CLIMATE CHANGE AND AUSTRALIAN WETLANDS A legacy of climate and catchment change: the real challenge for wetland management

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 Review Paper

A legacy of climate and catchment change: the real challenge for wetland management

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Abstract Wetland managers are faced with an array of challenges when restoring ecosystems at risk from changing climate and human impacts, especially as many of these processes have been operating over decadal–millennial timescales. Variations in the level and salinity of the large crater lakes of western Victoria, as revealed over millennia by the physical, chemical and biological evidence archived in sediments, attest to extended periods of positive rainfall balance and others of rainfall deficit. The recent declines in the depth of these lakes have been attributed to a 15% decline in effective rainfall since AD 1859. Whilst some sites reveal state shifts following past droughts, the response of most wetlands to millennial-scale climatic variations is muted. Regional wetland condition has changed comprehensively, however, since European settlement, on account of extensive catchment modifications. These modifications appear to have reduced the resilience of wetlands limiting their capacity to recover from the recent 'big dry'. These sedimentary archives reveal most modern wetlands to be outside their historical range of variability. This approach provides a longer-term context when assessing wetland condition and better establishes the restoration challenge posed by the impact of climate change and variability and human impacts.

Keywords Australia · Climate change · Ecological condition · Wetland response · Acceptable change

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Introduction

The management of wetlands has largely been underpinned by the assumption that their hydrology and biodiversity are stationary (Pittock et al., 2010) and this is reflected in the ecological condition assessment process of wetlands of international significance (Ramsar). Contemporary management requires 'limits of acceptable change' to be set (e.g. Newall et al., 2008) and this often relies on the identification of a baseline, or benchmark, condition against which present, or future, condition may be compared. Often, this is the condition of the wetland as described when it was listed under the convention, or from anecdotal evidence of some remembered condition of a past state. Whilst the forces that compromise this 'natural ecological character' often relate to catchment scale drivers of wetland change such as land clearance, river regulation and abstraction, secondary salinisation and

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eutrophication, it is increasingly clear that anthropogenic climate change is another driver of changing wetland condition. This has led to the concept of stationarity being 'declared dead' on account of climate-driven changes to the hydroecology of aquatic systems (Milly et al., 2008).

Climates vary over a range of timescales. Orbital forcing generates glacial–interglacial cycles that drive high-amplitude variations in sea level, temperature and rainfall over c. 100,000 years. Through the Holocene, southeast Australia has experienced considerable hydroclimatological variation (Mooney, 1997; Gell, 1998; Jones et al., 2001) as evident in the records of effective rainfall archived in the sediments of large crater lakes (Fig. 1c). The precipitation–evaporation (*P*/*E*) values reached 1.2 through the mid-Holocene filling these lakes to their crater rims. At c. 3,000 years ago, drier conditions prevailed under a ratio of 0.7 driving these lakes into saline states (Fig. 2). Whilst wetter conditions prevailed after 2,000 years ago, the last two centuries have been marked by a sustained decline in water balance of ~15%. These key crater lakes, akin to rain gauges in the landscape, reflect considerable hydrological variability. Those that view wetland management with the benefit of such temporal context rarely consider systems to be stationary. In fact, from the vantage point of the palaeoclimatologist, any number of baselines could be identified from the past, against which the present can be assessed.

The management of the catchment drivers of wetland condition faces an additional challenge when viewed from the long-term record of change. Again, it is usual for the natural ecological character of a wetland

