MURRAY-DARLING BASIN ESSAY

Essay #5 in a series of nine by Australia's leading water experts

Climate change Challenges and Adaptation Needs for Murray-Darling Basin Ramsar Wetlands of international importance

Kerri Muller and Nick Whiterod

DOI: 10.60902/b3n3-tt27

Above: Ramsar Wetlands, South Australia.
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EXECUTIVE SUMMARY

Muller and Whiterod note that most of the 16 MDB Ramsar Wetlands are at risk of failing to meet their water requirements under current water sharing rules due to partial implementation of the Basin Plan. To effectively manage the adaptive capacity of MDB Ramsar Wetlands, we need to know how to interpret climate velocity (the rate of climate change) which is a function of water regime alteration. The wetlands are indeed a natural solution to climate change; hence "dewatering" wetlands may lead to substantial methane emissions and losses of significant carbon storage ('Teal Carbon' ecosystem) facilities.

Muller and Whiterod also address recent assessments of climate change vulnerabilities in the MDB, which did not include an assessment of carbon stores or carbon sequestration capacity – carbon was only considered in terms of blackwater events. They advise that all water management decisions and operations need to be conducted primarily for ecological benefits and on-going ecosystem service provisions in the knowledge that this is ultimately the most cost-effective way of delivering, purifying and storing water for all users.

From: Radcliffe, John C and Flapper, Therese G (2024) (Eds), *A thriving Murray-Darling Basin in 50 years: Actions in the face of climate change*, Australian Academy of Technological Sciences and Engineering, Canberra ACT, 246 pp. DOI: 10.60902/he1w-gn75

Climate Change Challenges and Adaptation Needs for Murray-Darling Basin Ramsar Wetlands of International Importance

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Abstract

Our capacity to adapt to future climate change challenges will be a function of our collective actions. How we manage vulnerable ecosystems, such as wetlands, that support us through the provision of essential ecosystem services will be a key determinant of our success. Our nation has made commitments to the ‘wise use’ of all Australian Ramsar wetlands in the face of climate change challenges, including the maintenance of their described Ecological Character.

The Murray-Darling Basin (MDB or Basin) contains sixteen Ramsar-listed Wetlands of International Importance that are likely to have different climate change vulnerabilities and adaptive capacities. The wise use of these wetlands under a changing climate is an active and deliberate process for which we present four major strategies: 1) determining the nature of likely cumulative impacts for each wetland, 2) assessing each wetland’s adaptive capacity to meet these impacts and mitigate climate change by capturing carbon, 3) operationalise adaptive strategies where allocating water, operating existing infrastructure and approving new development are primarily made to benefits the ecosystems we depend on, rather than just avoiding negative impacts, and 4) implementing site-specific adaptive management plans to maintain a site’s Ramsar-listed Ecological Character, or adapt to a different, ecologically functional character less vulnerable to the emerging climate, if necessary, noting that this may lead to loss of international significance.

We describe a future where ecosystem services provided by MDB Ramsar wetlands and other ecosystems are highly valued and fully integrated into our policy frameworks, thereby enabling them to receive their appropriate share of water. The alternative would be the on-going degradation and loss of ecological function in the MDB, and ultimately the loss of resilience, adaptive capacity of its wetlands and decline in wellbeing for the humans that depend upon them.

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1. Introduction

The Ramsar Convention on Wetlands was held in Ramsar, Iran in 1971. It is an intergovernmental treaty whose mission is ‘the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world” (Ramsar 2010). The Convention clearly acknowledges that humans use wetlands, and that human well-being is intrinsically linked to the wetlands we use. Maintenance of the wetland’s Ecological Character (which includes Ecosystem Components, Ecological Processes and Ecosystem Services as defined by the Ramsar Convention on Wetlands, 1971) at the time of listing is a central tenet of the Convention. Limits of Acceptable Change to the Ecological Character are also defined to account for variability in condition, whilst still providing triggers to alert managers to unacceptable changes and provide evidence for investment.

Australia was one of the first signatories to the Ramsar Convention on Wetlands (21 December 1975) and currently has 66 sites, covering 8.3 million hectares, designated as Wetlands of International Importance. Of these, sixteen wetlands are situated with in the Basin (MDB) (Figure 1), covering 647,052 ha and representing a range of wetland types in a range of climatic and hydrological zones (Table 1). Each wetland meets at least two Ramsar criteria with the SA Riverland and The Coorong and Lakes Alexandrina and Albert sites meeting the most criteria (8 out of possible 9). These criteria assess at an international scale the wetland’s uniqueness, representativeness of near-natural wetland types; capacity to support threatened species, threatened communities or maintain bioregional diversity; importance for supporting biota at critical life stages; ability to regularly support more than 20,000 waterbirds or 1% of a wetland-dependent species population; significant proportion of indigenous fish populations; and importance for supplying fish food or nursery areas. Whilst the focus here is on Ramsar-listed wetlands, it is acknowledged that the MDB is a large catchment that includes more than 30,000 wetlands that provide a diversity of functions and habitats and require wise management.

Figure 1. Sixteen Murray-Darling Basin Ramsar-listed Wetlands of International Importance.

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2. Current condition and drivers of change in MDB Ramsar Wetlands

The 'current' ecological condition of a wetland can be relatively static, or it can be highly dynamic, depending on its characteristics. The science on how to interpret variations in wetland character and to what extent variations are 'acceptable' in terms of management outcomes is evolving (e.g. Boulton and Brock 1999; Campbell et al. 2022). The MDB, draining 14% of the Australian continent, is one of the most regulated river basins in the world (Nilsson et al. 2005), and the impacts of its regulation and development have led to significant degradation of some MDB Ramsar wetlands (e.g. Phillips and Muller 2006). Of the sixteen MDB Ramsar wetlands, two have been degraded to the point that their Ecological Character has changed. The Australian Government has informed the Ramsar Secretariat of these changes and made international commitments to improve the condition of these wetlands through Article 3.2 Notifications and detailed management responses (Table 1).

