Riverglen, Lower River Murray, South Australia.

Sample depth (AHD) m	^{14}C age (yr BP)	Calibrated age	Lab Code
−6.040	3373 ± 27	3467–3640	UBA-25980
−6.445	6216 ± 53	6939–7184	UBA-32733
−6.615	6020 ± 59	6667–6958	UBA-32735
−6.750	5425 ± 30	6172–6283	OTZ-021
−6.889	5838 ± 35	6490–6678	UBA-32739
−7.214	5895 ± 30	6558–6749	OTZ-022
−7.494	5843 ± 38	6492–6679	UBA-25112
−7.604	6755 ± 35	7551–7659	UBA-32738

Taylor and Poole (1931) had earlier suggested the existence of a southern outlet of Lake Albert to the sea during high-flow conditions. However, Murdoch (2009) concluded that freshwater pollen and algae, associated with freshwater eutrophic conditions, along with the absence of marine dinoflagellates in pollen assemblages, indicated that Lake Albert, since the mid-Holocene, was never directly connected to the Coorong Lagoon and became increasingly isolated as sea-level fell.

Waltowa Swamp Embayment

Olliver Geological Services (1995) carried out slip-hammer coring at 57 sites in Waltowa Swamp, a former backwater embayment of Lake Albert (Figure 4) revealing a stratigraphy comparable with that of the Cooke Plains Embayment. A persistent diatom-bearing soft white to grey clay was intersected near the base of Holocene as well as sapropel in six of the core holes. Barnett (1991) examined nine samples for sediment composition and diatoms from seven of the cores and reported that the diatoms mainly occur in brackish to freshwaters. As with the Cooke Plains Embayment, salinity variations appear to be related to distances from the edge of the lake.

The studies by von der Borch and Altmann (1979), Fitzpatrick *et al*. (2018), Gloster (1998), Murdoch (2009) and Olliver Geological Services (1995) all unequivocally demonstrated the freshwater character of lakes Alexandrina and Albert, and, by extension, the freshwater environment of the Lower River Murray. Furthermore, as outlined above, there have been sufficient radiocarbon ages obtained on the saprolitic and overlying diatomite deposits to relate the timing of their formation to the mid-Holocene highstand.

High freshwater lake levels

Holocene lacustrine sediments, abandoned cliffs, benches and beach/dune ridges around lake margins attest to a greater aerial extent of lakes Alexandrina and Albert (Bourman *et al*., 2000; de Mooy, 1959; von der Borch & Altmann, 1979) owing to a combination of an elevated sea-level in conjunction with increased river flows. A sequence of quartz sand ridges 850 m wide and up to 2–3 m high occupies the northeastern shore of Lake Alexandrina on Nalpa Station for some 9 km (Figure 4). The toe of the highest ridge stands at 1.75 m AHD, and between it and the lakeshore at 0.75 m AHD, there are 10 progressively smaller regressive lake shore/dune ridges. The quartz sands of the ridges are of refractory quality, indicating a terrestrial freshwater source rather than a marine origin, the latter more likely to be a mixed quartz-skeletal carbonate sand (Murray-Wallace, 2018). A sample from the basal area of the largest ridge at 35°19′46″ S, 139°16′03″ E was dated at 8.0 ± 1.2 ka (W2696) by thermoluminescence (Bourman, Murray-Wallace, Ryan, Belperio, & Harvey, 2018). This age is commensurate with the maximum water level in the lake during the Holocene. The construction of such a large body of sand indicates the persistence of elevated freshwater lake levels over a considerable period.

Other evidence for freshwater lake levels higher than present occurs at 'The Willows' (35°19′33″ S, 139°16′03.11″ E) (Figure 4), on the west-facing shore of Lake Alexandrina where masses of the freshwater mussel, *Corbicula australis*, are cemented together. These shells have been radiocarbon-dated at 2650 ± 90 year BP (Wk-5409) (Bourman Murray-Wallace, Ryan, Belperio, & Harvey, 2018). These lithified shell deposits, which lie approximately 2 m above the current lake level, indicate that during their deposition, freshwater lake levels extended over the soils of the Malcolm Combination of de Mooy (1959) (Figure 4) who described the Malcolm deposits as predominantly freshwater, fine black clays accreted in low-lying lake margins during a period of higher lake levels.

River Murray Mouth

A most obvious manifestation of freshwater flow through the system is an open Murray Mouth. Without a river, there would be no mouth. During conditions of low or no flows, the mouth closes and requires dredging, while the mouth may be substantially cleared by flows of 20 000 ML/day for a month or more (Harvey, 1996). Natural mouth maintenance is dependent on river flows, demonstrated *par excellence* during the flood of 1956 when flows of up to 326 000 ML/day, with a stage height of 1.43 m AHD at the mouth, scoured out accumulated tidal sediments. An open mouth is a clear indicator of freshwater outflows and, by association, freshwater upstream.

Thomson (1975) noted a progressive reduction in the width of the mouth between 1839 and 1967 as river discharges declined in association with increasing upstream water extractions. Precipitated by increasing salinity levels owing to the reduced downstream flows, barrages were installed upstream of the Murray Mouth between 1935 and 1940, but there is no record of inlet closure in the century before barrage installation (James, 2004a, 2004b). The mouth closed over for the first time in recorded history in 1981 (Bourman & Harvey, 1983), and this issue has been of considerable concern since and has been considered a matter of cultural trauma for the Ngarrindjeri people (Murray–Darling Basin Commission, 2002), highlighting the need for substantial freshwater flows for the long-term maintenance of the mouth and the overall health of the entire river system.

There is considerable evidence that the location and morphology of the Murray Mouth have changed over time. Since the 1830s, the mouth has migrated over a range of ~2 km, whereas over at least the past 3000 years, it migrated within an envelope of ~6 km (Bourman *et al*., 2000; James, 2004a, 2004b; Thomson, 1975). The extremes of mouth migration are constrained by the distribution of Aboriginal middens and fossil flood-tidal deltas preserved by a vegetation cover of sedge and lignum (Bourman & Murray-Wallace, 1991). Unlike the present-day flood-tidal delta of Bird Island, no dunes occur on the paleo-deltas, reflecting ongoing dynamism and an open mouth, thereby inhibiting dune formation (James *et al*., 2015). Foraminiferal investigations by Cann *et al*. (2000) also concluded that the mouth had not closed permanently for at least the past 3500 years before the closure in 1981. In addition to ongoing mouth migration over the past 3000 years, former outlets have also been identified at about 6000 years ago near the central portion of the Coorong, and about 5000 years ago near Barkers Knoll (Harvey *et al*., 2006), suggesting sufficient freshwater outflow at this time to maintain the openings.

Thom *et al*. (2020), who emphasised the role of coastal processes in delivering vast amounts of sand into the Murray Mouth, noted that the Murray–Darling Basin Plan did not take this factor into account. Most sediment is delivered by longshore transport, as the inner Lacepede Shelf is a shaved shelf, with little sediment above the storm-weather wave base to nourish the modern/Holocene shoreline (James & Bone, 2011, 2021). Harvey (1996) reported an annual movement of sand along the coast by longshore drift of between 0.25 and 1 million tonnes of sand, amounts compatible with the volumes currently being dredged from the mouth (James *et al*., 2015). Given the increasing demands of irrigation, the impacts of future climate changes, the failure of planners to maintain an open Murray Mouth and the ongoing costs of dredging, Thom *et al*. (2020) discussed the implications of barrage removal.

While the barrier shoreline is wave-dominated, in its natural state the Murray Mouth itself was river-dominated (Shuttleworth *et al*., 2005). Without a river, there would be no open mouth. For most of the Holocene, the Lower Murray Gorge, Lower Lakes and Murray Mouth were flushed regularly by winter–spring runoff from the Australian Alps, interspersed with major floods and occasional drought years (Shuttleworth *et al*., 2005). However, over the past century, with a proliferation in dams, diversions, river-regulation and increasing extractions, regular flushing and flooding have become non-existent, with the mouth succumbing to wave- and tide-dominance, requiring dredging for its maintenance. Waves transport sediment along the fronting beach towards the mouth, while flood tides move sediment landward through the mouth constructing a flood-tidal delta, which progressively enlarged to form a permanent island, Bird Island (James *et al*., 2015). Notably, dredging, which occurred between 2002 and 2010 during the Millennium Drought, ceased following drought-breaking rains in 2010, but was recommenced in 2015 as the mouth once closed, with dredges operating in the Tauwitchere and Goolwa channels to maintain a mouth opening until the present.

The Coorong Lagoon

The morphology of the Coorong Lagoon is closely related to the orientation of Pleistocene coastal dune eolianites, the landward shore of which follows the last interglacial shoreline (MIS 5e) (the Bonney Coastline of de Mooy, 1959). The coastal shore comprises Younghusband Peninsula, a Holocene barrier system primarily draped on the eolianite substrate of Interstadial Marine Isotope Substage 5a (*ca* 80 ka) age (Harvey *et al*., 2006; Short & Hesp, 1984; von der Borch, 1975). The MIS 5e barrier extends across the estuary, and the barrages, apart from the Goolwa barrage, were built on this shallow foundation, while areas between the barrages were formed of higher remnants of the barrier, which would have restricted marine flooding of the estuary (Bourman *et al*., 2016) (Figure 8). The Younghusband barrier was already fully developed by 6100 year BP (Short & Hesp, 1984), and given that this is a near-surface radiocarbon age, the barrier would have been in place considerably earlier. Given the high-energy surf zone and the wave-dominated environment (Short & Hesp, 1984), the Holocene barrier complex would have restricted the size of the River Murray Mouth and the tidal prism.

Evolution of endemic obligate freshwater fishes

Small obligate freshwater fishes commonly have limited dispersal capacity and show evolutionary histories influenced by the geomorphological and climatic history of their riverine catchments (Avise, 2000; Beheregaray, 2008; Unmack, 2001; Waters *et al*., 2007). Their populations display patterns of genetic divergence, population demography and adaptation that generally reflect the spatial constraints of the drainage network and local environmental conditions (Grummer *et al*., 2019; Unmack, 2001; Waters *et al*., 2007). The wetlands of Lake Alexandrina are home to the southern pygmy perch (*Nannoperca australis*), a freshwater species of high conservation significance that has been the topic of comprehensive biogeographic, phylogenetic, population genetic and genomic studies (*e.g.* Attard *et al*., 2016; Beheregaray *et al*., 2020; Brauer *et al*., 2017; Buckley *et al*., 2021; Cole *et al*., 2016; Unmack *et al*., 2013). Analyses of population genetic and genomic data from across the range of this species indicate that the Lake Alexandrina population is genetically isolated and evolutionarily divergent to populations found elsewhere in the River Murray and in coastal rivers of southeast Australia (Brauer *et al*., 2017; Cole *et al*., 2016; Unmack *et al*., 2013). Modelling of historical niche distribution based on precipitation and temperature data and coalescent demographic analyses based on genetic and genomic data suggest that the Lake Alexandrina population has persisted *in situ* since the late Pleistocene (Attard *et al*., 2016; Buckley *et al*., 2021).