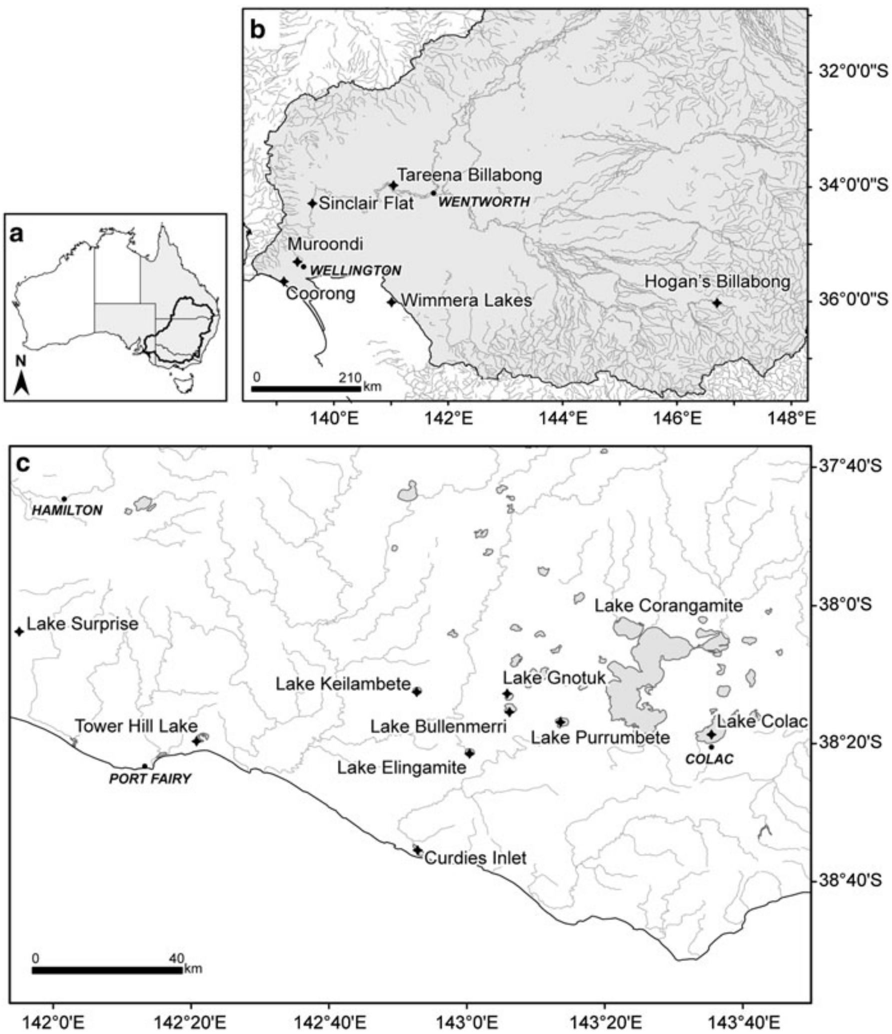

Fig. 1 Map showing sites discussed in the text: **a** location of the Murray-Darling Basin, **b** the wetlands of the Murray-Darling Basin and **c** the crater lakes of the Victorian Volcanic Plains

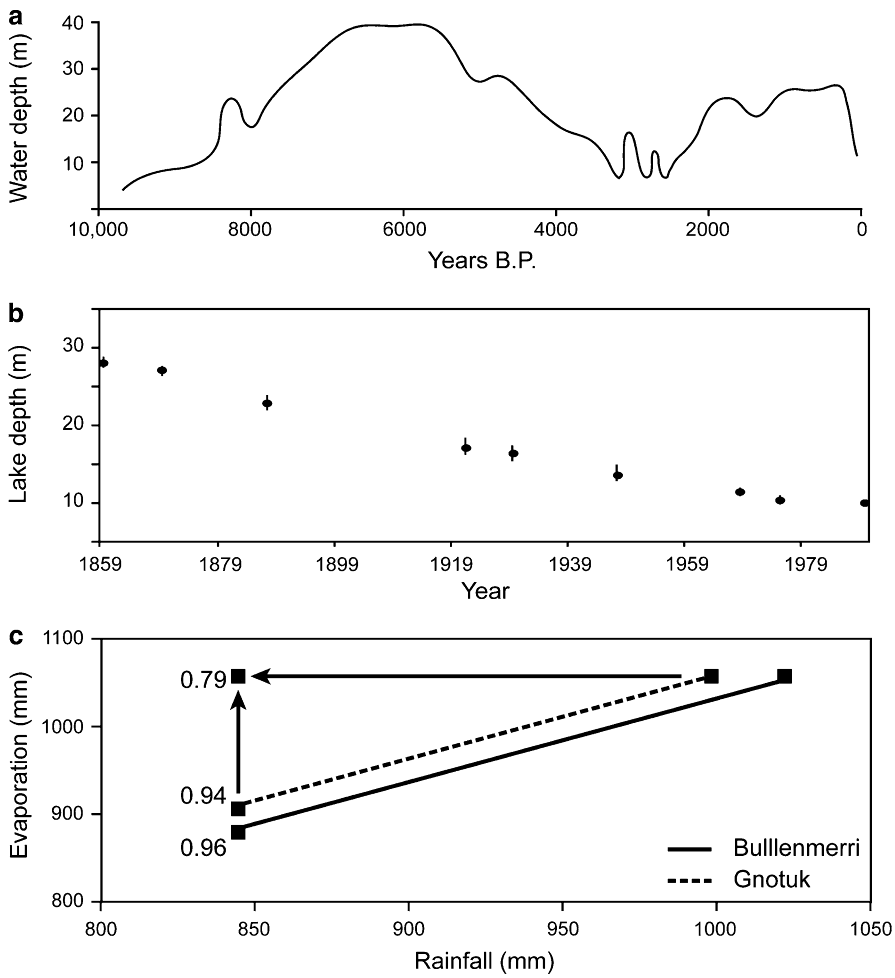

Fig. 2 Hydrological changes in three crater lakes of the Victorian volcanic plains over different timescales. **a** The inferred water-level changes during the Holocene (last 10,000 years) at Lake Keilambete, reflecting fluctuating water levels as a result of natural hydrological changes in precipitation and evaporation ratios (redrawn from Bowler, 1981), **b** historical water depths since AD 1860 for Lake Keilambete (estimated to the nearest 1 metre) based on land survey data, depth sounding and aerial photography (redrawn from Jones et al., 2001) and **c** modelled climate change for Lakes Gnotuk and Bullenmerri showing the *P*/*E* ratios (adapted from Jones et al., 2001). The pre-European climate is situated along the lower lines of the *P*–*E* matrix. From AD 1841, the modelled climate change progresses from the heavy lines within the bounded range of the arrows towards the current climate (0.79; refer to Jones et al., 2001 for further detail)