The first Article 3.2 Notification (2006) was for The Coorong and Lakes Alexandrina and Albert site (listed 1985), which lies where the River Murray meets the Southern Ocean. It is the most downstream of the MDB Ramsar wetlands, and the only estuary in the vast MDB. This naturally estuarine-freshwater wetland system has been in ecological decline since at least the mid 20th Century and nearly half of the 53 key Components and Processes were categorised as being 'of alarm' and a further third as "of serious concern' by Phillips and Muller (2006). Further declines in ecological health have been observed since, including losses of rare and endemic species such as Yarra Pygmy Perch (*Nannoperca obscura*) (Lewis et al. 2022; Wedderburn et al. 2022). Key drivers of change have been identified as climate, hydrology, River Murray flow regulation, water extraction and operation of water infrastructure, (e.g. barrages) and dredging needed to keep the Murray Mouth open. These factors have combined to escalate the salinity of the South Lagoon of the Coorong to five times the salinity of seawater during the Millennium Drought (Webster 2010). Modelled natural flows show salinities staying below seawater (36 ppt) for the majority of the last 60 years, except for times of extended low flows (Figure 2). The 2022–23 floods have reduced salinity markedly, but this is likely to only be temporary given that the freshening effects of previous floods have not been sustained in modern times, e.g. high flows in the 1970s (Figure 2).

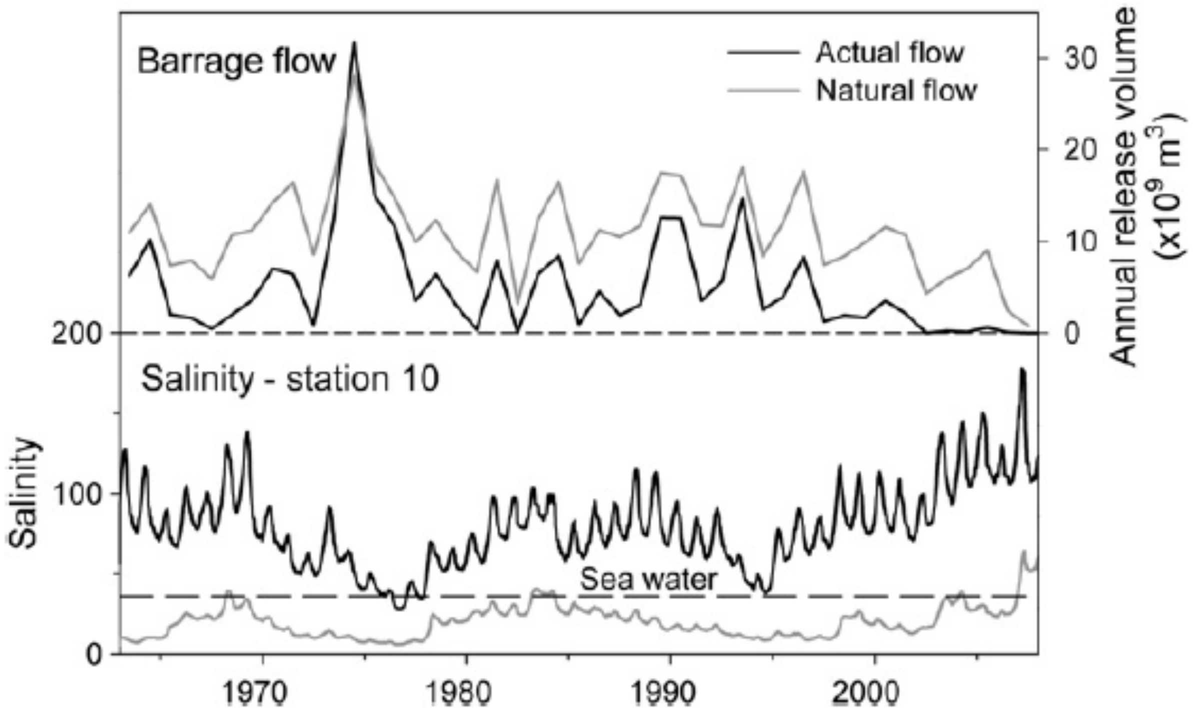

Figure 2. Annual release volumes for actual and natural barrage flows (top) and modelled salinity in the South Lagoon of the Coorong for actual and natural barrage flows (bottom), showing seawater concentrations (36 ppt, dashed line). Source: Webster (2010).

The second Ramsar Article 3.2 Notification (2009) was for the Macquarie Marshes on the lower reaches of the Macquarie River Basin in NSW. This significant wetland system has supported some of largest waterbird breeding events ever recorded in Australia (OEH 2013). The Macquarie Marshes are one of the largest of the MDB's 30,000 wetlands, covering an area of almost 20,000 ha (Crabb 1997), part of which is nominated as a Ramsar site. Significant reductions in inundation frequency have resulted in significant declines in River Red Gum (*Eucalyptus camaldulensis*) forests, losses of Water Couch (*Paspalum* sp.) grasslands and Cumbungi (*Typha* sp.) rushlands, increased colonisation by terrestrial flora down the elevation gradient (e.g. chenopods) and changes in waterbird breeding (OEH 2013). These changes in Ecological Character show a clear drying trend and a change in wetland type from a semi-permanent wetland to an ephemeral wetland in parts of the Ramsar site. Water availability and management were found to be the key drivers of this change. Improvements in critical Components and Processes were observed following large floods in 2010–11 and 2011–12 (OEH 2013), but unregulated flows (i.e. those that exceed the regulating capacity of MDB infrastructure) can no longer be relied upon to achieve long-term ecological outcomes and avoid on-going ecological decline.

Other Ramsar wetlands in the MDB have also been degraded but have not (yet) triggered Article 3.2 Notification. For example, river regulation, irrigation supply and water extraction have greatly modified the frequency, magnitude and duration of inflows to the SA Riverland, Kerang Wetlands, Gwydir Wetlands and Barmah Forest Ramsar sites, which are also threatened by saline groundwater intrusion (Parks Victoria 1999a; WWF and NPWS 1999; DEH 2007; DELWP 2019). Flow regulation through irrigation supply channels plus discharge of treated effluent threaten the Fivebough and Tuckerbil Swamps (OEH 2002). Losses of small and medium floods from river regulation and water extraction threaten the long-term water regime of sites such as NSW Central Murray Forests and Lake Albacutya (Parks Victoria 1999b; OEH 2012). Banrock Station (SA) was degraded by permanent wetland inundation for more than 80 years, but a variable water regime has been recently implemented that has recovered some aspects of its Ecological Character and has partially addressed threatening processes such as Acid Sulfate Soils accumulation (DEWHA, 2009; Fitzpatrick et al. 2016).