An expectation derived from these findings (Grummer *et al*., 2019) is that this isolated population would have evolved adaptations in response to the unique freshwater environment of the terminal lakes. This hypothesis has been supported by studies of genotype–environment associations and gene expression (Brauer *et al*., 2017) that show that the Lake Alexandrina population is adaptively distinct compared with other populations of southern pygmy perch, with dozens of regions along the genome showing unique associations with local hydroclimatic conditions. The combined evidence across all these studies indicates that the endemic population of southern pygmy perch shows a deep history of evolution linked to freshwater conditions in the terminal lakes of the River Murray. This is consistent with the freshwater preference and limited salinity tolerance of southern pygmy perch, which is known to inhabit well-vegetated, off-channel freshwater habitat and other similar habitats with very low salinity ($<1.57\,g\ L^{-1}$; Koehn & O'Connor, 1990; Wedderburn & Hammer, 2003; Wedderburn *et al*., 2012). The Lower Lakes region, which represents a hotspot for freshwater biodiversity, has been substantially impacted by river regulation, including local and catchment-wide water abstraction (Hammer *et al*., 2013). This has recently led to major declines of aquatic biodiversity, including the southern pygmy perch population, which now only persists in Lake Alexandrina owing to extensive captive breeding and reintroduction programmes (Attard *et al*., 2016; Beheregaray *et al*., 2020; Hammer *et al*., 2013).

Appraisal of Helfensdorfer *et al.* (*2019, 2020*), Power *et al.* (*2020*) and Hubble *et al.* (*2021*)

The physical evidence presented above for a freshwater Holocene history of the Lower Murray and its terminal lakes, Alexandrina and Albert, is the antithesis of the marine/estuarine environment postulated by Helfensdorfer *et al*. (2019, 2020), Power *et al*. (2020) and Hubble *et al*. (2021). The entire thrust of their interpretations and predictions rests on their reconstruction of the Lower Murray during the mid-Holocene, using three-dimensional numerical modelling of marine and fluvial dynamics, involving, in some scenarios, a 2 m-higher-than-present sea-level and extreme widening of the Murray Mouth. They postulated that a 2 m-higher sea-level at the Murray Mouth in the mid-Holocene led to the penetration of the sea into the Lower River Murray from 8500 years BP, forcing the estuarine limit upstream and developing a massive central basin environment more than 200 km long. This model was used to explain the deposition of finely laminated estuarine muds in a

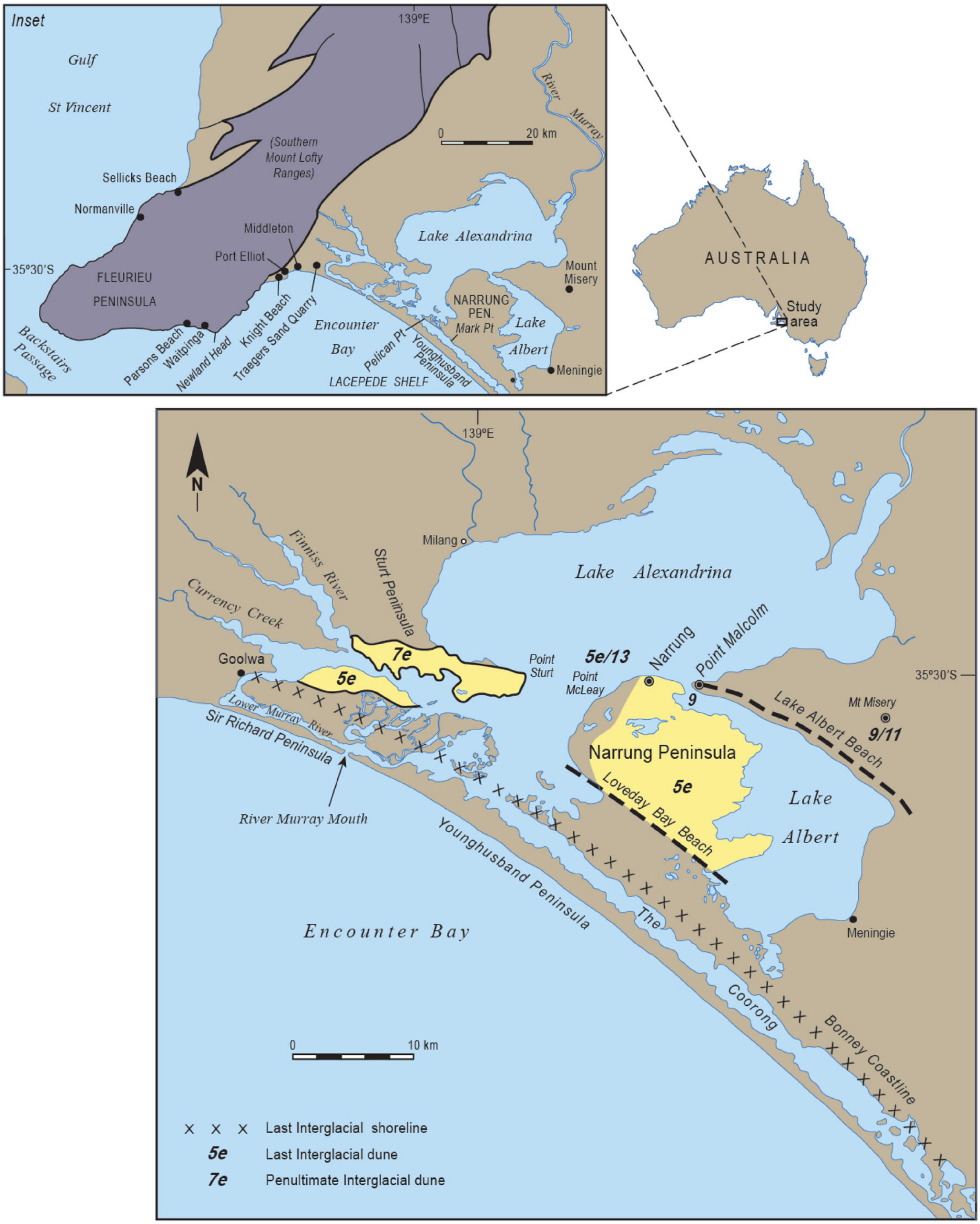

Figure 8. Location of the Murray Estuary showing positions of the last interglacial (125 ka) shoreline (Bonney Coastline), last interglacial coastal dunes (MIS 5e), and the penultimate interglacial dune (MIS 7e). Remnants of older dunes occur at Narrung, Point Malcolm and Mount Misery. The last interglacial shoreline extends along the landward side of the Coorong Lagoon and through the centre of Hindmarsh Island, towards Goolwa. Parts of the barrier shoreline of Younghusband Peninsula are underlain by eolianite of Interstadial MIS 5a (*ca* 80 ka). Source: Murray-Wallace *et al*. (2010, figure 4.2).

central basin. The muds were described as estuarine, and their deposition ascribed to the inhibiting effects of the purported 'estuary' inhibiting sediment transport into the ocean. Although these studies obtained radiocarbon ages between 8518 and 5067 cal year BP on charcoal and organic material from the mud successions, no physical or sedimentological evidence was presented to support an interpretation of an estuarine environment. Modelling was used to delimit three zones, *viz.* Brackish, Brackish–Fresh and Fresh–Brackish in the Lower River

Murray reach (Figure 2). Below, we examine the specific assertions articulated in these papers.

Was there a 2 m mid-Holocene sea-level highstand near the Murray Mouth?

There is abundant evidence that the relative sea-level record around the Australian coast is variably affected by neotectonism and glacio-hydro-isostatic adjustments (Belperio *et al*., 2002; Lewis *et al*., 2013), a finding that is supported by this study. Hubble *et al*. (2021) justify their choice of a 2 m mid-Holocene sea-level by using data sets derived from corals and sedimentary records from the eastern, northern and western Australian coasts. However, it is well known that Holocene sea-level estimates vary widely around the Australian coast, and the current orthodoxy is to apply local evidence to individual sites rather than rely on remotely acquired data to infer sea-levels (Lewis *et al*., 2013), a practice neglected by Helfensdorfer *et al*. (2020), Power *et al*. (2020) and Hubble *et al*. (2021). Even the Holocene sea-level curve for South Australia is poorly constrained because not all sites present data points with finite sea-level estimates (Belperio *et al*., 2002). Taking all factors into consideration, the most reliable estimate for the mid-Holocene relative sea-level in Encounter Bay is ∼1 m AHD based on local evidence (Bourman, 2006, table 2; Dillenburg *et al*., 2020; von der Borch & Altmann, 1979). Accordingly, the mid-Holocene sea-level highstand of 1 m AHD, at the Murray Mouth, is not strictly a 'eustatic sea-level' owing to hydro-isostasy. This represents 50% of the sea-level rise assumed by Helfensdorfer *et al*. (2019, 2020) and may partly explain why their subsequent conclusions are unsupportable.

Fundamental to the interpretations of Helfensdorfer *et al*. (2020) and Hubble *et al*. (2021) is the requirement for a 2 m-high sea-level to occur at 8.5 ka, which they suggest marked the establishment of a putative paleo-Murray estuary. However, various lines of evidence presented in Belperio *et al*. (2002), Cann *et al*. (2006), De Deckker and Murray-Wallace (2021) and Lambeck *et al*. (2014) indicate that sea-level was at −40 m some 10 ka ago, and ∼−13.1 m at 7966–8169 cal yr BP, making an oceanic connection with the Murray Gorge at 8.5 ka impossible.

Hubble *et al*. (2021) used a crude, remarkably linear across-shelf estimate of hydro-isostatic adjustment to justify a 2 m sea-level highstand at the Murray Mouth as 'fit for purpose' for their modelling. However, they failed to justify this approach and ignored an array of opposing empirical evidence, resulting in an erroneous modelling outcome.