to be presumed, and it is not unusual for this to represent a derived state, one that has already shifted owing to human impact on catchment processes (Tibby et al., 2007; Gell, 2010; Dick et al., 2011). Again, across southern and eastern Australia, few wetlands remain unaffected from the impacts of direct catchment disturbance and most have drifted beyond their historical range of variability (e.g. Gell, 2012; Gell et al., 2012; Tibby et al., 2012). Furthermore, several Ramsar-listed wetlands were severely degraded at their time of listing, challenging the notion of their defined natural ecological character. So, whilst the recent 'big dry' in eastern Australia has prompted many to ponder the prospects for wetland ecosystems, and has generated a plan for the Murray-Darling Basin to return 27–37% of flows to the environment (MDBA, 2010), the longer-term view recognises that the condition of wetlands that exist today, or even before the recent drought, has departed greatly from 'natural' and that the management challenge is greater than widely perceived. "Whither water management" (Milly et al., 2008, p. 573) indeed?

This review paper aims to look at past evidence for wetland change across southeastern Australia against which management practices could be based. Current management practices rarely account for the legacy of past changes in climate and catchment, which pose many challenges and affect the functioning and resilience of ecosystems to future changes and stressors.

Methods

The evidence for this article synthesises that from a wide range of published palaeoenvironmental and, particularly, palaeolimnological records of wetland change in southeastern Australia. The review draws upon case studies from 15 lakes and wetlands from across Victoria, South Australia and New South Wales. Table 1 in Supplementary material includes information for each of the lakes included in this study and a list of the references relating to the original published study. This information can also be accessed online via the OZPACS meta-database (http://www.aqua.org.au/Archive/OZPACS/OZPACS.html).

The palaeolimnological approach utilises sediment cores from wetlands that preserve natural archives of change. These sediment records can be radiometrically dated so that calendar ages to can be assigned to samples and the timing of changes observed in the archives can be understood. A wide range of sub-fossil indicators have been used in wetland studies, both in southeastern Australia and worldwide.

The most common fossil indicator used in this region is diatom analysis. Diatoms are microscopic, unicellular algae that demonstrate, in many cases, clear habitat and water chemistry preferences in the modern environment. The principle, and preparation of samples, for diatom analysis generally follows that of Battarbee (1986) and Battarbee et al. (2001). Changes in diatom assemblages through a sediment core (and hence through time) are a reflection of the water chemistry at the time the diatoms were living in the water body. Changes in water chemistry are intrinsically linked to natural (and anthropogenically driven) fluctuations in the water balance (e.g. causing changes in salinity and water depth) and anthropogenically induced catchment changes (e.g. increases in turbidity and nutrient availability). Past water chemistry is often derived using inference models ('transfer functions'), where the modern distribution of diatoms across a water chemistry gradient is analysed and understood ('calibration' or 'training set') and the regression coefficients can be used to infer unknown environmental conditions to species' changes observed in sediment cores (see Mackay et al. (2003) for a detailed overview).

In the case of diatom autecology, while several international species-environment calibration sets can be considered, several Australian transfer functions (Gell, 1997; Tibby & Reid, 2004; Philibert et al., 2006) attest to the local rigour in these relations. Based on the evidence of responses of modern assemblages to water quality and habitat changes (Reid & Ogden 2009), diatom palaeolimnology provides a rare opportunity to trace the condition of a wetland through time, providing a retrospective means of assessing contemporary wetland condition.

Similarly, sediment cores may also be analysed for fossil pollen which provides a record of local, and regional, terrestrial and aquatic vegetation. Pollen analysis is often supported by the analysis of plant macrofossils. In aquatic systems, the analysis of macrofaunal remains (e.g. ostracods) can provide additional water chemistry information, and high-resolution analyses of the carbonates and major ions contained within the shells of ostracods can be used to infer changes in water balance.

Wetland responsiveness to climate variability

The large crater lakes of the volcanic plains of western Victoria and southeastern South Australia have largely responded, in concert, to millennial-scale shifts in water balance (Barr, 2010; Gell et al., 2012). Having clearly defined catchment boundaries and small catchment to lake area ratios, they tend to integrate inter-annual variability and respond to sustained shifts over decadal–millennial scale (Churchill et al., 1978; Chivas et al., 1985; Gell, 1998; Barr, 2010; Gouramanis et al., 2010). All sites show evidence of considerable deepening at the height of the mid-Holocene pluvial, or at least very fresh conditions (e.g. Edney et al., 1990). At this time, the western Victorian landscape was particularly wet with conditions sufficient for these large lakes to overflow and temperate rainforest to expand (Dodson, 1974, 1979). Given such consistent responses it could be expected that a range of other lakes would show evidence of such substantial shifts in climate.