The final group of MDB Ramsar wetlands represent sites that remain in a state consistent with their Ecological Character Description, although they are negatively influenced by human factors to some degree (Table 1). For example, the Paroo River Wetlands are on a near natural, arid inland river, the last free-flowing river in the MDB, but they are subject to some water extraction via diversion and capturing of overland flows (OEH 2005). The River Ecosystem Health of the Paroo River was rated as “good” in the second Sustainable Rivers Audit, being one of the higher rated rivers in the MDB (MDBA 2012). The ecological condition of the Paroo River is also predicted to be further subjected to decreased flooding frequency, increasingly intermittent flows and higher temperatures (greater evaporation) due to climate change (OEH 2007). The Currawinya Lakes that are fed by the Paroo River in high flows with baseflows from the Great Artesian Basin are not currently threatened by hydrological factors, but that could change under a changing climate or if water extraction or mining activities increase (Fu et al. 2020).

Ginini Flats Subalpine Bog in Namadgi National Park is in the headwaters of the MDB in the Australian Capital Territory (ACT) and is high enough in the catchment to avoid most water resource development impacts, but it is still likely to be affected by changes to catchment infrastructure, reduced snowfall due to climate change and other anthropogenic factors such as altered fire regime and recreational impact (ACT Government 2017). It is vulnerable because it is already at the most northerly extent of subalpine bogs in the Australian Alps and thus changes in climate may result in significant changes in water regime (ACT Government 2017).

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Table 1. The Ecological Character of the Sixteen Murray Darling Basin Wetlands of International Importance and maintenance challenges.

Wetland	State	Size (ha)	Ecological Character summary	Challenges to Maintaining Ecological Character
Currawinya Lakes QDEHP (2014)	QlLD	151,300	Listed 1996; Meets 6/9 Criteria; Diverse mosaic of river, lakes, alluvial plains, creeks and springs.	Use and management of water in the Great Artesian Basin; Frequency and variability of flooding from largely unregulated Paroo River.
Ginini Flats EPD (1996)	ACT	350	Listed: 1996; Meets 3/9 Criteria; Most northerly Subalpine Sphagnum Bog in Australian Alps.	Headwaters therefore limited management influence over water regime. Important for Canberra water quality and moderating runoff.
Paroo River Wetlands OEH (2005)	NSW	138,304	Listed: 2007; Meets 2/9 Criteria; Last free-flowing river in MDB, Mound springs.	Extraction by diversions or overland flows.
Gywdir Wetlands WWF and NPWS (1999)	NSW	823	Listed: 1999; Meets 5/9 Criteria; Terminal semi-permanent wetlands	River regulation and irrigation expansion; reduced frequency and duration of inundation.
Narran Lakes OEH (2011b)	NSW	8,447	Listed: 1999; Meets 3/9 Criteria; Terminal intermittent wetlands	Continuous upstream water extraction, loss of small to medium floods.
Macquarie Marshes OEH (2011a)	NSW	19,850	Listed: 1986; Meets 6/9 Criteria; One of MDB's largest most diverse freshwater wetlands	Greater dependence on environmental water due to reduced water availability. Article 3.2 Notification – assess capacity to adapt.
Fivebough and Tuckerbil Swamps OEH (2002)	NSW	619	Listed: 2002; Meets 3/9 Criteria; Permanent and intermittent (fresh & brackish) wetlands	Irrigation supply channels (altered water regime through irrigation supply channels); Loss of small and medium floods; used for treated effluent disposal.
Barmah Forest Parks Victoria (1999a)	VIC	28,515	Listed: 1982; Meets 4/9 Criteria; River Murray Redgum Forest	Altered flooding frequency, timing and extent due to river regulation and water extraction.
Gunbower Forest Ecological Associates (2006)	VIC	19,931	Listed: 1982; Meets 2/9 Criteria; River Murray Redgum Forest	Altered water regime from river regulation and irrigation supply; Loss of small and medium floods.
NSW Central Murray Forests OEH (2012),	NSW	83,992	Listed: 2003; Meets 4/9 Criteria; River Murray Redgum Forest	Loss of small floods and declines in moderate overbank flows.

Wetland	State	Size (ha)	Ecological Character summary	Challenges to Maintaining Ecological Character
Lake Albacutya Parks Victoria (1999b)	VIC	5,659	Listed: 1982; Meets 4/9 Criteria; Temporary Wetlands	Only receives water in exceptionally wet years (~1 in 20 year); Rising saline groundwater and reduced flood occurrence.
Kerang Wetlands DELWP (2019)	VIC	9,784	Listed: 1982; Meets 4/9 Criteria; Permanent & intermittent wetlands	Regulated inflows to permanent wetlands along flow paths modified for irrigation supply. Saline wetlands used as salt disposal basins.
Hattah-Kulkyne Lakes Ecological Associates (2005)	VIC	955	Listed: 1982; Meets 2/9 Criteria; Floodplain Lakes	Only receive water in wet years; Rising saline groundwater and reduced flood occurrence.
Riverland SA River Murray system (Renmark to SA Border) DEH (2007)	SA	34,618	Listed: 198; Meets 8/9 Criteria; Major floodplain with two fast-flowing anabranches	Stabilised water levels from river regulation; flow regime affected by Lock 6 operations; Loss of small to medium floods.
Banrock Station Privately-owned DEWHA (2009)	SA	1,375	Listed: 2002; Meets 3/9 Criteria; Managed River Murray wetland.	River regulation and water extraction. Site watering regulated to induce wetting/drying cycles.
The Coorong and Lakes Alexandrina and Albert DEWNR (2013)	SA	142,530	Listed: 1985; Meets 8/9 Criteria; River Murray estuary, freshwater lakes and estuarine-saline wetlands.	Murray Mouth kept open by dredging sand (except during very high flows) and salinisation due to river regulation and water extraction. May require transition to new 'desired state' (see Article 3.2 Notification).