Kumarangk (Hindmarsh Island) Sand flat

To support their purported 2 m-higher-than-present mid-Holocene sea-level, Helfensdorfer *et al*. (2019, 2020), Power *et al*. (2020) and Hubble *et al*. (2021) cited Bourman *et al*. (2000). The evidence they relied upon was a sandflat that Bourman *et al*. (2000) mapped standing at ∼1–2 m AHD and forms most of the southern portion of Hindmarsh Island. Bourman *et al*. (2000) collected molluscs at a minimum depth of 0.6 to 1.0 m below this ground surface. Mature and juvenile types of paired *Tellina (Eurytellina) albinella* and *Tellina (Macomana) deltoidalis*, as well as paired *Sanguinolaria (Psammotellina) biradiata*, along with other minor gastropods, were located in a soil pit on the sand flat at (35°31′54.4″ S, 138°52′33.2″ E). The molluscs were radiocarbon-dated at 5980 ± 80 year BP (WK 4784). The articulated character of some of the shells indicated that they were living in a position characteristic of low-energy intertidal sandflat zones in sheltered bays and estuaries (Ludbrook, 1984). During sandflat formation, it is highly likely that the Murray Mouth was significantly wider than now and migrated over far greater distances than it currently does, aggrading the sand flat in the process.

In addition, a sandflat on its own is not a reliable sea-level indicator, as its elevation does not coincide with mean sea-level. For example, James *et al*. (2015, figure 21) have described in detail the aggradation of the sand flat of the current flood-tidal delta fronting Bird Island immediately landward of the Murray Mouth. Part of the modern sandflat lies between 0.6 and 0.8 m AHD and formed over a 5-year period with a constant mean sea-level as small nebka and shadow dunes trapped by sea rocket (*Cakile maritima*) and samphire (*Sarcocornia quinqueflora*) subsequently coalesced into larger nebkhas later levelled by high-water events such as king tides and storm surges. In this manner, the sand flat has aggraded well above mean sea-level, demonstrating that using the surface elevation of sandflats to estimate sea-level is a flawed approach.

Association of the Holocene and last interglacial sandflats

There is a broad coincidence of the last interglacial (LIG) shoreline, which formed about 125 ka ago, and the Holocene shoreline of *ca* 6 ka on the southern half of Hindmarsh Island. Mapping of the LIG shoreline around South Australia reveals that on the stable Gawler Craton on the west coast of Eyre Peninsula, LIG back-barrier lagoonal shells stand consistently at slightly higher than 2 m AHD over hundreds of kilometres (Murray-Wallace *et al*., 2016). In the River Murray Estuary, however, this shoreline has undergone tectonic subsidence, and on Hindmarsh Island the LIG shoreline is currently about 1 m AHD, explaining the general coincidence of the last interglacial and Holocene shorelines. Since its accretion in the mid-Holocene, both the Holocene and the LIG shorelines have emerged by hydro-isostatic uplift of the land.

'The Granites'

Support for a 1 m AHD high mid-Holocene sea-level comes from the work of Dillenburg *et al*. (2020) who reported a sea-level position of 0.76 m AHD at 'The Granites' near the southeastern end of the Peninsula in Encounter Bay at around 6.7 ka. The top of the estuarine record at 1.23 m AHD, adjusted for neotectonic uplift of 0.47 m at a rate of 0.07 mm $yr^{-1,}$ produced a regional sea-level elevation of 0.76 m AHD.

River terraces on the adjacent Fleurieu Peninsula

Around the contiguous Fleurieu Peninsula, flights of river terraces flank many streams, ranging from the Hindmarsh and Inman rivers of Encounter Bay (Figure 1d) to the Onkaparinga River in Gulf St Vincent. Consistently, the lowest terraces are developed on mid-Holocene (*ca* 8–4 ka) grey/black Waldeila Formation, graded to the shoreline at ~1 m AHD (Bourman, 2006; Bourman & Milnes, 2016). Estuarine shell species in small sheltered paleo-estuaries in the lower reaches of many of the coastal valleys have been correlated with the Holocene St Kilda Formation (Cann & Gostin, 1985), while radiocarbon and amino acid racemisation dating confirm their mid-Holocene age (Gill & Bourman, 1972; Kimber & Milnes, 1984).

The last interglacial shoreline stands at 6 m AHD at Victor Harbor, having been uplifted tectonically ~4 m over the past 125 ka (Bourman *et al*., 1999), at an average annual uplift rate of 0.032 mm. Applying this value to the past 7000 years, Holocene shell beds, dated by radiocarbon and amino acid racemisation techniques, have been uplifted ~22 cm by ongoing neotectonism of the Southern Mount Lofty Ranges, with additional uplift owing to hydro-isostasy. Thus, the elevation of the mid-Holocene terrace at the shoreline varies depending on the impacts of coastal erosion, neotectonics and emergence owing to hydro-isostasy.

It should be noted that owing to the barrage system across the lower estuary, Lower River Murray and Lower Lake levels are commonly regulated at an average of approximately 0.75 m AHD with some spring surcharges increasing the level up to 0.85 m AHD and late summer fluctuations decreasing the level to 0.4 m AHD, to more fully mimic the natural conditions. The maximum level of 0.85 m AHD provides a lake level not far below the estimated 1 m AHD peak mid-Holocene sea-level, while the stage height of the river at the mouth during the 1956 flood of 1.43 m AHD is relevant to the impact of any possible future sea-level rises. Furthermore, lake and river levels may be impacted by wind seiche, as exampled by the reports of Noye (1973) and Noye and Walsh (1976), who reported a wind-generated lake setup of 600 mm over 2 h in the Coorong Lagoon.

Evaluation of evidence provided for marine/estuarine conditions in the Murray Gorge area

Helfensdorfer *et al*. (2019, 2020) provided no compelling confirmation for the alleged estuarine–marine conditions during accumulation of mid-Holocene sediments in the River Murray Gorge. They reported no estuarine or marine fossils such as shells, diatoms or dinoflagellates from the Monteith clays. They did infer that clay flocculation and deposition would have been aided by higher salinities, but they also conceded that flocculation of clays also occurs in slow-moving fresh–brackish water. Mosley and Liss (2020) verified this view, noting that particle aggregation in estuaries commonly occurs at the very low salinities of <2 PSU [practical salinity units (PSU) are expressions of salinity values, where 1 PSU ≈ 1 g L^{-1} (total dissolved solids), and seawater has an average salinity of 35 PSU]. Before agricultural development, the dense freshwater reeds present in these river floodplain areas, known locally as the 'Lower Murray Swamps', would also have assisted in trapping fluvial sediment.

It is significant that the main load carried by the river is in suspension and was so in pre-regulation times. For example, Tate (1884) observed overbank deposition of muds from turbid water onto floodplains and the slow return of clear water into the river as its level dropped, thereby building up the floodplain. Johnston (1917) also noted the dominance of suspended load in the lower reaches of the river. Helfensdorfer *et al*. (2020) and Hubble *et al*. (2021) ascribed widespread deposition of a fine-grained central basin facies to a marine/estuarine source, but there is nothing atypical about fine-grained sediments accumulating in meandering river valleys, via in stream (point bar) and overbank deposition, particularly when the stream load consists predominantly of clays.

Lower Murray sedimentary deposits

Helfensdorfer *et al*. (2020) developed their reconstruction of the mid-Holocene Lower Murray, using three-dimensional numerical modelling of marine and fluvial dynamics, to suggest that a mid-Holocene sea-level highstand of 2 m higher than present filled a central basin, previously scoured out during low sea-levels of glacial times. They asserted that the central basin, which extended >140 km upstream into the Murray Gorge, sequestered finely laminated mud deposits in a valley 1–3 km wide, >60 km long and >10 m thick. The fine-grained sediments were regarded as atypical responses of a large catchment river to the Holocene sea-level highstand. Radiocarbon ages between 8518 and 5067 cal yr BP were obtained on charcoal and organic material in the mud deposits. Laminae and banding within the varicoloured clays were attributed to flood events.

Helfensdorfer *et al*. (2020) did not characterise the mineralogy of the clays, which would have given a clue to the source of the clays: *e.g.* the Darling River predominantly carries smectites, whereas the clays of the River Murray are dominantly kaolinitic (Gingele & De Deckker, 2004). These disparities are well illustrated where the streams join at Wentworth in New South Wales, by pronounced colour variations. Helfensdorfer *et al*. (2020) also maintained that these fine-grained sediments are atypical of riverine deposits. However, it is common for low-gradient, slowly flowing lowland rivers to carry predominantly clays and silts as suspended load, a scenario well illustrated by the modern River Murray and the Mississippi River at the Gulf of Mexico.

There is also previous evidence that is consistent with riverine sediment deposition on the floodplains. Fitzpatrick *et al*. (2017) carried out X-ray diffraction studies of soils from 3 m-deep cores across former floodplains, now reclaimed irrigation areas, at Jervois and Long Flat, which are located upstream and downstream of Monteith (Figure 2), the locality of the alluvial cross-section of Helfensdorfer *et al*. (2020). All samples were composed of dominant quartz, sub-dominant kaolin, illite and smectite, with traces of feldspars (albite and orthoclase) and pyrite. Near-surface samples also contained basanite, which was most likely originally gypsum but dehydrated to basanite upon oven drying. Dominant quartz sand and sub-dominant clays are consistent with a fluvial source from the River Murray. Ryan (2015) also noted that quartz sand extends across the Lacepede Shelf off from the Murray Mouth, producing a tongue of terrestrial sediments in the marine carbonate shelf sand, indicating the deposition of terrestrial, fluvially derived sediments into the ocean. De Deckker and Murray-Wallace (2021) provided a recent review of the many studies of sedimentation on the Lacepede Shelf. The findings of Auricht *et al*. (2018) are consistent with the sedimentary record and show that even contemporary floods influence the coastal waters for tens of kilometres from the Murray Mouth.

Helfensdorfer *et al*. (2019, 2020) proposed a shift to freshwater lake conditions as sea-level dropped to its current elevation from the mid-Holocene highstand, while the situation during the proposed mid-Holocene higher sea-level was modelled to highlight the possible impacts of impending climatically induced sea-level rise. However, in this modelling, they ignored the increased river discharge during the mid-Holocene humid period from approximately 8000 to 5000 years ago (*e.g.* Bowler, 1981). In addition, they suggested that the large central basin, in capturing the sediment load of the river, thwarted the delivery of terrestrial sediments to the ocean and concluded that this finding demanded reconsideration of the paleo-climatic conditions of southeastern Australia as postulated by Gingele *et al*. (2004), a judgement that we consider to be completely unwarranted, as did De Deckker and Murray-Wallace (2021) and Tibby *et al*. (2021).

Otoliths as seasonal paleosalinity indicators

Evidence for pronounced seasonality of salinities within the Lower River Murray during the mid- to late Holocene was assumed by Helfensdorfer *et al*. (2020) because of fluctuating paleo-salinities identified in fish otoliths from middens allegedly located immediately upstream from Monteith (Figure 2). Disspain *et al*. (2011) was cited in this context, but that paper actually discusses analyses of otoliths from two euryhaline species well adapted to a wide range of salinities, *viz.* mulloway (*Argyrosomus japonicas)* and black bream (*Acanthopagrus butcheri*), specimens of which were actually recovered from the saline Coorong shore (Figure 2) rather than the Lower River Murray for their research. These fish species are currently present in the Coorong–Murray Mouth region. Furthermore, the late Holocene age from this Coorong site corresponds with the period of prevailing freshwater conditions proposed by Helfensdorfer *et al*. (2019, 2020) in the Lower River Murray. The spatial variability and dynamics of salinity in the estuary were not appreciated, whereas it is common for freshwater to occur in the lakes with saline waters prevailing in the Murray Mouth and Coorong regions synchronously.