In semi-arid, western Victoria, Kemp et al. (2011) have demonstrated the salinity of groundwaterdominated lakes to co-vary with the more southern crater lakes reflecting hemispheric patterns in orbital and solar forcing on the prevalence of westerly driven winter effective rainfall. In the Murray-Darling Basin, however, few floodplain lake records extend back to the mid-Holocene to test their responsiveness to the changes in effective rainfall responsible for the rises and falls in the crater lakes. Gell et al. (2005a) recorded fresh, lagoonal conditions within Tareena Billabong, 50-km downstream from Wentworth (NSW), at c. 5,000 years B.P. when the crater lakes remained high. In fact, the commencement of sedimentation in this lagoon may have arisen through its abandonment by the Murray River, or its distributary, as discharge declined after the mid-Holocene pluvial phase. Effective rainfall remained high sustaining very fresh conditions evident in high values of the diatoms *Synedra* (syn: *Ulnaria*) *ulna* and *Planothidium frequentissimum*. An increase in the planktonic (free-floating) taxa *Aulacoseira granulata* (which is often indicative of River input; Bormans & Webster, 1999; Gell et al., 2002), coincident with increases in salt tolerant taxa such as *Gyrosigma* spp., is explained as an increase in climatic variability coincident with a fall in crater lake water levels. After 3,000 years B.P., perhaps driven by increased landscape instability and sediment influx during the low lake phase, the flora shifted to tychoplanktonic species [periphytic organisms occasionally carried into the plankton, often as a result of turbulence]. This flora persisted until European settlement despite the crater and Wimmera lakes responding to substantial shifts in effective moisture. Whilst this suggests that evidence exists for the moisture shifts documented in the volcanic plains, further inland, Tareena Billabong does not appear to respond to the lower amplitude variations of the last 3,000 years.

Other floodplain lake records that extend to the mid-Holocene reveal little of this humidity. While Muroondi Wetland near Wellington (SA; Fig. 1b) was dominated by *A. granulata* at the time (Gell et al., 2005b), this may have owed as much to its depth, as to climate. The 14-m sediment record reveals hydroseral changes, from open water to shallow water/marsh flora, consistent with relatively rapid infilling.

Coastal wetlands are a function of both the tidal prism affected by changing sea levels and river runoff related to rainfall. Therefore, it may be expected that the substantial moisture of the mid-Holocene would be reflected in their sediment records. Almost invariably, however, the diatom records of wetland condition that span this period reveal strong marine influence. This may be attributable to their relative immaturity in a geomorphic sense, being inundated valleys initially that gradually in-filled with sediment. The Coorong (SA), at the mouth of the largest catchment in the continent, the Murray-Darling Basin, is dominated by marine diatom (Fluin et al., 2007) and ostracod communities for the 7,000 years before European settlement. Other than a brief peak in river plankton at the north end of the Coorong at c. 2,500 years B.P., there is little evidence of the impact of heightened runoff at the millennial scale. Closer to the crater lakes themselves, the Curdies estuary is at the mouth of a catchment that includes Lake Purrumbete, Victoria's deepest lake. Despite this responding in tandem with the rain gauge lakes of the region, the estuary itself has remained strongly tidal (Fig. 3).

Fine resolution analysis of intra-decadal variation from lakes in Victoria reveals the incidence of past droughts. Lake Surprise is a crater lake within the Mt Eccles National Park, Victoria and reveals multi-decadal droughts over the last 1,500 years (Barr, 2010). This is supported by Barr's pre-European record of Crater Lake Elingamite near Cobden, Victoria. At Lake Colac, mulitproxy (diatom, pollen, macrofossil and pigment) analyses of a sediment core spanning the last 9,000 years reveal a substantial salinisation event, evident at c. 500 years B.P., which appears to have lasted several decades (Fig. 4; Gell et al., 2012). This is coincident with a shift from an aquatic macrophyte (*Myriophyllum* spp.) community, as revealed by pollen analysis (Gell et al., 2012) to a green algal flora (*Botryococcus* spp.), perhaps revealing a drought-driven state switch (sensu Scheffer et al., 1993) independent of industrialised people.

Historical records attest to Lake Keilambete being level has 29-m deep in AD 1859. Since this time, the lake level has steadily declined to a recent ~9-m deep, even after the significant La Niña event of 2010–2011. This substantial fall in level represents a sustained fall in effective rainfall, or a persistent response to a stepped shift to a drier climate (Jones et al., 2001). As this shift most likely postdates European settlement, a wetland's response is coupled with that of catchment disturbance, and so a climate cause cannot simply be invoked with all documented changes. Outside the crater lakes few situations