Data for this table was collated from the Ramsar Information Sheets (RIS) available for each wetland on the Australian Government website (https://www.dcceew.gov.au/water/wetlands/australian-wetlands-database/australian-ramsar-wetlands). The number of Ramsar criteria which the wetland meets out of a possible nine criteria are taken from these RIS. It is acknowledged that many of these RIS are out of date and are currently being updated.

3. Climate change challenges for MDB Ramsar Wetlands

Regardless of current ecological condition, position in the catchment and the sufficiency of antecedent watering, all sixteen MDB Ramsar wetlands are at risk from the effects of climate change (Finalyson et al. 2013) and subsequent failure to provide sufficient water in the right regime to meet their environmental water requirements.

Climate change impacts will be realised through increased temperature, more variable rainfall and extreme climatic events that will alter wetland inflow patterns and water regimes, with wetlands in coastal areas also being affected by sea level rise and ocean storm surges (Junk et al. 2013; Xi et al. 2021). The magnitude of these impacts will depend on such factors as current ecological condition, geographic location, position in the catchment and the sufficiency of antecedent watering. For instance, the alpine Ginini Flats is likely to be most impacted by increasing temperatures and altered rainfall patterns and more frequent and intense extreme events (such as bushfires) (ACT Government

2017), whereas reduced inflows, sea level rise and storm surges pose the greatest challenges to The Coorong and Lakes Alexandrina and Albert (Thom et al. 2020). The impacts will also manifest differently in different wetlands, but generally wetland condition and biodiversity are likely to decline whilst the prevalence of alien species is likely to increase. The capacity to effectively manage the Ecological Character of Ramsar wetlands in the MDB will be challenged, heightening the importance of identifying and implementing solutions that help to understand and adapt the impact to the changing climate (Pittock et al. 2010).

3.1 The need to adapt

Prior to European colonisation and water resource development, MDB wetlands and other aquatic habitats received all the water provided by the climate and catchment characteristics. For the 40 Aboriginal Nations in the MDB, "….water is a sacred and elemental source and symbol of water. The resources provided by aquatic ecosystems are a pivotal part of spirituality and the cultural economy……Aboriginal people have a moral obligation to care for water resources, as part of their commitment to looking after Country" (MILDRIN, NBAN and NAILSMA, 2017).

In the heavily regulated MDB, climate is only one driver of a wetland's water regime, albeit one that is changing towards a drier regime (Prosser et al. 2021). Water no longer simply runs downhill, but is pumped out, captured in major storages and multitudinous farm dams, and regulated by more than 3000 regulatory structures (including 14 weirs and 13 locks on River Murray), levees, five barrages near the Murray Mouth and other water management infrastructure, including 13 salt interception schemes along the lower Murray (MDBA 2021). In some cases, MDB Ramsar wetlands have their own specific site-based infrastructure built to manage their water regime for environmental values (e.g. Banrock Station, Chowilla anabranch in the SA Riverland site), but site management is still constrained by water delivery and sharing rules (Wallace and Whittle 2014).

Water policy that addresses overallocation is underway in the MDB with the Basin Plan (MDBA 2012) being the primary tool. Water is being bought back by the government for the environment and water sharing between all users, including the environment, is being managed through the implementation of Sustainable Diversion Limits for each MDB sub-catchment and the use of infrastructure and refined strategies to optimise environmental water delivery. The Basin Plan has only been partially implemented to date, and the timelines for completion and the renewal of the Basin Plan are under review. This is at a time that most of our sixteen MDB Ramsar wetlands have already declined in health and the Ecological Character of some are at further risk from failure to meet their water requirements, especially under a drying climate (e.g. challenges summarised in Table 1). Degraded MDB Ramsar wetlands are likely to have reduced capacity to adapt to climate change, particularly in such a heavily regulated system, and therefore are more vulnerable (see Section 3.2).

In some cases, wise use in the context of the Ramsar Convention can lead to significant ecosystem improvements without needing to allocate 'new' water. For example, water levels in the SA Riverland Ramsar site have typically been static since the installation of the weirs and locks approximately 100 years ago. River regulation fundamentally changed the character of this part of the river and its wetlands from a perennial, lotic (fast-flowing) river with an annual variation in water level of ~8m, generating highly variable wetland water regimes, to a series of lentic (slow-moving) pools with water level variation tightly controlled around 'normal pool level' (~10cm variation) (Mallen-Copper and Zampatti, 2018; Muller and Creeper 2021). Instead of following a natural river flows model, Muller and Creeper (2021) used a "Deconstructed River Pulse" concept to make decisions based on flow predictions. Under this plan, the operational capacity will be extended to allow operation over a much greater range (e.g. up to 2m variation), and at times that achieve specific watering objectives and manage the inherent management trade-off between achieving inundation and lotic outcomes in a highly regulated river. Operating the weir pools differently will also confer greater drought resilience

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to irrigation communities as well by repositioning offtakes lower in the river channel. Weir pool lowering will also extract salt, organic matter and nutrients from pool-connected areas, thereby reducing water quality risks to all users and allowing people to make more of the water they have due to its higher quality. Operating weirs more often and over a greater range, in accordance with this new plan, will also greatly enhance Ecological Services, such as carbon sequestration and storage, at a range of scales to improve ecological health and capacity to adapt to climate change with available water. If lotic conditions can be achieved by running the river lower in the channel, then threatened species such as Murray Cod (*Maccullochella peelii*) will benefit and locally extinct species such as Murray Crayfish (*Euastacus armatus*) and Trout Cod (*Maccullochella macquariensis*) could be returned to the wild in SA.