In subsequent papers, Disspain *et al*. (2012, 2016) discussed analyses of otoliths from two other fish, Murray cod (*Maccullochella peelii*) and golden perch (*Macquaria ambigua*), found in middens along the Lower River Murray. While the Murray cod is entirely a freshwater species unable to tolerate elevated salinity levels, the golden perch is widely distributed in the freshwater rivers of the Murray–Darling Basin but can also tolerate salinities up to 33 g L^{-1} (Lintermans, 2007) in contrast to the previously discussed pygmy perch. Disspain *et al*. (2012, 2016) sounded warnings that fish can migrate into more saline waters but also that variations in trace elements reflect differences in uptake among species of fish inhabiting the same region. Consequently, there is a need for caution in definitely attributing trace-element concentrations to brackish and saline conditions. Thus, the evidence for pronounced seasonal salinity variations based on otoliths provided by Helfensdorfer *et al*. (2020) is unconvincing. More importantly, they ignored compelling evidence for predominantly freshwater conditions afforded by the presence of freshwater fish, mussels, turtles and crayfish in the middens in which the otoliths were found.

Modelling evidence

Helfensdorfer *et al*. (2019, 2020) used modelling evidence to justify their attribution of marine conditions in the Lower Murray during the mid-Holocene. We find this modelling to be seriously flawed in several areas. This includes using (1) an unjustifiable sea-level highstand of 2 m and width of opening for the Murray Mouth in the model setup (see detailed commentary in Tibby *et al*., 2020), (2) using the Millennium Drought salinities as the initial conditions for the model, when these were the highest salinities in contemporary records and include a large anthropogenic influence (see Mosley *et al*., 2012), and (3) only running the model for 20 days and assuming that it had reached steady state when it fact the natural system took several months (Lake Alexandrina) to years (Lake Albert) for lake water salinities to recover from the Millennium Drought (see Aldridge *et al*., 2018). In contrast, Gibbs (2020) provided more realistic model setup parameters and ran it for a period consistent with the time required to demonstrate a return to steady state. In doing so, the output showed a predominance of freshwater conditions consistent with other evidence we have described herein. Helfensdorfer *et al*. (2019) reported that water velocities across most of the model domain were below 0.3 m/s. As it is 209 km (Helfensdorfer *et al*., 2019, figure 1) from the inflow point of the model at Blanchetown to the entrance to Lake Alexandrina, a minimum 8-day travel time is required for inflows to reach Lake Alexandrina using a maximum velocity of 0.3 m/s. This travel time is based on wave-front propagation, which is faster than the advection–dispersion process transporting salt. Hence, steady-state water levels in a model do not mean there are steady-state salinity levels.

At zero metres AHD water level with current bathymetry, the volume of the Lower Lakes is approximately 1300 GL (Gibbs *et al*., 2018) and possibly close to double this for a 2 m sea-level scenario, and much more for the lowered bathymetry scenarios. At the pre-regulation average flow considered (419 m^3/s), a period of 36 days is required for the lakes to completely turn over with a zero metre AHD water level, and close to three times longer for the Millennium drought low-flow scenario considered (152 m^3/s). This simple calculation assumes perfect mixing, and factors such as preferential flow paths and constrictions such as the Narrung Narrows will require longer periods to reach steady state.

Implications for river management

Helfensdorfer *et al*. (2019, 2020), Power *et al*. (2020) and Hubble *et al*. (2021) have argued that the Lower Murray Lakes and Lower River Murray were marine/estuarine in character during the mid-Holocene, and that this assumption should form the basis for future management of the river system. However, evidence presented here demonstrates the flawed nature of their argument and that there is a need to maintain freshwater conditions in the Lower Lakes based on its natural history.

The investigations of Helfensdorfer *et al*. (2019, 2020), Power *et al*. (2020), Hubble *et al*. (2021) and Job *et al*. (2021) favour the view that the Murray Estuary is wave-dominated and developed during a transgressive sea-level rise, which produced a marine to estuarine environment in the Lower Lakes and Murray Gorge for up to 200 km upstream. They also argued that large quantities of fine-grained sediments were trapped in a central basin preventing their dispersal to the ocean. We accept the view of a Post-Glacial marine transgression providing a forcing mechanism to sweep lowstand shelf sediments landwards across the shelf to form Sir Richard and Younghusband peninsulas. However, we do not accept that the transgression resulted in a major marine incursion into the Murray Gorge because of the lack of empirical evidence provided for this conclusion, together with the evidence assembled here for freshwater conditions in the Lower River Murray and the Lower Lakes at this time. While the shoreline fronting the estuary is wave-dominated, with the general location of the Murray Mouth being influenced by reversed directions of longshore transport (Bourman & Murray-Wallace, 1991), the original estuary itself was river-dominated, and it was the river that cut through the coastal barrier to form the mouth. Without a river, there would be no mouth.

Job *et al*. (2021) concluded that the health of the Lower Lakes should be judged on their condition of 80 years ago, immediately before barrage completion in 1940, in the light of 'its previously mature estuarine state which persisted from *ca* 3.5 ka BP until anthropogenic modifications fundamentally changed its hydro-sedimentological function' (p. 13). However, without the restoration of natural pre-water resource development flows to the environment, the natural freshwater ecology of the lakes that had existed for millennia would be destroyed. Moreover, the barrages were constructed primarily to retain freshwater in order to restore the balance upset by the upstream abstraction of large volumes of water (Beasley, 2021). Immediate pre-barrage environments are not representative of so-called 'pristine conditions', after so much freshwater had been abstracted from the system. An independent report (Chiew *et al*., 2020) demonstrated that the Lower Lakes were predominantly fresh during the 300 years before European settlement. This condition should be the baseline for future management because it best approximates the environmental condition of the lakes today. There may, however, be opportunities for more flexible management of the estuarine interface under suitable flow conditions if the barrages were fully automated. For example, barrages could be opened for short periods of time when water levels on both sides of the barrages are equal, or higher on the freshwater side, to facilitate the migration of estuarine dependent fish. Furthermore, the barrages could be operated to vary flows through the different barrage systems, rather than directing flow primarily through the Goolwa barrage. Discharge through the Tauwitchere barrage could be utilised to freshen the Coorong waters, while flows through the Mundoo barrage could help to clear flood-tidal delta sediments. The Mundoo barrage, which is built across the most direct course to the Murray Mouth, has been rarely opened over the past 80 years because it also acts as a bridge and is cumbersome to operate, resulting in extensive sedimentation.

One of the management strategies considered by Thom *et al*. (2020) was to construct a barrage at Wellington and remove the existing barrage system in order to tidally flush the estuary with seawater: this would be a huge physical experiment. This proposal also required the establishment of a new tidal inlet from the main Goolwa Channel, to the west of the present Murray Mouth, with training walls extending seawards out to a water depth of 15 m (Thom *et al*., 2020). However, Encounter Bay experiences a microtidal spring high-water range of 0.8 m with a lower tidal range in the estuary, which would inevitably lead to

Figure 9. Oblique aerial view over the Murray Mouth taken in 1983 showing the flood-tidal delta of Bird Island, the Mundoo Channel, which separates Hindmarsh and Mundoo Islands, and Point Sturt Peninsula, beyond which is Lake Alexandrina. Today the flood tidal delta has grown, joining Bird Island onto Hindmarsh Island. Failure to maintain the mouth at its current location will result in the complete blockage of the Goolwa and Coorong channels, ultimately linking the barrier shoreline to Hindmarsh Island.

sediment accumulation in the estuary, and, as at Lakes Entrance (Wheeler *et al*., 2010), regular dredging would almost certainly be required to maintain the channels.

The training walls of the new tidal inlet would also interfere with the longshore transport of sand along the beach and impact the coastal configuration as well as halting vehicular access along the coast. The general location of the Murray Mouth relates to longshore transport of sand from opposed directions focussing on the mouth. The mouth fluctuates within a range of ~2 km involving the annual sand movement of up to 1 000 000 m^3 (Bourman, Harvey, *et al*., 2018). Sand will still accumulate at the site of the original mouth (Figure 9) and join onto the existing flood-tidal delta of Bird Island, effectively blocking the channel between the Goolwa Channel and the Coorong. The ecological impacts of such an intervention are unclear but are likely to be very significant, with risks of unintended consequences being high.

Conclusions

The primary evidence used by Helfensdorfer *et al*. (2019, 2020) and Hubble *et al*. (2021) for the existence of a large, mid-Holocene estuary and central basin within the lower Murray Gorge that resulted in the deposition of a >100 km long, valley-wide, and >10 m-thick mud deposit was based on hydrodynamic modelling involving a postulated mid-Holocene high sea-level of 2 m at the Murray Mouth. They considered the 2 m-high sea-level to be a 'reasonable estimate' and 'fit-for-purpose' value for their modelling, the output from which produced scenarios describing salinities higher than at present in the Lower River Murray. However, they provided no local corroborating evidence to support the validity of using this 2 m higher sea-level, whereas there is ample multi-disciplinary evidence from a variety of scientists demonstrating that the mid-Holocene sea-level at the mouth did not exceed 1 m AHD when neotectonism and glacio-hydro-isostatic adjustments were taken into account. There are many other criticisms of the modelling approach noted above.

Most importantly, no direct fossil evidence was provided to demonstrate the alleged estuarine/marine character of the clays deposited in the Murray Gorge during the mid-Holocene. We, however, present multiple lines of independent evidence substantiating that freshwater conditions existed in the Lower River Murray and the Lower Lakes during this time, including freshwater diatom evidence in alluvial deposits adjacent to their Monteith field site. Archaeological investigations of Aboriginal middens throughout the Lower River Murray and the Lower Lakes region all contain evidence of mussel shells, fish otoliths, crayfish and turtles of freshwater origin, with a chronology spanning the entire Holocene epoch, providing further support for the freshwater character of the system.

Furthermore, unlike every other coastal lake/embayment along the South Australian coastline, and after much investigation, no marsh, mangrove, intertidal, seagrass or shellbank deposits, which could be used/dated as sea-level data points, have been located around the lakes or in the Murray Gorge. This suggests a dominant fluvial freshwater influence throughout the Holocene.