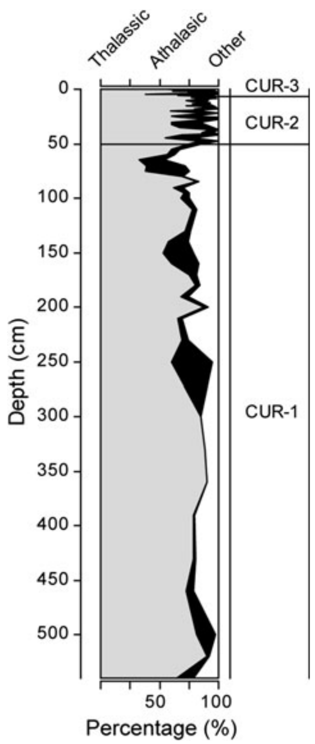

Fig. 3 Summary record of the diatom stratigraphy from the Curdies estuary, Victoria. Seventy-five samples were analysed over 5.5 m of sediment and 83 species were identified. The diatom species have been grouped according to their environmental preference: thalassic (marine) and athalassic (inland). Those species that cannot be assigned to either group have been recorded as 'other'. Shifts in the environmental preferences of the diatoms indicate the changing influence of the marine and river environment on the Curdies estuary through time. The three statistically significant zones (CUR-1 to CUR-3) were determined using the program ZONE (Juggins, 2002)

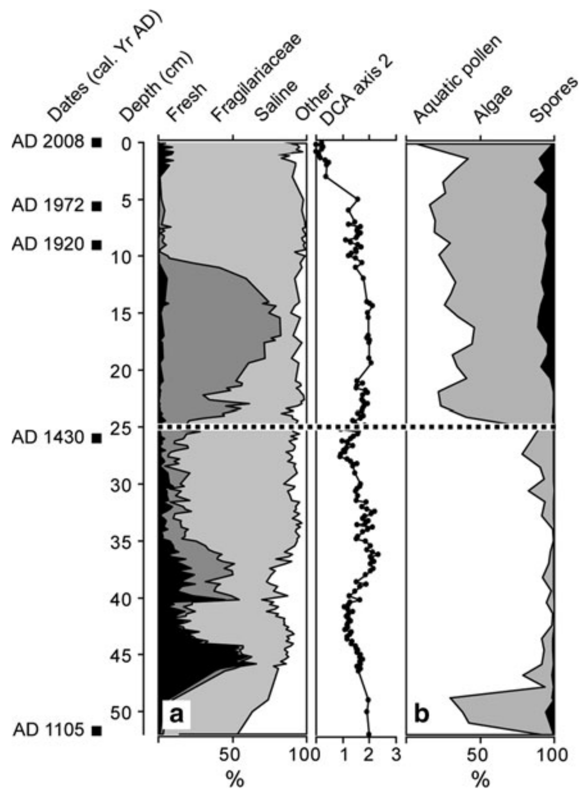

Fig. 4 Summary record of **a** fossil diatoms and **b** aquatic pollen, algae and spores from Lake Colac, Victoria (Gell et al., 2012). The record spans the last c. 1000 years, and the *dashed line* represents the shift from a macrophyte-dominated system (*Myriophyllum* spp.), to an algal-dominated (*Botryococcus* spp.) system c. 500 years ago. Two-hundred and nineteen diatom species were identified in the Lake Colac record and they have been grouped according to their preference for saline or fresher water conditions. Species that are found in the Fragilariaceae have been separated as many of these species do not have a specific habitat preference and can indicate periods of instability in the system, given their 'weedy' nature (Sonneman et al., 2000). Species that have been classed as 'other' have wide ecological preferences. The DCA axis 2 sample scores are displayed alongside the diatom data and demonstrates the unprecedented change in the diatom assemblage data in the last 30 years

preclude direct catchment disturbance. Even the evidence of climate change from Crater Lake Elingamite is truncated in the 1800s by water diversions. In fact, so overwhelming has been the impact of catchment disturbance, river regulation and abstraction and direct releases of nutrient or salt laden waters that the influence of climate variability and change is largely masked. That said, the recent drying of many lakes in western Victoria, and elsewhere, is unusual. At Lake Colac, the recent shift to a saline diatom flora (Fig. 4) has shifted this system to an unprecedented state, at least as revealed by the DCA axis scores. Similar drying is evident at Tower Hill (Barry et al., 2005) and this appears not to have occurred since c. 7,000 years B.P. (Fig. 5).

Impact of catchment change

The relative unresponsiveness of all but the crater lakes to late Holocene climate variability is in stark contrast to the changes evident in the post-European records. Many floodplain lakes shifted from clear water, macrophyte-dominated sites, as evident in epiphytic diatom and cladoceran communities (Ogden, 2000; Reid et al., 2007), to planktonic diatom flora and bosminid fauna. Those most sensitive to the