It is clear, however, that unless water sharing policies are recast and water delivery models reconsidered, only a minority of the 30,000 MDB wetlands will be protected by the current levels of environmental watering (Chen et al. 2021) and those that are priortised may still have to rely on 'unregulated' flows occuring often enough to prevent significant losses of components, processes and services. Some scientists argue that there is a need to reconsider environmental water delivery to achieve the best long-term outcomes from significantly less water. Gawne and Thompson (2023) postulate moving from a 'restore and protect' flow delivery model to one of delivering 'functional flows' under an adaptation model where social, economic, cultural and environmental value trade-offs are navigated. They acknowledge that the major challenge will be adapting wetland and floodplain ecosystems to reduced flows and argue that some loss of diversity through an adaptation approach is better than greater losses of diversity, functions and services through a failed approach to protect and restore. Schweizder et al. (2022) discuss the need for a conservation triage approach which 'entails reframing relationships between people and nature and values, rules and knowledge used by stakeholders'. The premise is that wetlands that are unable to persist as wetlands in a changing climate should not receive water and be allowed to transition to a new state such that water can then be prioritised for wetlands that are more likely to persist. In the case of MDB Ramsar wetlands, they will only receive water if watering maintains Ramsar listing under this model.

This discussion poses some difficult questions for decision-makers under a changing climate:

- Should we further reduce watering of water dependent assets, including the sixteen Ramsar wetlands and at least some of the other 30,000 MDB wetlands, acknowledging the potential loss of diversity, function and future services to people?
- If so, how will we 'dewater' appropriately whilst using water (and wetlands) wisely and how would we prioritise which natural and built assets receive water?
- What will be the true cost of not meeting environmental water requirements now and in the future?

The answers to these questions will ultimately be 'community' decisions and thus will depend on the values assigned to wetlands and other forms of natural capital in a catchment with increasing deficits in meeting water demands. The way in which we 'dewater' a site, if required, will determine how those catchment areas transition. For example, if we simply turn off the tap and abruptly stop the water, then we may generate weedy areas or areas of bare salinised floodplain that do not support functional ecological communities (Nicol et al. 2010). If we decide to dewater sites, then adaptation needs to be actively supported through on-ground works (e.g. revegetation, introduced species management, soil amelioration) and strategies for mitigating risks (e.g. large floods that may infrequently inundate areas that have been terrestrialised and therefore unable to respond).

We also need to value appropriately what we will have lost if we 'dewater' wetlands. In parts of the world, such as the United States, work is occurring to assess the economic benefits of protecting healthy ecosystems in a cost-benefit context. In the case of New York City, a new filtration plant would have cost USD$8-10 billion in capital and operating costs, whereas watershed conservation to achieve the same water quality cost only USD$1.5 billion (Appleton 2002; NASEM 2020). Similarly, nitrogen reduction in Chesapeake Bay through forest buffers cost USD$3.10/lb nitrogen compared with USD$8.56/lb for wastewater treatment and on average wastewater treatment costs were found to be USD$3.24/1000 gallons for conventional treatment compared to USD$0.47 for constructed wetland treatment (https://www.epa.gov/sites/default/files/2015-10/documents/economic_benefits_factsheet3.pdf).

Providing water to aquatic ecosystems of the MDB and maintaining them through a changing climate, may ultimately be the most cost- and energy-effective way of providing essential community services such wastewater treatment. We argue that as climate change effects deepen, Australians may come to depend more heavily on ecosystems that can adapt and flourish than infrastructure that may fail and/or be increasingly expensive to operate reliably, especially if aging infrastructure is not maintained or reconstructed after large flood events or if energy becomes prohibitively expensive or unreliable over the next 50 years. In which case, we will want all the functional wetland environments we can get and may regret 'dewatering' without accounting for the social, cultural and ecological costs of losing natural assets as well as the financial costs of replacing their services. The adaptive capacity of a given wetland needs to be robustly assessed and its transition to a less water hungry ecosystem carefully managed, if that is the preferred option. Dewatering may be irreversible, may not lead to an alternate ecosystem state that is desirable and may come with considerable long-term costs that are far greater than the immediate financial cost of increased environmental water allocations.

3.2 Understanding climate change velocity

Wetlands are typically at the lowest topological point in their catchment and therefore the ecosystem components cannot move further downhill to a more suitable climate in response to climate change (noting that groundwater-fed or alpine systems may be higher in the catchment, but these discharge points are typically highly constrained by geomorphology). Climate velocity is a vector that describes the speed and direction that a point (or a habitat) needs to move to remain in a static climate under a changing climate (Brito-Morales et al 2018). It refers to how quickly a species or the ecological components of a wetland would need to adapt or how far they need to disperse to keep pace with the changing climate. Loarie et al. (2009) developed an index of the velocity of temperature change (km/y) likely to occur under climate change, and found that riverine flooded grasslands, mangroves and deserts have the highest velocity (1.26 km/y) compared with the global average across all ecosystems of 0.42 km/y. This means that populations need to move to new areas along this gradient at these rates to remain viable, a process that is likely to be significantly hampered by the geomorphology and the high levels of riverine and floodplain disconnection in the MDB.

Climate velocity is one aspect of the climate change impacts that a wetland may be exposed to. The vulnerability of that wetland to the cumulative, adverse impacts of climate change can be qualitatively assessed as a function of exposure, sensitivity and adaptive capacity, as shown in Figure 3. Vulnerability can be strongly driven by climate velocity, if the magnitude, rate of change and/or the variation in the climate experienced at a given location (i.e. a wetland) is greater than the adaptive capacity of the ecosystem's components, processes and services (Allen Consulting 2005). Climate velocity can also be useful for management, if it can be represented by a simple function relevant to the ecosystem (Brito-Morales et al. 2018).

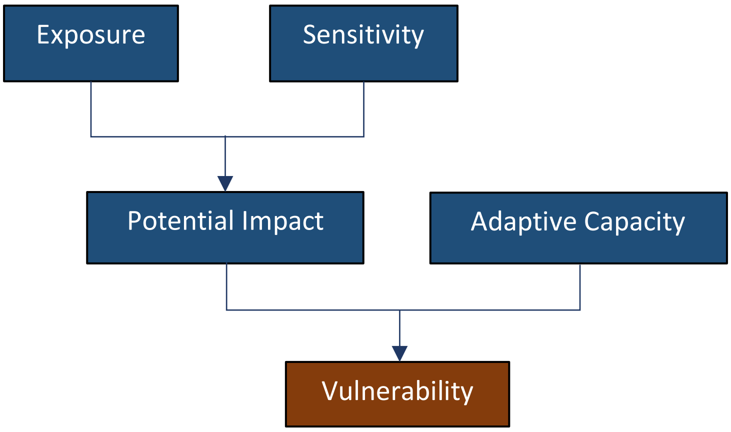

Figure 3. Qualitative climate change vulnerability assessment model. Source: Allen Consulting (2005).