A broad array of other data assembled in this paper garnered from sites throughout the region, including freshwater diatoms, sapropels, freshwater terrestrial and lacustrine successions, and evidence of an open Murray Mouth, combine to demonstrate the freshwater nature of the Lower River Murray and the Murray Lakes since *ca* 8000 calendar years ago, which were flushed regularly by winter–spring runoff from the Alps, apart from during occasional drought years. Helfensdorfer *et al*. (2019, 2020) seemed to ignore the climatically induced (Quigley *et al*., 2010) impacts of increased river flows during the mid-Holocene, focussing on the movement of marine waters inland as the sole basis for their hypothesis.

It is important to firmly establish the salinity status of the Lower River Murray and the Lower Lakes over time, so that their freshwater ecologies can be sustained to maintain their standing as a Ramsar Wetland of International Importance. Some workers such as Thom *et al*. (2020) are considering barrage removal to allow the system to return to a 'more "natural" estuarine environment'. However, this would destroy the existing freshwater system and replace it with an increasingly saline environment. While the current state is not identical to the original, because so much water has been extracted from the system, it most closely simulates the natural character of the Lower Lakes compared with simply removing the barrages and replacing freshwater with seawater. Further, as we have demonstrated throughout this paper, the Lower River Murray and Lakes environment is replete with the archaeological evidence of Aboriginal occupation. As such, there are also significant Aboriginal cultural perspectives to consider in relation to all water management (Hemming & Rigney, 2016), as illustrated by the Ngarrindjeri statement in the Murray–Darling Basin Commission (2002) report on the Murray Mouth:

> *The link with the land lies at the heart and soul of Ngarrindjeri culture. A proper relationship and role in management of the land is a fundamental platform in building and maintaining Ngarrindjeri culture and Ngarrindjeri self-respect. Ngarrindjeri believe that their future involvement in the management of the land would be positive and beneficial to all members of the community, not just Ngarrindjeri. It would represent a significant step in the process of reconciliation and co-existence. The strengthening of Ngarrindjeri people and their culture requires a serious involvement in the managing of their traditional lands.*

Our findings are consistent with a recent independent review, which reported that the Lower Lakes of the River Murray, and hence also the river channel and floodplains immediately upstream, had been predominantly fresh before European settlement in the near-term (past 200–300 years), with temporary saltwater incursions occurring only during droughts (Chiew *et al*., 2020). The findings of this study are compatible with the retention of the barrages to maintain the freshwater status of the lakes. The barrages were built only after upstream water extractions resulted in a greater penetration of seawater into the lakes, impacting on the environmental values of this Ramsar-listed ecosystem. We are concerned that the Helfensdorfer *et al*. (2019, 2020), Hubble *et al*. (2021), Thom *et al*. (2020) and Job *et al*. (2021) studies have the potential to mislead environmental managers of the Murray–Darling Basin; there is a need to manage environmental flows and barrage operations to maintain the current state as closely as possible to replicate the thousands of years of predominantly freshwater conditions in the past.

Funding

The research of Chris Wilson is supported by the Ngarrindjeri Aboriginal Corporation. His work has been approved by the Flinders University Social and Behavioural Research Ethics Committee [number 8406].

ORCID

R. P. Bourman http://orcid.org/0000-0003-3384-8254
C. V. Murray-Wallace http://orcid.org/0000-0002-3029-9141
C. Wilson http://orcid.org/0000-0002-0218-6895
L. Mosley http://orcid.org/0000-0002-7446-8955
J. Tibby http://orcid.org/0000-0002-5897-2932
D. D. Ryan http://orcid.org/0000-0002-1931-9033
E. D. De Carli http://orcid.org/0000-0001-9575-3408
A. Tulley http://orcid.org/0000-0001-6121-5046
A. P. Belperio http://orcid.org/0000-0002-9577-0432
D. Haynes http://orcid.org/0000-0002-1977-5936
A. Roberts http://orcid.org/0000-0002-9004-292X
C. Westell http://orcid.org/0000-0003-2405-6861
E. J. Barnett http://orcid.org/0000-0003-0801-8275
S. Dillenburg http://orcid.org/0000-0003-0072-7018
L. B. Beheregaray http://orcid.org/0000-0003-0944-3003
P. A. Hesp http://orcid.org/0000-0003-4573-2945

References

Aldridge, K., Mosley, L. M., & Oliver, R. (2018). Water quality in the Coorong Lower Lakes and Murray Mouth. Ch. 2.10. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 253–270). Royal Society of South Australia.

Attard, C. R. M., Möller, L. M., Sasaki, M., Hammer, M. P., Bice, C., Brauer, C., Carvalho, D., Harris, J., & Beheregaray, L. B. (2016). A novel holistic framework for genetic-based captive-breeding and reintroduction programs. *Conservation Biology: The Journal of the Society for Conservation Biology*, *30*(5), 1060–1069. https://doi.org/10.1111/cobi.12699

Auricht, H., Clarke, K., Lewis, M., & Mosley, L. M. (2018). Have droughts and increased water extraction from the River Murray (Australia) reduced coastal ocean productivity? *Marine and Freshwater Research*, *69*(3), 343–356. https://doi.org/10.1071/MF17226

Avise, J. C. (2000). *Phylogeography: The History and Formation of Species*. Harvard University Press.

Barnett, E. J. (1990). Identification of diatoms genera or species and abundance of diatoms for selected Cooke Plains and Waltowa Swamp samples. The Flinders University of South Australia School of Earth Sciences report 62091 (unpublished). In Olliver Geological Services (1995). *EL 1628 MALCOLM PLAINS. Progress Reports to Licence Expiry Surrender for the Period 22/12/1989 to 21/12/1993*. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/image/DDD/ENV08281.pdf

Barnett, E. J. (1991). Identification of diatoms genera or species and abundance of diatoms for Waltowa Swamp samples. The Flinders University of South Australia School of Earth Sciences report 111090 (unpublished). In Olliver Geological Services (1995). *EL 1628 MALCOLM PLAINS. Progress Reports to Licence Expiry Surrender for the Period 22/12/1989 to 21/12/1993*. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/image/DDD/ENV08281.pdf

Barnett, E. J. (1993). *Recent sedimentary history of Lake Alexandrina and the Murray Estuary* [Unpublished PhD thesis]. School of Earth Sciences, Flinders University of South Australia.

Barnett, E. J. (1994). A Holocene paleoenvironmental history of Lake Alexandrina, South Australia. *Journal of Paleolimnology*, *12*(3), 259–268. https://doi.org/10.1007/BF00678024

Barnett, E. J. (1995). Distinguishing natural and anthropogenic influences: A case study of Lake Alexandrina. *South Australian Geographical Journal*, *94*, 36–49.

Barnett, S. (2018). Hydrogeology of the Lower Lakes and Coorong Region. Chapter 2.8. In L. Mosley, S. Shepherd, Q. He, S. Hemming, and R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 217–226). Royal Society of South Australia.

Beasley, R. (2021). *Dead in the water: A very angry book about our greatest environmental catastrophe… the death of the Murray–Darling Basin*. Allen & Unwin, 296. pp.

Beheregaray, L. B. (2008). Twenty years of phylogeography: The state of the field and the challenges for the Southern Hemisphere. *Molecular Ecology*, *17*(17), 3754–3774. https://doi.org/10.1111/j.1365-294X.2008.03857.x

Beheregaray, L. B., Attard, C. R. M., Brauer, C. J., Whiterod, N., Wedderburn, S., & Hammer, M. (2020). Conservation breeding and reintroduction of pygmy perches in the lower Murray–Darling Basin, Australia: Two similar species, two contrasting outcomes. In P. S. Soorae (Ed.), *IUCN Global Reintroduction Perspectives. Case Studies from Around the Globe* (pp. 26–31).

Bell, D. (1998). *Ngarrindjeri Wurruwarrin: A world that is, was, and will be*. Spinifex Press.

Belperio, A. P., Harvey, N., & Bourman, R. P. (2002). Spatial and temporal variability in the Holocene sea-level record around the South Australian coastline. *Sedimentary Geology*, *150*(1–2), 153–169. https://doi.org/10.1016/S0037-0738(01)00273-1

Blaauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis*, *6*(3), 457–474. https://doi.org/10.1214/11-BA618

Bourman, R. P. (2006). River terraces of the Fleurieu Peninsula. *South Australian Geographical Journal*, *105*, 1–24.

Bourman, R. P., & Barnett, E. J. (1995). Impacts of river regulation on the terminal lakes and mouth of the River Murray, South Australia. *Australian Geographical Studies*, *33*(1), 101–115. https://doi.org/10.1111/j.1467-8470.1995.tb00688.x

Bourman, R. P., Belperio, A. P., Murray-Wallace, C. V., & Cann, J. H. (1999). A last interglacial embayment fill at Normanville, South Australia, and its neotectonic implications. *Transactions Royal Society of South Australia*, *123*(1), 1–15.

Bourman, R. P., & Harvey, N. (1983). The Murray Mouth Flood Tidal Delta. *Australian Geographer*, *15*(6), 403–406. https://doi.org/10.1080/00049188308702844

Bourman, R. P., Harvey, N., James, K. F., Murray-Wallace, C. V., Belperio, A. P., & Ryan, D. D. (2018). The mouth of the River Murray. Chapter 2.3. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 103–121). Royal Society of South Australia.

Bourman, R. P., Milnes, A. R. (2016). *The geology and landforms of the Inman River Catchment*. Report to the Inman River Catchment Landcare Group (December 2016), 237 pp. http://www.victor.sa.gov.au/page.aspx?u=856

Bourman, R. P., & Murray-Wallace, C. V. (1991). Holocene evolution of a sand spit at the mouth of a large river system: Sir Richard Peninsula and its significance for management of the Murray Mouth, South Australia. *Zeitschrift für Geomorphologie, Suppl.-Bd*, *81*, 63–83.

Bourman, R. P., Murray-Wallace, C. V., Belperio, A. P., & Harvey, N. (2000). Rapid coastal geomorphic change in the River Murray Estuary of Australia. *Marine Geology*, *170*(1–2), 141–168. https://doi.org/10.1016/S0025-3227(00)00071-2

Bourman, R. P., Murray-Wallace, C. V., & Harvey, N. (2016). *Coastal Landscapes of South Australia*. The University of Adelaide Press, 405p. http://www.jstor.org/stable/10.20851/j.ctt1sq5wk8.9

Bourman, R. P., Murray-Wallace, C. V., Ryan, D. D., & Belperio, A. P. (2018). The geological evolution of the River Murray Estuary Region. Chapter 2.1. In L. Mosley, S. Shepherd, Q. He, S. Hemming and R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 37–69). Royal Society of South Australia.

Bourman, R. P., Murray-Wallace, C. V., Ryan, D. D., Belperio, A. P., & Harvey, N. (2018). Geomorphological evolution of the Murray Estuary Region. Chapter 2.2. In L. Mosley, S. Shepherd, Q. He, S. Hemming and R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 72–102). Royal Society of South Australia.