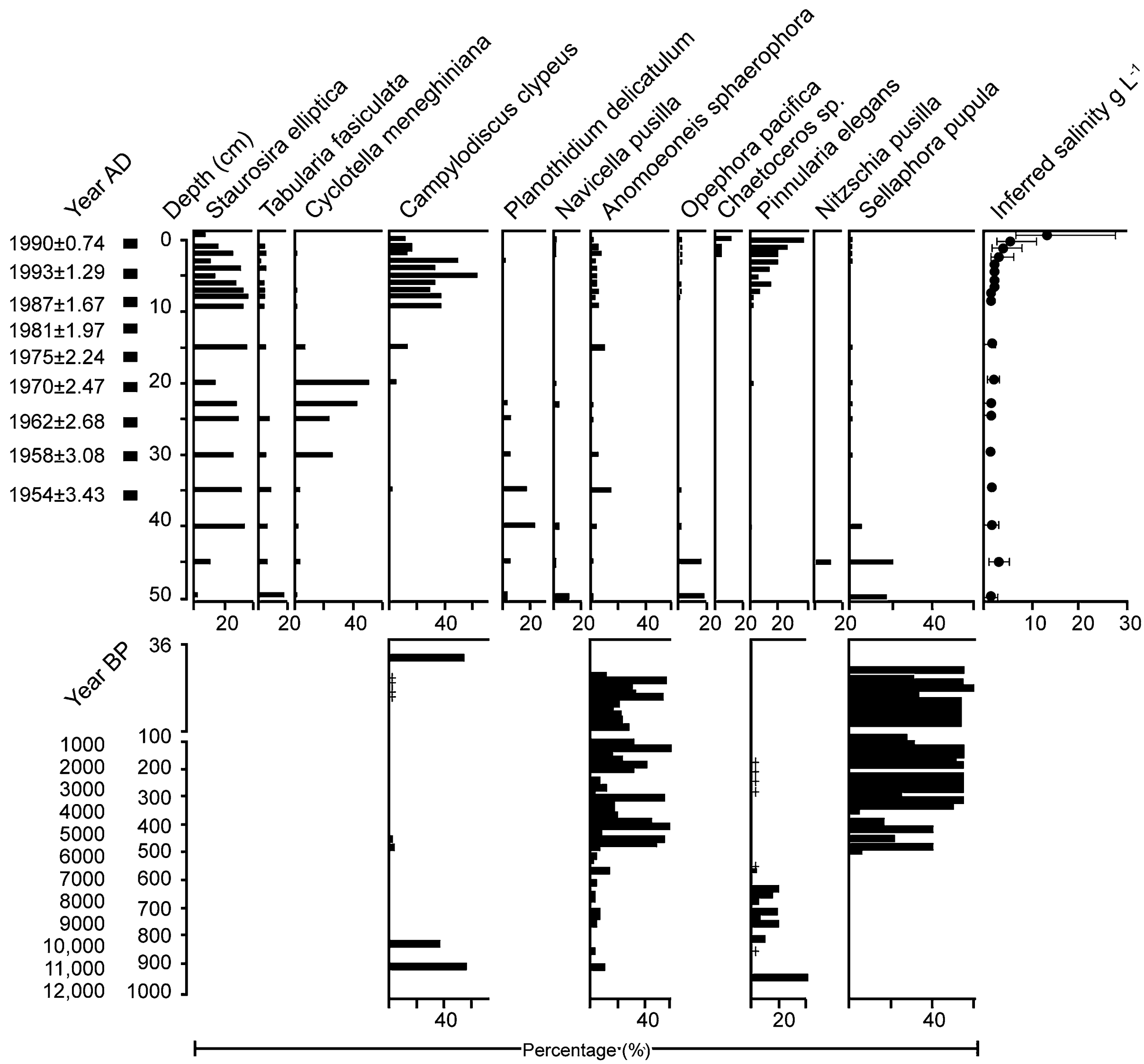

Fig. 5 Synthesis of long-term, and shorter, fine resolution diatoms records from Tower Hill main lake, Victoria [adapted and redrawn from D'Costa et al., 1989 (*lower*) and Barry et al., 2005 (*upper*)]. Note the return of *Pinnuavis elegans* (syn. *Pinnularia elegans*; salinity optimum 26.2 g l^{-1}; Gell, 1997) after an absence of 7,500 years. Only the species that can be confidently ascribed to both diagrams have been included. It should also be noted that there is likely to be some overlap on the time/depth scale of the diagrams, but due to the lack of dating on the upper core sections of the long-term data (D'Costa et al., 1989), splicing has not been undertaken

influx of sediment from the disturbed catchment were the larger and deeper wetlands that have a relatively large flat benthic profile. These, unlike smaller and shallow lakes, tended to lose a larger proportion of suitable macrophyte habitat once increased sediment loads reduced photic depth. This occurred abruptly in some upper-catchment sites such as Hogan's Billabong, where planktonic diatoms came to dominate soon after increases in sediment flux, as revealed by peaks in magnetic susceptibility and aerophilous diatoms. It occurred more gradually at Sinclair Flat near Blanchetown, where the turnover from benthic to planktonic, turbidity tolerant flora took place from 1950 to 1990 (Gell, 2010; Grundell et al., 2012). While it is unclear whether these changes reflect a true state switch, driven by internal feedbacks, it is clear that the systems are subject to a sustained increase in sediment input. Rates of sediment accumulation have increased from 5 to 80 times (Gell et al., 2006), and, given their shallow nature and the reduction in middle levels floods, the prospects for their long-term persistence is limited (Gell et al., 2009).