To effectively manage the adaptive capacity of MDB Ramsar wetlands we need to know how to interpret climate velocity and several key questions emerge:

- Does exposure simply increase with increasing distance from the headwaters? Or are there other more important factors that affect water regime changes?
- Is there a gradient in exposure? Or are all parts of the MDB equally exposed?
- Are certain wetlands or particular species more sensitive to the expected exposure?
- Are the extreme ends of the catchment the most vulnerable (i.e. headwaters and mouth)?
- How quickly do we need to act to maintain or transition MDB Ramsar wetlands?

The persistent extremely hypersaline (>100 ppt) and hypereutrophic condition of the South Lagoon of the Coorong (noting the temporary reduction in salinity by the 2022–23 flood), would support the argument that cumulative exposure to climate change is a function of river length, given it is typically the most degraded MDB Ramsar site and is the most downstream. But perhaps climate velocity is more a function of water regime alteration – i.e. changes in the quantity, frequency, duration, extent and timing of inflows. For example, Ginini Flats is a subalpine bog at the very top of the catchment, but it is still vulnerable to climate change, if snow fall is reduced and evaporation increases due to higher temperatures, which drive changes in water regime that the system cannot adapt to quickly enough. Movement of biota along the elevation gradient to match a changing climate is likely to be hindered by the relative isolation of peat bogs across the Alps. Effective flow reductions with river length may also differ across different sub-catchments. The Paroo River is only expected to have small reductions in flows due to climate change (OEH 2005), whereas flows in the already overallocated River Murray are expected to be significantly reduced by climate change (Whetton and Chiew 2021). Furthermore, other climate change vulnerabilities, including rates of change in water quality, will differ across sites. Climate change will also present challenges to MDB Ramsar managers that are not water related. In particular, changes to the fire regime resulting from climate change also have the potential to be very detrimental to River Red Gum forests, especially if the intensity and frequency of fires increases. These factors are likely to increase vulnerability (e.g. escalate the extinction risk of threatened species and further reduce suitability of habitats) across the MDB unless species or assemblages can adapt quickly enough. *In toto*, this will create more opportunity for pest plants and animals to proliferate in degraded wetlands, further reducing ecosystem health and service provisions.

Understanding how to interpret and manage climate velocity and exposure is a critical part of the puzzle for managing the vulnerabilities and adaptive capacity of MDB Ramsar wetlands and the whole catchment. This interpretation will gain more gravity if it is used to underpin extreme policy measures, such as not watering part, or all, of a MDB Ramsar wetland because it is considered unlikely to adapt to climate change. Additional research and precautionary policies are required now to prevent losses of vulnerable systems and/or improve adaptive capacity while our knowledge builds.

4. Adaptation Opportunities for MDB Ramsar Wetlands

4.1 Wise use and ecosystem service provision

Wetlands are vital parts of the natural capital of a catchment, retaining water in the landscape and providing ecosystem services – the benefits that people obtain from ecosystems - such as water purification, flood mitigation and drought survival (Ramsar Secretariat 2011). The interaction and linkages between wetland health/function, human well-being and human livelihood linkages need further exploration to ensure wetlands can continue to provide ecosystem services as well as supporting diverse species and processes that contribute to our cultural and spiritual connections to our environment. Ecosystem services provided by wetlands can be considered as 'priceless' because other than a few specific case studies (e.g. New York State watershed) there is yet to be a valuation method that truly accounts for the total economic values of water-dependent ecosystems, including Ramsar wetlands, and does not underestimate them (Jacobs Marsden 2012).

In November 2022, Ambassadors of the Contracting Parties signed the Wuhan declaration, reaffirming the principles of the Ramsar Convention to conserve, restore and ensure the wise use of wetlands (COP14; https://www.ramsar.org/news/ministers-and-ambassadors-adopt-the-wuhan-declaration). The signing of the declaration comes in the face of reported acceleration of wetland loss at a global level and includes key themes around wetland actions for climate mitigation and the integration of actions into national policy and the value of ecosystem services into financial frameworks. There is also consideration in the declaration of reframing 'Ecological Character' as 'Wetland Character' to overcome the human-nature dualism and accommodate a plurality of world views and multiple value systems (Kumar et al. 2020).

Four major strategies are needed to wisely use MDB Ramsar Wetlands under a changing climate and ensure that the Ecosystem Services we depend on continue to be provided.

1) **Evaluating likely climate change impacts and climate exposure at a wetland scale.**
   Determining the climate change exposure likely to be experienced by different parts of the MDB, their sensitivity to that exposure and the rate that potential impacts may occur (climate velocity) against their adaptive capacity is essential to determining vulnerability, and therefore, management objectives and actions. This is especially important if climate change is likely to result in irreversible decline of wetland condition and 'dewatering' of wetland areas that are unable to persist is being considered for transition to alternate ecosystems that may or may not be more vulnerable. Part of this evaluation would also involve quantifying wetland carbon stores and factoring changes to the carbon budget into management decisions, i.e. wetlands could be watered to store more carbon.

2) **Assessing and building adaptive capacity to better meet climate change challenges.**
   Highly degraded wetlands will need to be improved in ecological condition within 10-15 years to enable adaptation towards alternate ecosystems that are less vulnerable to climate change, if recovery is not feasible. Less degraded wetlands are still vulnerable to climate change and will benefit from improved water delivery and/or on-ground actions that increase their adaptive capacity,

3) **Allocating water, operating existing water infrastructure and approving new infrastructure primarily for ecological benefits.**
   If the primary aim of all our policy and planning decisions changes was to not just avoid environmental impacts, but achieve ecological benefits, then our ecosystems and their

services will be appropriately valued, integrated into our socio-economic fabric and attract investment to build their natural capital over time, and

4) **Implementing local, regional and national adaptation management plans.** These tailored plans need to either (i) enable maintenance of the current Ecological Character under a changing climate, where appropriate, or (ii) map out how to transition wetlands with poor adaptive capacity and high vulnerability from their current state to a new, functional Ecological Character that is better able to withstand climate change whether that be a new type of wetland or a terrestrial system.