Bowler, J. M. (1981). Australian salt lakes: A palaeohydrologic approach. *Hydrophobia*, *82*, 431–444.

Bowler, J. M., & Hamada, T. (1971). Late Quaternary stratigraphy and radiocarbon chronology of water level fluctuations in Lake Keilambete, Victoria. *Nature*, *232*(5309), 330–332. https://doi.org/10.1038/232330a0

Bowler, J. M., Hope, G. S., Jennings, J. N., Singh, G., & Walker, D. (1976). Late Quaternary climates of Australia and New Guinea. *Quaternary Research*, *6*(3), 359–394. https://doi.org/10.1016/0033-5894(67)90003-8

Bowler, J. M., Johnston, H., Olley, J. M., Prescott, J. R., Roberts, R. G., Shawcross, W. F., & Spooner, N. A. (2003). New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature*, *421*(6925), 837–840. https://doi.org/10.1038/nature01383

Bowler, J. M., Kotsonis, A., & Lawrence, C. R. (2006). Environmental evolution of the Mallee region, Western Murray Basin. *Proceedings of the Royal Society of Victoria*, *118*(2), 161–210.

Brauer, C., Unmack, P. J., & Beheregaray, L. B. (2017). Comparative ecological transcriptomics and the contribution of gene expression to the evolutionary potential of a threatened fish. *Molecular Ecology*, *26*(24), 6841–6856. https://doi.org/10.1111/mec.14432

Bronk-Ramsey, C. (2010). OxCal Program v4.0.5. http://c14.arch.ox.ac.uk/

Buckley, S., Brauer, C. J., Unmack, P. J., Hammer, M. P., & Beheregaray, L. B. (2021). The roles of aridification and sea level changes in the diversification and persistence of freshwater fish lineages. *Molecular Ecology*, *30*(19), 4866–4883. https://doi.org/10.1111/mec.16082

Cann, J. H., Bourman, R. P., & Barnett, E. J. (2000). Holocene foraminifera as indicators of relative estuarine-lagoonal and oceanic influences in estuarine sediments of the River Murray, South Australia. *Quaternary Research*, *53*(3), 378–391. https://doi.org/10.1006/qres.2000.2129

Cann, J. H., & Gostin, V. A. (1985). Coastal sedimentary facies and foraminiferal biofacies of the St Kilda Formation at Port Gawler, South Australia. *Transactions of the Royal Society of South Australia*, *109*, 121–142.

Cann, J. H., Murray-Wallace, C. V., Riggs, N., & Belperio, A. P. (2006). Successive foraminiferal faunas inferred palaeoenvironments associated with the postglacial (Holocene)marine transgression, Gulf St

Vincent, South Australia. *The Holocene*, *16*(2), 224–234. https://doi.org/10.1191/0959683606hl907rp
Chiew, F. H. S., Hale, J., Joehnk, K. D., Reid, M. A., Webster, I. T. (2020). *Independent review of Lower Lakes science informing water management*. Report for the Murray–Darling Basin Authority. http://www.mdba.gov.au/sites/default/files/images/LowerLakesScienceReview_FINALREP ORT_29Apr2020-web.pdf
Cole, T. L., Hammer, M. P., Unmack, P. J., Teske, P. R., Brauer, C. J., Adams, M., & Beheregaray, L. B. (2016). Range-wide fragmentation in a threatened fish associated with post-European settlement modification in the Murray–Darling Basin. *Conservation Genetics*, *17*(6), 1377–1391. https://doi.org/10.1007/s10592-016-0868-8
De Deckker, P., & Murray-Wallace, C. V. (2021). Results from the 2003 Auscan Cruise offshore Kangaroo Island and the veracity of the records of two deep-sea cores obtained during the cruise, with a discussion on the Holocene history of the River Murray Estuary. *Quaternary Australasia*, *38*, 17–24.
de Mooy, C. J. (1959). Notes on the geomorphic history of the area surrounding Lakes Alexandrina and Albert, South Australia. *Transactions of the Royal Society of South Australia*, *82*, 99–118.
Dillenburg, S. R., Hesp, P. A., Keane, R., Miot da Silva, G., Sawakuchi, A. O., Moffat, I., Barboza, E. G., & Bitencourt, J. B. (2020). Geochronology and evolution of a complex barrier, Younghusband Peninsula, South Australia. *Geomorphology*, *354*, 107044–107013. https://doi.org/10.1016/j.geomorph.2020.107044
Disspain, M. C. F., Ulm, S., & Gillanders, B. M. (2016). Otoliths in archaeology: Methods, applications and future prospects. *Journal of Archaeological Science: Reports*, *6*, 623–632. https://doi.org/10.1016/j.jasrep.2015.05.012
Disspain, M. C. F., Wallis, L. A., & Gillanders, B. M. (2011). Developing baseline data to understand environmental change: A geochemical study of archaeological otoliths from the Coorong, South Australia. *Journal of Archaeological Science*, *38*(8), 1842–1857. https://doi.org/10.1016/j.jas.2011.03.027
Disspain, M. C. F., Wilson, C. J., & Gillanders, B. M. (2012). Morphological and chemical analysis of archaeological fish otoliths from the Lower Murray River, South Australia. *Archaeology in Oceania*, *47*(3), 141–115. https://doi.org/10.1002/j.1834-4453.2012.tb00126.x
Fitzpatrick, R. W., Shand, P., & Mosley, L. M. (2017). Acid sulfate soil evolution models and pedogenic pathways during drought and reflooding cycles in irrigated areas and adjacent natural wetlands. *Geoderma*, *308*, 270–290. https://doi.org/10.1016/j.geoderma.2017.08.016
Fitzpatrick, R. W., Shand, P., & Mosley, L. M. (2018). Soils in the Coorong, Lower Lakes and Murray Mouth Region. Chapter 2.9. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 227–252). Royal Society of South Australia.
Fluin, J. (2002). *A diatom-based palaeolimnological investigation of the lower River Murray, south eastern Australia* [Unpublished PhD thesis]. School of Geographical and Environmental Studies, Monash University, Melbourne.
Fluin, J., Gell, P., Haynes, D., Tibby, J., & Hancock, G. (2007). Palaeo-limnological evidence for the independent evolution of neighbouring terminal lakes, the Murray Darling Basin, Australia. *Hydrobiologia*, *591*(1), 117–134. https://doi.org/10.1007/s10750-007-0799-y
Fluin, J., Haynes, D., & Tibby, J. (2009). *An environmental history of the Lower Lakes and The Coorong*. A report for the Department of Environment and Heritage (South Australia). University of Adelaide.
Foged, N. (1978). Diatoms in eastern Australia. *Bibliotheca Phycologica*, *47*, 1–255.
Gell, P. A. (2020). Watching the tide roll away—contested interpretations of the nature of the Lower Lakes of the Murray Darling Basin. *Pacific Conservation Biology*, *26*(2), 130–141. https://doi.org/10.1071/PC18085
Gibbs, M. (2020). *Scenario modelling of the Lower Lakes during the Millennium Drought. Technical Report*. South Australia Department of Environment and Water.
Gibbs, M., Joehnk, K., Webster, I., & Heneker, T. (2018). Hydrology and hydrodynamics of the Lower Lakes, Coorong and Murray Mouth. Chapter 2.7. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 197–216). Royal Society of South Australia.
Gill, E. D., & Bourman, R. P. (1972). Research on Quaternary shorelines in Australia and New Zealand—a summary report of the ANZAAS Quaternary Shorelines Committee: Report for South Australia. *Search*, *3*(4), 103–104.
Gingele, F. X., & De Deckker, P. (2004). Fingerprinting Australia's rivers with clay minerals and the application for the marine record of climate change. *Australian Journal of Earth Sciences*, *51*(3), 339–348. https://doi.org/10.1111/j.1400-0952.2004.01061.x
Gingele, F. X., De Deckker, P., & Hillenbrand, C.-D. (2004). Late Quaternary terrigenous sediments from the Murray Canyons area, offshore South Australia and their implications for sea level change, palaeoclimate and palaeodrainage of the Murray–Darling Basin. *Marine Geology*, *212*(1–4), 183–197. https://doi.org/10.1016/j.margeo.2004.09.001
Gloster, A. (1998). *The Late Pleistocene and Holocene sedimentary history of Lake Albert, South Australia* [Unpublished MSc thesis]. Flinders University of South Australia.
Grummer, J. A., Beheregaray, L. B., Bernatchez, L., Hand, B., Luikart, G., Narum, S. R., & Taylor, E. B. (2019). Aquatic landscape genomics and environmental effects on genetic variation. *Trends in Ecology & Evolution*, *34*(7), 641–654. https://doi.org/10.1016/j.tree.2019.02.013
Hale, H. M., & Tindale, N. B. (1930). Notes on some human remains in the Lower Murray Valley. South Australia. *Records of the South Australian Museum*, *4*, 145–218.
Hammer, M. P., Bice, C. M., Hall, A., Frears, A., Watt, A., Whiterod, N. S., Beheregaray, L. B., Harris, J. O., & Zampatti, B. P. (2013). Freshwater fish conservation in the face of critical water shortages in the southern Murray–Darling Basin, Australia. *Marine and Freshwater Research*, *64*(9), 807–821. https://doi.org/10.1071/MF12258
Harvey, N. (1996). The significance of coastal processes affecting management of the River Murray Estuary. *Australian Geographical Studies*, *34*(1), 45–57. https://doi.org/10.1111/j.1467-8470.1996.tb00102.x
Harvey, N., Bourman, R. P., & James, K. J. (2006). Evolution of the Younghusband Peninsula, South Australia: New evidence from the Northern Tip. *South Australian Geographical Journal*, *105*, 37–50.
Haynes, D., Tibby, J., Fluin, J., & Skinner, R. (2018). Palaeolimnology of the Lower Lakes and Coorong lagoon. Chapter 2.4. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 122–143). Royal Society of South Australia.
Helfensdorfer, A. M., Power, H. E., & Hubble, T. C. T. (2019). Modelling Holocene analogues of coastal plain estuaries reveals the magnitude of sea-level threat. *Scientific Reports*, *9*(1), 2667. https://doi.org/10.1038/S41598-019-39516-4
Helfensdorfer, A. M., Power, H. E., & Hubble, T. C. T. (2020). Atypical responses of a large catchment river to the Holocene sea-level highstand: The Murray River. *Scientific Reports*, *10*(1), 7503. https://doi.org/10.1038/S41598-020-61800-x
Hemming, S., Rigney, D. (2016). *Restoring Murray Futures: Incorporating Indigenous knowledge, values and interests into environmental water planning in the Coorong and Lakes Alexandrina and Albert Ramsar Wetland.* Goyder Institute for Water Research Technical Report Series No. 16/8. https://data.environment.sa.gov.au/Content/Publications/Hemming%20and%20Rigney%202016.pdf
Hill, P. J., De Deckker, P., von der Borch, C., & Murray-Wallace, C. V. (2009). Ancestral Murray River on the Lacepede Shelf, southern Australia: Late Quaternary migrations of a major river outlet and

strandline development. *Australian Journal of Earth Sciences*, *56*(2), 135–157. https://doi.org/10.1080/08120090802546993