Salinity

In many instances, fossil diatom bioindicator assemblages shifted towards medium and high salinity indicators after European settlement. At Tareena Billabong a switch to more saline conditions occurred from AD 1880 (Gell et al., 2005a). Elsewhere salt tolerant taxa appear in records somewhat later, and even seemingly high quality sites show signs of increases in salinity (Gell et al., 2007). This phenomenon is also apparent in coastal systems but more as a consequence of a lack of river flow and subsequent mouth closure, leading to evaporative concentration of less active, tidal systems (Fluin et al., 2007). In some unusual examples, outfalls of relatively fresh, yet nutrient enriched waters, have transformed naturally saline, shallow lakes into deeper, freshwater systems (Haynes et al., 2007), at odds with the recollections of the local community (Tibby et al., 2007). While salinisation events occurred before European settlement it is clear that the regional trend has been towards elevated wetland salinity that may, in part, be explained by a drying climate. Interestingly, some floodplain wetlands in close connection to the River Murray have records of plankton, derived from the river, that transition to taxa with higher tolerance of salinity and a clear preference for elevated nutrients. The prevalence of *Actinocyclus normanii* at Sinclair Flat since the 1980s attests to changing water quality of the River *per se* (Grundell et al., 2012), when monitoring data show little clear trend. Such elevated nutrient status through the twentieth century is widespread (Gell et al., 2006) revealing a regional increase in wetland trophic status.

A more recent trend is to wetland acidification. While acid sulphate soils are a management issue for coastal systems, where sulphate salts have been buried through the Holocene and reduced to sulphides, this appears to be a recent phenomenon in the riverlands, associated with the maintenance of permanent water levels in wetlands since river regulation in the 1920s. Dissolved sulphate salts have accumulated in the rapidly deposited sediments of river floodplain wetlands and have become reduced, under high water levels by sulphur-reducing bacteria driven by elevated nutrient loads (Baldwin et al., 2006). Steadily decreasing river levels through the recent drought have limited connection to wetlands causing their levels to fall, exposing sediments to oxidation. Several wetlands have acidified and the large, terminal lakes were at risk of acidifying until an intense La Niña event returned flows to the system in 2010.

Co-variation

Several wetlands show that shifts to diatom species with higher salinity tolerances are also coincident with a shift in taxa that have a preference for elevated nutrients and turbidity (Battarbee et al., 2012). This may reflect a shift to taxa indicative of disturbance in general, rather than specific stressors. Certainly, the prevalence of tychoplanktonic taxa within the Fragilariaceae in modern assemblages has been explained by their 'weedy' character and tolerance of disturbed habitats (Sonneman et al., 2000). However, wetlands have inherited species widely recognised for elevated concentrations of particular pollutants. This coincident shift may arise through co-variation in the stressors (Gell et al., 2007; Dearing, 2012). In the Murray-Darling Basin, floodplains hold reserves of buried, 'native' phosphorus that is carried into waterways as disturbed surfaces erode. So, it holds that increased sedimentation and turbidity also bring elevated nutrient loads (Olley & Wallbrink, 2004). Similarly, dryland and irrigation salinity bring saline aquifers to the surface depositing halite on soil surfaces. This increased sodicity exacerbates erosion (Neave & Rayburg, 2006), leading to high sediment flux and clay-bound nutrient transport. Finally, salinisation and high sedimentation rates conspire to bury sulphates that, driven by elevated nutrient loads, are reduced to high acid potential sulphides. In sites in the lower part of the system, receiving salts, sediments and nutrients from upstream land users, there is almost an inevitability that their fate is to complete transformation to a degraded state and, in some instances, unprecedented acidification.

The management challenge and the dilemma of 'limits of acceptable change'

One of the major challenges facing wetland managers is the need to assess natural and anthropogenically induced change against a set of management objectives in order to develop suitable management strategies. However, the detection of 'unacceptable change' is ultimately a complex and difficult judgement. The level of acceptable change is dependent on the individual wetland, and must take into account its ecological components as well as acknowledging the various timescales over which many processes have been operating. Without this knowledge understanding and setting benchmark conditions can be challenging (Davis & Brock, 2008). Management strategies such as the Ramsar convention were developed to halt and reverse loss and degradation of wetlands as well as encouraging the implementation of planning and management to maintain ecological character and promote conservation. Whilst a move in the right direction, the Ramsar protocol does not take into account the timescales that are needed to understand benchmark conditions, and many sites listed are already in an altered state.

It has been argued that there can be no single approach to characterising ecological change (Davis & Brock, 2008) and that conceptual models should be employed to understand limits of acceptable change in wetland ecosystems (using a control or stressor approach; Davis & Brock, 2008). Davis et al. (2010) used a unique set of identifiers to understand multiple stressors and regime response in Thomsons Lake, WA, suggesting that a loss or change to anyone of the identifiers may lead to the likely occurrence of unacceptable ecological change. However, without a time perspective and only a contemporary understanding of these systems, limits of acceptable change can be difficult to pinpoint. Davis & Brock (2008) also acknowledge the difficulty of providing quantitative boundaries for detecting and managing change due to lack of data available for many ecosystems.