In this way, MDB Ramsar wetlands and other natural capital assets in their catchments will better support human communities and industries to increase their adaptive capacity and reduce their vulnerability into an uncertain future.

4.2 Capture and store carbon – direct climate change action

The Ramsar Secretariat state that wetlands are a natural solution to climate change, being the most effective carbon sinks in the world with peatlands alone storing nearly a third of all land-based carbon, twice as much as global forests (Urrego 2017). Wetlands can sequester atmospheric carbon (e.g. photosynthesis, methanotrophy) and store large quantities of carbon (e.g. woody vegetation, deep anoxic sediments). Carnell et al. (2018) estimated that wetlands in Victoria have a soil carbon stock in the upper 1 m of soil of 68 million tons of organic carbon with an annual sequestration rate of 3 million tons of CO_2 equivalence.

Wetlands are, however, particularly vulnerable to climate change impacts, and if managed poorly, can be significant sources of atmospheric carbon (e.g. polluted or disturbed wetlands release more methane). There is a strong relationship between carbon stocks in wetlands and anthropogenic disturbance. For example, drainage and loss of 260,530 ha of wetlands in Victoria since European colonisation is estimated to have released between 20 and 75 million tons of CO_2 eq. (Carnell et al. 2018). Wetland protection is, therefore, a significant global strategy for mitigating avoidable contributions to climate change (Nahlik and Fennessy, 2016).

“Teal carbon” is the term given to (non-tidal) freshwater wetland carbon (Carnell et al. 2018). In the MDB, it represents a potentially massive opportunity. where specific strategies for MDB Ramsar wetlands to protect stored carbon, reduce avoidable carbon emissions and sequester atmospheric carbon are urgently required as part of a national suite of direct climate change actions. “Dewatering’ wetlands may lead to substantial methane emissions and losses of significant carbon storage facilities at a time when global communities are only starting to embrace the carbon economy. There is not currently an approved method for ‘Teal Carbon’ as tradeable carbon credits but that could be realised within the next 50 years to unlock a new natural capital income stream. Recent assessments of climate change vulnerabilities in the MDB did not include an assessment of carbon stores or carbon sequestration capacity – carbon was only considered in terms of blackwater events (MDBA 2020). In our opinion, this is a significant oversight and one that could be rectified through greater understanding of the whole carbon cycle and the role healthy wetland ecosystems play in climate change mitigation.

4.3 Vision for MDB Ramsar Wetlands in 50 years

There are many possible ecological trajectories over 50 years for the sixteen MDB Ramsar wetlands, individually and as a collective. Two alternate visions are presented below. Which vision is realised depends on collective actions taken by governments, MDB communities and industries over the coming decades, particularly with regard to environmental water delivery and the integration of water policies, infrastructure operations and financial systems.

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4.3.1 Vision 1: a degraded MDB

It is expected that if we continue “business as usual’ (i.e. continued underappreciation of the value of wetlands, partial Basin Plan implementation, insufficient watering of only iconic wetlands), environmental water provisions will remain inadequate and progressive losses of the Ecosystem Components, Processes and Services for which the MDB Ramsar wetlands were listed as Wetlands of International Importance, will continue over the next 50 years. This degradation will also occur in other MDB wetlands and is likely to be accelerated and more severe in the majority of the 30,000 wetlands in the MDB that are not prioritised for environmental watering as internationally recognised sites.

Wetland degradation will set up a negative feedback loop where degraded wetlands will provide less sutiable habitats and less effective ecosystem services, such as poorer water purification, flood mitigation, nutrient cycling and landscape water storage, and thus catchment water will degrade further in quality, thereby further reducing the quantities of fit-for-purpose water, increasing the cost of water treatment and increasing the gap between supply and demand. Higher temperatures and poorer quality water will likely lead to more frequent blackwater events with associated fish kills, leading to further losses of threatened species. Shorter and less frequent periods of inundation are likely to lead to waterbirds failing to nest or abandoning nests and failed recruitment of other aquatic fauna (e.g. frogs, fish, turtles, inverebrates). Nutrients and salt will accumulate in the aquatic environment, becoming increasingly less suitable for key Components and Processes and thus Services. With wetlands in a degraded condition, the effects of extreme events, such as droughts and floods, will have greater impact on the environment, and all the people (communities and industries) that depend upon it.

If currently agreed water sharing outcomes shift further towards prioritising consumptive use over environmental use, as predicted by Prosser et al. (2021), and the overall volumes of fit-for-purpose water provided to wetlands decreases further, then ecosystem vulnerabilities will increase and declines in Ecologcial Services provision will accelerate beyond that driven by climate change alone. This will further reduce not only the adaptive capacity of MDB Ramsar wetlands to climate change, but that of all water users. At the extreme this may result in cessation of environmental water delivery, which could lead to severe degration and loss of ecosystem services, such as flood mitigation, which will further increase vulnerability of human communities.

4.3.2 Vision 2: a healthy MDB

This alternate vision sees all sixteen MDB Ramsar wetlands improve in ecological condition and adapt to a changing climate as part of a continuum of connected ecosystems with high adaptive capacity and reduced vulnerability to climate change across the MDB. By 2030, those wetlands that were degraded were either restored to their former Ecological Character, or transitioned to a new healthy Ecological Character, and have continued to meet the Ramsar criteria for Wetlands of International Importance. The Article 3.2 Notification for Macquarie Marshes was rescinded through water regime restoration. The Coorong South Lagoon has been ’restored’ to a brackish-marine wetland that supports a diverse, functional and complex ecosystem. In achieving these outcomes for the most-downstream Ramsar site, many other aquatic ecosystems have benefitted along the way. The water quality targets described by Verhoeven et al. (2024) were achieved, which means that the ecological health of the whole Basin has improved and solutions to problems of transitioning aquatic ecosystems that were not being adequately watered to healthy terrestrial ecosystems were found.