Hogg, A. G., Heaton, T. J., Hua, Q., Palmer, J. G., Turney, C. S. M., Southon, J., Bayliss, A., Blackwell, P. G., Boswijk, G., Bronk Ramsey, C., Pearson, C., Petchey, C., Reimer, P., Reimer, R., & Wacker, L. (2020). SHCal20 Southern Hemisphere Calibration, 0–55 000 years cal BP. *Radiocarbon*, *62*(4), 759–778. https://doi.org/10.1017/RDC.2020.59

Hötzel, G., & Croome, R. (1996). Population dynamics of *Aulacoseira granulata* (Ehr.) Simonson (Bacillariophyceae, Centrales), the dominant alga in the Murray River, Australia. *Archiv für Hydrobiologie*, *136*(2), 191–215. https://doi.org/10.1127/archiv-hydrobiol/136/1996/191

Hubble, T. C. T., Helfensdorfer, A. M., Job, T. A., & Power, H. E. (2021). Reply to: A large mid-Holocene estuary was not present in the lower River Murray, Australia. *Scientific Reports*, *11*(1), 12083. https://doi.org/10.1038/s41598-021-89076-9

James, K. F. (2004a). *The bio-geomorphological evolution of a former/flood tide delta (Bird Island) in the Murray Mouth estuary of South Australia* [Unpublished Master of Applied Science Thesis]. School of Natural and Built Environments, University of South Australia, 249 pp.

James, K. F. (2004b). Shifting sands at the Murray Mouth: Evidence from historic surveys 1839–1938. *South Australian Geographical Journal*, *103*, 25–42.

James, K. F., Bourman, R. P., & Harvey, N. (2015). Rapid evolution of a flood tidal deltaic island in the River Murray Estuary, South Australia: a canary in the cage of river management. *Journal of Coastal Research*, *315*(5), 1103–1119. https://doi.org/10.2112/JCOASTRES-D-13-00100.1

James, N. P., & Bone, Y. (2011). *Neritic carbonate sediments in a Temperate Realm—Southern Australia*. Springer, 254 pp.

James, N. P., & Bone, Y. (2021). *Biogenic Sedimentary Rocks in a Cold, Cenozoic Ocean—Neritic Southern Australia*. Springer, 216 pp.

Job, T., Penny, D., Morgan, B., Hua, Q., Gadd, P., & Zawadzki, A. (2021). Multi-stage Holocene evolution of the River Murray Estuary, South Australia. *The Holocene*, *31*(1), 50–65. https://doi.org/10.1177/0959683620961487

Johnston, E. N. (1917). *Report on the harbour for the River Murray Valley*. Parliamentary Paper, Adelaide, No. 38 (pp. 3–71). R. E. E. Rogers, Government Printer.

Kimber, R. W. L., & Milnes, A. R. (1984). The extent of racemisation of amino acids in Holocene and Pleistocene marine molluscs in Southern South Australia: Preliminary data on a time framework for calcrete formation. *Australian Journal of Earth Sciences*, *31*(3), 279–286. https://doi.org/10.1080/14400958408527930

Koehn, J. D., & O'Connor, W. G. (1990). *Biological information for management of native freshwater fish in Victoria*. Department of Conservation and Environment, Freshwater Fish Management Branch, Arthur Rylah Institute for Environmental Research, 165 p, Melbourne.

Krammer, K., & Lange-Bertalot, H. (1986). *Süßwasserflora von Mitteleuropa. Bacillariophyceae 1: Bacillariaceae, Epithemiacaeae, Surrirellaceae*. Fischer.

Krammer, K., & Lange-Bertalot, H. (1988). *Süßwasserflora von Mitteleuropa. Bacillariophyceae 2: Bacillariaceae, Epithemiacaeae, Surrirellaceae*. Fischer.

Krammer, K., & Lange-Bertalot, H. (1991a). *Süßwasserflora von Mitteleuropa. Bacillariophyceae 3: Centrales, Fragilariaceae, Eunotiaceae*. Fischer.

Krammer, K., & Lange-Bertalot, H. (1991b). *Süßwasserflora von Mitteleuropa. Bacillariophyceae 4: Achnanthaceae*. Fischer.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., & Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *PNAS*, *111*(43), 15296–15303. https://doi.org/10.1073/pnas.1411762111

Lewis, S. E., Sloss, C. R., Murray-Wallace, C. V., Woodroffe, C. D., & Smithers, S. G. (2013). Post-glacial sea-level changes around the Australian margin: A review. *Quaternary Science Reviews*, *74*, 115–138. https://doi.org/10.1016/j.quascirev.2012.09.006

Lintermans, M. (2007). *Fishes of the Murray–Darling Basin: An introductory guide*. https://www.mdba.gov.au/sites/default/files/archived/mdbc-NFS-reports/2202_factsheet_native_golden_perch.pdf

Littleton, J., Petchey, F., Walsh, K., & Pate, D. (2017). A preliminary redating of the Holocene Roonka burials, south-eastern Australia. *Archaeology in Oceania*, *52*(2), 98–107. https://doi.org/10.1002/arco.5126

Ludbrook, N. H. (1984). *Quaternary molluscs of South Australia*. South Australia, Department of Mines and Energy, Handbook No. 9, 327 pp.

McCarthy, D., Rogers, T., & Casperson, K. (Eds.) (2006). *Floods in South Australia 1836–2005* (pp 189–210). Australian Government, Bureau of Meteorology. ISBN 0-978-0-64270699-7)

McLaren, S., Wallace, M. W., Pillans, B. J., Gallagher, S. J., Miranda, J. A., & Warne, M. T. (2009). Revised stratigraphy of the Blanchetown Clay, Murray Basin: Age constraints on the evolution of paleo-Lake Bungunnia. *Australian Journal of Earth Sciences*, *56*(2), 259–270. https://doi.org/10.1080/08120090802547074

Mortimer, P. (1985). *Flood—Riverlanders face the flood of Fifty-six*. The Murray Pioneer Pty Ltd, 208 pp.

Mosley, L. M., & Liss, P. S. (2020). Particle aggregation, pH changes and metal behaviour during estuarine mixing; review and integration. *Marine and Freshwater Research*, *71*(3), 300–310. https://doi.org/10.1071/MF19195

Mosley, L. M., Zammit, B., Leyden, E., Heneker, T. M., Hipsey, M. R., Skinner, D., & Aldridge, K. T. (2012). The impact of extreme low flows on the water quality of the Lower Murray River and Lakes (South Australia). *Water Resources Management*, *26*(13), 3923–3946. https://doi.org/10.1007/s11269-012-0113-2

Mulvaney, D. J., Lawton, G. H., Twidale, C. R., Macintosh, N. W. G., Mahoney, J. A., & Wakefield, N. A. (1964). Archaeological excavation of rock shelter. *Fromm's Landing, South Australia. Proceedings of the Royal Society of Victoria*, *77*(6), 479–516.

Murdoch, C. (2009). *A Holocene palaeoenvironmental reconstruction of Lake Albert, South Australia: An isotopic, geochemical and palynological interpretation* [Unpublished BSc. Hons Thesis]. University of Adelaide.

Murray–Darling Basin Commission (2002). *The Murray Mouth: Exploring the implications of closure or restricted flow*. Murray–Darling Basin Commission.

Murray-Wallace, C. V. (2018). *Quaternary History of the Coorong Coastal Plain, Southern Australia—An archive of environmental and global sea-level changes*. Springer International Publishing AG, 229 pp. [Hardback: ISBN: 978-3-319-89341-9; eBook—978-3-319-89342-6].

Murray-Wallace, C. V., Belperio, A. P., Dosseto, A., Nicholas, W. A., Mitchell, C., Bourman, R. P., Eggins, S. M., & Grün, R. (2016). Last interglacial (MIS 5e) sea level determined from a tectonically stable, far-field location, Eyre Peninsula, southern Australia. *Australian Journal of Earth Sciences*, *63*(5), 611–630. https://doi.org/10.1080/08120099.2016.1229693

Murray-Wallace, C. V., Bourman, R. P., Prescott, J. R., Williams, F., Price, D. M., & Belperio, A. P. (2010). Aminostratigraphy and thermoluminescence dating of coastal aeolianites and the later Quaternary history of a failed delta: The River Murray mouth region, South Australia. *Quaternary Geochronology*, *5*(1), 28–49. https://doi.org/10.1016/j.quageo.2009.09.011

Ngarrindjeri Regional Authority Inc (2009). *Ngarrindjeri Murrundi Management Plan, No. 1. Pomberuk Lewunanangk (Murray Bridge Railway Precinct and Hume Reserve)*, 34 pp. https://www.murraybridge.sa.gov.au/data/assets/pdf_file/0020/534341/Ngarrindjeri-Murrundi-Management-Plan.pdf

Noye, B. J. (1973). *The Coorong, past, present, future*. The University of Adelaide, Department of Adult Education, 47 pp.

Noye, B. J., & Walsh, P. J. (1976). Wind induced water level oscillations in shallow lagoons. *Marine and Freshwater Research*, *27*(3), 417–430. https://doi.org/10.1071/MF9760417

Olliver Geological Services (1995). *EL 1628 MALCOLM PLAINS. Progress Reports to Licence Expiry Surrender for the Period 22/12/1989 to 21/12/1993*. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/image/DDD/ENV08281.pdf

Pate, D. (2000). Bone chemistry and palaeodiet: Bioarchaeological research at Roonka Flat, Lower Murray River, South Australia 1983–1999. *Australian Archaeology*, *50*, 67–74.

Paton, D. C. (2010). *At the End of the River—The Coorong and Lower Lakes*. ATF Press, 247 pp.

Philippi, R. A. (1847). *Abbildungen und Beschreibungen neuer oder wenig gekannter Conchylien unter Mithülfe meherer Deutscher Conchyliologen* (Vol. 2, pp. 153–232). Cassel, T. Fischer. https://doi.org/10.5962/bhl.title.10589

Pollitzer, S. (1883). *A study about the River Murray. With prominent notes about the utilisation of its potential energy*. Title of a paper read before the Royal Society of South Australia July 3, 1883, and of a pamphlet privately printed, 50 pp.