Understanding external drivers and internal dyna mics of ecosystems at appropriate temporal and spatial scales is paramount to detecting acceptable change in many of Australia's wetlands; a challenge that cannot be addressed at a contemporary monitoring timescale.

Wetland management

The contemporary focus on State of the Environment reporting (CoA, 2001; Beeton et al., 2006), the EU Water Framework Directive (Bennion & Battarbee, 2007; Gell et al., 2009; Gell, 2010) and ecological character assessments under the Ramsar protocol occur within a framework that largely reflects recent changes in wetland conditions, with little or no historical perspective. Yet studies, such as that of Bradshaw et al. (2005), reveal changes in lake nutrient regimes in relation to anthropogenic land-use changes over the last 6,000 years. Many of these changes occur during periods of intense modification of the natural environment in response to agricultural and technological advances [e.g. Roman Iron Age (500 BC–AD 1050) and the Mediaeval Period (c. AD 1000)]. It is clear that, in continents with a long industrial history, a very long record is required to fully understand 'natural ecological condition'.

Notwithstanding the debate over the impact of indigenous Australians on their landscape, it is not unreasonable to expect the frameworks that underpin natural resource management in Australia to consider the last few centuries of change, particularly now that such intensive palaeolimnological research effort has revealed clear trajectories of human impact. In essence, policy documents such as the Murray-Darling Basin Draft Plan are disarmed when they portray the present ecological status of wetlands in terms of decades, rather than centuries. The decision-making process, with its endemic political myopia, will inevitably under-represent the magnitude of the loss of heritage and the management challenge to restore systems to adequate function.

Of somewhat tangential interest is the dilemma of ecological character definition under the Ramsar protocol. Curiously, the Coorong wetland of South Australia was misidentified as a hypersaline lagoon for its listing under Ramsar, leading to embargoes on the release of freshwater from the hinterland. This, and drought, led to its inexorable shift to extreme hypersalinity, and a state-shift in the ecosystem and foodweb (from a complex *Ruppia* sp. macrophyte-dominated system to a simple phytoplankton- and brine shrimp-dominated system; Fluin et al., 2007, Krull et al., 2009; Gell, 2010, Dick et al., 2011). Its true, natural ecological character was as a subsaline, strongly tidal system; however, its listing has contributed to its demise. Towards what baseline should this system be restored? Should this wetland be cited under the Montreaux List of Degraded Wetlands when it was already degraded before listing and its very listing has driven it to a new ecological character? Simply, what are its 'limits of acceptable change' and when did it exceed them?

Finally, drying scenarios identify southeastern Australia as a climate change hotspot (Giorgi, 2006) and runoff scenarios of 25–50 % decline in river flow raise questions as to whether any Murray-Darling Basin wetland will remain within 'limits of acceptable change' as defined in recent ecological character reviews. Clearly, climate change is a threatening process through changing wetting and drying regimes. While wetlands will continue to retain attributes that continue to qualify them as wetlands of international significance, a key challenge lies in the wider acknowledgement of the climate-driven shifts in ecological character and more significantly, the capacity for the global waterway management community to deal with such 'wicked' drivers of change.

Conclusion

The palaeolimnological record identifies an extended range of past climates and wetland responses to changes and variability in effective moisture. In most, but not all instances, it attests to the considerable, inherent resilience of these systems to climate as a driver of wetland condition. Increasingly common records revealing that wetlands are now outside this historic range of variability suggest that the adaptive capacity of the wetlands has been compromised by the extensive, and pervasive, effect of direct catchment disturbance and hydrological modifications. Climate scenarios of even further reductions in effective moisture across southeast Australia, overlain on a landscape severely stressed by direct human impacts, represent the real challenge for wetland managers and require them to manage for change, and not for stationarity.

It is now widely recognised that many of the world's wetlands have been placed under considerable stress through anthropogenic disturbance to catchment surfaces and hydrology, and the direct release of human waste products. In many instances, this observation is made from truncated records of change based on short-term instrumental records or anecdotal evidence. Palaeolimnological approaches to extend this record of knowledge tend to reveal that the shorter-term record greatly underestimates the magnitude of wetland change and natural heritage loss, and the challenge for ecosystem function restoration. In several notable examples, as clearly revealed by long term, palaeo-data, one of the most important issues facing modern management is the fact that many of these modern systems are now operating outside of their natural variability which has diminished the resilience of these wetlands to both the recent and future, climate change. This issue of compromised resilience, coupled with the misdiagnosis of lake and wetland characteristics, and that the identification of old baselines tend to undermine the legitimacy of modern regulations, will undoubtedly lead to the implementation of measures that only serve to exacerbate the trend of degradation.

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