Power, H. E., Helfensdorfer, A. M., & Hubble, T. C. T. (2020). 6,000 years of climate history: an ancient lake in the Murray–Darling has yielded its secrets. *The Conversation*, May 6, 2020, 5.53am AEST.

Pretty, G. L. (1977). The cultural chronology of the Roonka Flat, a preliminary consideration. In R. V. S. Wright (Ed.), *Stone tools as cultural markers: Change, evolution and complexity* (pp. 288–331). Australian Institute of Aboriginal Studies.

Quigley, M. C., Horton, T., Hellstrom, J. C., Cupper, M. L., & Sandiford, M. (2010). Holocene climate change in arid Australia from speleothem and alluvial records. *The Holocene*, *20*(7), 1093–1104. https://doi.org/10.1177/0959683610369508

R Core Team (2020). *R: A language and environment for statistical computing*. Foundation for Statistical Computing.

Renberg, I. (1990). A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Paleolimnology*, *4*(1), 87–90. https://doi.org/10.1007/BF00208301

Roberts, A. L., & the Mannum Aboriginal Community Association Inc. (2012). *Ngaut Ngaut: An interpretive guide*. IPinCH and MACAI, 32 pp.

Rogers, P. A. (1990). Late Quaternary stratigraphy of the Roonka archaeological sites. *Geological Survey of South Australia Quarterly Geological Notes*, *113*, 6–14.

Ryan, D. D. (2015). *The Quaternary geomorphological evolution of the River Murray mouth and Lakes region, southern Australia* [Unpublished PhD thesis]. University of Wollongong.

Short, A. D., & Hesp, P. A. (1984). *Beach and Dune Morphodynamics of the southeast coast of South Australia*. Tech. Rept. 84/1. Coastal Studies Unit, Department of Geography, University of Sydney, 142 pp.

Shuttleworth, B., Woidt, T., Paparella, S., Herbig, S., & Walker, D. (2005). The dynamic behaviour of a river-dominated tidal inlet, River Murray, Australia. *Estuarine Coastal and Shelf Science*, *64*(4), 645–657. https://doi.org/10.1016/j.ecss.2005.04.007

Smith, M. (1977). *Devon downs reconsidered: An exercise in bioarchaeology* [Unpublished BA (Hons) Thesis]. Department of Prehistory and Anthropology, The Australian National University.

Smith, M. A. (1982). Devon Downs reconsidered: changes in site use at a Lower Murray Valley rockshelter. *Archaeology in Oceania*, *17*(3), 109–116. https://doi.org/10.1002/j.1834-4453.1982.tb00052.x

Snowball, D., Gibbs, J., Bourman, R. P., & Alley, N. F. (2006). Prehistoric flooding in the River Murray, South Australia. In D. McCarthy, T. Rogers & K. Casperson (Eds.), *Floods in South Australia 1836–2005* (pp 189–210). Australian Government, Bureau of Meteorology. ISBN 0-978-0-64270699-7)

Sonneman, J. A., Sincock, A., Fluin, J., Reid, M., Newall, P., Tibby, J., & Gell, P. (2000). *An Illustrated guide to common stream diatoms from temperate Australia*. Cooperative Research Centre for Freshwater Ecology.

Tate, R. (1884). Notes on the physical and geological features of the basin of the Lower Murray River. *Transactions of the Royal Society of South Australia*, *7*, 24–46.

Taylor, J. K., & Poole, H. G. (1931). Report on the soils and the bed of Lake Albert, South Australia. *Journal of Council for Scientific and Industrial Research*, *4*, 83–95.

Thom, B., Rocheta, E., Steinfeld, C., Harvey, N., Pittock, J., & Cowell, P. (2020). The role of coastal processes in the management of the mouth of the River Murray, Australia: Present and future challenges. *River Research and Applications*, *36*(4), 656–667. https://doi.org/10.1002/rra.3551

Thompson, M. B., Spencer, R.-J. (2021). *Murray River Turtle information package*. https://www.turtlesat.org.au/turtlesat/default.aspx. Accessed: 24.8.21

Thomson, R. M. (1975). *The geomorphology of the Murray Valley in South Australia* [Unpublished MA thesis]. University of Adelaide.

Tibby, J., Bourman, R., Wilson, C., Mosley, L., Belperio, A., Ryan, D., Hesp, P., Murray-Wallace, C., Miot da Silva, G., Dillenburg, S., & Haynes, D. (2021). A large mid-Holocene estuary was not present in the lower River Murray, Australia. *Scientific Reports*, *11*(1), 12082. https://doi.org/10.1038/s41598-021-90025-9

Tibby, J., Haynes, D., & Muller, K. (2020). The predominantly fresh history of Lake Alexandrina, South Australia, and its implications for the Murray–Darling Basin Plan: A comment on Gell (2020). *Pacific Conservation Biology*, *26*(2), 142–148. https://doi.org/10.1071/PC19039

Tibby, J., & Reid, M. A. (2004). A model for inferring past conductivity in low salinity waters derived from Murray River (Australia) diatom plankton. *Marine and Freshwater Research*, *55*(6), 597–607. https://doi.org/10.1071/MF04032

Unmack, P. J. (2001). Biogeography of Australian freshwater fishes. *Journal of Biogeography*, *28*(9), 1053–1089. https://doi.org/10.1046/j.1365-2699.2001.00615.x

Unmack, P. J., Hammer, M. P., Adams, M., Johnson, J. B., & Dowling, T. E. (2013). The role of continental shelf width in determining freshwater phylogeographic patterns in south-eastern Australian pygmy perches (Teleostei: Percichthyidae). *Molecular Ecology*, *22*(6), 1683–1699. https://doi.org/10.1111/mec.12204

von der Borch, C., & Altmann, M. (1979). Holocene stratigraphy and evolution of the Cooke Plains Embayment, a former extension of Lake Alexandrina, South Australia. *Transactions of the Royal Society of South Australia*, *103*, 69–78.

von der Borch, C. C. (1975). Geological history of the Coorong Lagoon. In J. Noye (Ed.), *The Coorong* (pp. 29–35). University of Adelaide, Department of Adult Education Publication No. 39.

Walker, K. F. (1981). *Ecology of freshwater mussels in the River Murray*. Australian Water Resources Council Technical Paper 63. (Australian Water Resources Council, Canberra).

Walker, K. F. (2017). Reproductive phenology of river and lake populations of freshwater mussels (Unionida: Hyriidae) in the River Murray. *Molluscan Research*, *37*(1), 31–44. https://doi.org/10.1080/13235818.2016.1206166

Walker, K. F., Corbin, T. A., Cummings, C. R., Geddes, M. C., Goonan, P. M., Kokkin, M. J., Lester, R. E., Madden, C. P., McEvoy, N. W., & Zukowski, S. (2018). Freshwater macro-invertebrates. Chapter 3.5. In L. Mosley, S. Shepherd, Q. He, S. Hemming, & R. Fitzpatrick (Eds.), *Natural History of the Coorong, Lower Lakes and Murray Mouth (Yarluwar-Ruwe)* (pp. 349–370). Royal Society of South Australia.

Waters, J. M., Rowe, D. L., Apte, S., King, T. M., Wallis, G. P., Anderson, L., Norris, R. J., Craw, D., & Burridge, C. P. (2007). Geological dates and molecular rates: Rapid divergence of rivers and their biotas. *Systematic Biology*, *56*(2), 271–282. https://doi.org/10.1080/10635150701313855

Wedderburn, S. D., & Hammer, M. P. (2003). *The lower lakes fish inventory: distribution and conservation of freshwater fishes of the Ramsar Convention wetland at the terminus of the Murray Darling Basin, South Australia*. Native Fish Australia (SA), 38 p.

Wedderburn, S. D., Hammer, M. P., & Bice, C. M. (2012). Shifts in small-bodied fish assemblages resulting from drought-induced water level recession in terminating lakes of the Murray–Darling Basin, Australia. *Hydrobiologia*, *691*(1), 35–46. https://doi.org/10.1007/s10750-011-0993-9

Westell, C., Roberts, A. L., Morrison, M., & Jacobsen, G. (2020). Initial results and observations on a radiocarbon dating programme in the Riverland region of South Australia. *Australian Archaeology*, *86*(2), 160–175. https://doi.org/10.1080/03122417.2020.1787928

Wheeler, P., Peterson, J., & Gordon-Brown, L. (2010). Flood-tide delta morphological change at the Gippsland Lakes Artificial Entrance, Australia (1889–2009). *Australian Geographer*, *41*(2), 183–216. https://doi.org/10.1080/00049181003742302

Wilkins, D., Gouramanis, C., De Deckker, P., Fifield, L. K., & Olley, J. (2013). Holocene lake-level fluctuations in Lakes Keilambete and Gnotuk, southwestern Victoria, Australia. *The Holocene*, *23*(6), 784–795. https://doi.org/10.1177/0959683612471983

Wilson, C., Fallon, S., & Trevorrow, T. (2012). New radiocarbon ages form the Lower Murray River, South Australia. *Archaeology in Oceania*, *47*(3), 157–160. https://doi.org/10.1002/j.1834-4453.2012.tb00128.x

Wilson, C., Roberts, A., Langley, M. C., Wallis, L. A., Luebbers, R., Westell, C., & Morton, C. (2021). Analysis and contextualisation of a Holocene bone point from Murrawong (Glen Lossie), Lower Murray River Gorge, South Australia. *Australian Archaeology*, *87*(1), 36–48. https://doi.org/10.1080/03122417.2021.1886893

Wilson, C. J. (2017). *Holocene archaeology and Ngarrindjeri Ruwe/Ruwar (Land, Body, Spirit): A critical indigenous approach to understanding the lower Murray River, South Australia*. [Unpublished PhD Thesis]. Flinders University.

Wood, A. (2008). *Of billabongs and broken dreams: tales of the Murray River*. Alistair Wood, 180 pp.

Appendix 1. Methods utilised in investigating Riverglen Marina core (RG2)

Ages were determined using accelerator mass spectrometry (AMS) techniques (carried out at 14CHRONO Centre (Lab ID: UBA) and ANSTO (Lab ID: OZT)). Sediment ages were modelled using the rbacon package (Blaauw & Christen, 2011) in R (R Core Team, 2020) using the Southern Hemisphere calibration curve (Hogg *et al*., 2020) to calibrate the dates. An erosional hiatus at 10 cm depth relates to a missing record of sedimentation of *ca* 2000 years. Samples for diatom analysis were taken from the core mostly at 10 cm intervals. Microscope slides were prepared following Renberg (1990) HCl and H_2O_2 digestion method from a solution contained in a 10 mL centrifuge. Counting and identification of diatoms took place at the paleoecology analytical lab at the University of Adelaide. Species were identified following reference to Foged (1978), Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b) and Sonneman *et al*. (2000). Ecological information about the species recorded was also taken from these texts.