Ecosystem Services provided by MDB Ramsar wetlands, and the catchment, have been investigated, valued and integrated into the nation’s accounting system. All water management decisions and operations are conducted primarily for ecological benefits or maintenance and on-going ecosystem service provisions in the knowledge that this is ultimately the most cost-effective way of delivering, purifying and storing water for all users. Rural and urban communities have a strong understanding of how climate change has affected the MDB, what future climate challenges lie ahead, what mitigation strategies are the most successful and how best to manage their local resources as part of a whole Basin.

5. Conclusions

Wetlands are vitally important to sustain human populations and biodiversity. Each of the sixteen Ramsar wetlands of the MDB has been valued by the global community or it would not have been listed as a Wetland of International Importance. Two of these wetlands have been so degraded as to have changed in Ecological Character and it is imperative that they are improved by 2030 to enable them to adapt to future climate challenges.

Current environmental water initiatives and actions may not be sufficient to maintain the Ecological Character of the MDB Ramsar wetlands in the face of climate change (Schweizder et al. (2022), especially given that most Ramsar wetlands are already declining, and they represent only a small fraction of the aquatic ecosystems that require watering in the MDB. Given that water availability is likely to decrease for all users in the future, there will be on-going losses of aquatic components, processes and services unless social-economic policies and operations are recast to achieve ecological benefits.

Our four strategies for increasing adaptive capacity, and thereby reducing climate change vulnerability, of wetlands and other aquatic ecosystems of the MDB will generate co-benefits for communities and industries, making progress towards the UN Sustainable Development Goals and the Paris Agreement on Climate Change. Implementation will require significant investment and the integration of 'priceless' ecosystem services into our social and financial fabric. Water invested in the natural capital of wetlands will pay dividends through the provision of ecosystem services, thereby, increasing the resilience of Australian industries and communities. There may also be opportunities for direct climate action through well-watered wetlands sequestering carbon and in so doing, unlocking additional income through teal carbon credits to further invest in ecosystem services.

In some cases, it may be necessary to transition wetlands to a new type of ecosystem due to historic degradation, climate change impacts and development legacies. We propose that any 'dewatering' of wetlands is undertaken as an absolute 'last resort' strategy and actively managed to ensure that species are able to move and adapt, and the novel ecosystems that arise are better able to adapt to climate change and provide appropriate ecosystem functions in the landscape.

We have described a future where ecosystem services provided by MDB Ramsar wetlands and other ecosystems are highly valued and fully integrated into our economic and policy frameworks, thereby enabling them to receive their appropriate share of water. Thriving aquatic ecosystems throughout the MDB will provide ecosystem services that purify catchment runoff, retain water in the landscape, capture sediments and store carbon – thereby supporting our national social, cultural and financial economies – whilst sustaining biodiversity and threatened species, supporting migratory birds and providing healthy environments that renew the human spirit. The alternative is the on-going degradation and loss of ecological function in the MDB, including loss of essential ecosystem services that ultimately support human wellbeing and prosperity.

We may be running out of time for mitigating climate change impacts, but we still have some capacity to choose how we adapt. Whether we will choose to support a healthy, functional and diverse MDB, or not, will fundamentally determine how successful the adaptation of our communities that rely on it will be, or not.

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References

ACT Government (2017). Ginini Flats Wetland Complex Ramsar Site Management Plan. ACT Government, April 2017.

Allen Consulting (2005). Climate change risk and vulnerability. Australian Greenhouse Office Department of Environment and Water Resources, Canberra, Australia.

Appleton, A.F. (2002). How New York City used an ecosystem services strategy carried out through an uran-rural partnership to preserve the pristine quality of its drinking water and save billions of dollars and what lessons it teaches us about using ecosystem services. https://www.cbd.int/financial/pes/usa-pesnewyork.pdf

Bergstrom D. M., Wienecke B. C., van den Hoff J., Hughes L., Lindenmayer D. B., Ainsworth T. D., Baker C. M., Bland L., Bowman D. M., Brooks S. T., Canadell J. G., Constable A. J., Dafforn K. A., Depledge M. H., Dickson C. R., Duke N. C., Helmstedt K. J., Holz A., Johnson C. R., McGeoch M. A., Melbourne-Thomas J., Morgain R., Nicholson E., Prober S. M., Raymond B., Ritchie E. G., Robinson S. A., Ruthrof K. X., Setterfield S. A., Sgrò C. M., Stark J. S., Travers T., Trebilco R., Ward D. F. L., Wardle G. M., Williams K. J., Zylstra P. J., and Shaw J. D. (2021). Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology*. 27 1692-1703

Boulton, A.J. and M.A. Brock (1999). Australian Freshwater Ecology: Processes and Management. Gleneagles Publishing, Glen Osmond, SA. ISBN 1 875553 05 3.

Brito-Morales, I., J.G. Molinos, D.S. Schoeman, M.T. Burrows, E.S. Poloczanska, C.J. Brown, E. Ferrier, T.D. Harwood, C.J. Klein, E. McDonald-Madden, P.J. Moore, J.M. Pandolfi, J.E.M. Watson, A. S. Wenger and A.J. Richardson (2018). Climate velocity can inform conservation in a warming world. *Trends in Ecology and Evolution* 33(6): 441-457.

Campbell, C.J., Thompson, R.M., Capon, S.J. and Dyer, F.J., 2022. Rethinking condition: Measuring and evaluating wetland vegetation responses to water management. *Frontiers in Environmental Science*, 9, p.764.

Carnell, P.E., S.M. Windecker, M. Brenker, J. Baldock, P. Masque, K. Brunt and P.I. Macreadle (2018). Carbon sticks, sequestration and emissions of wetlands in south-eastern Australia. *Global Change Biology* 24 (9), 4173-4184. https://doi.org/10.1111/gcb.14319

Chen, Y. W., et al. (2021). "A trickle, not a flood: environmental watering in the Murray-Darling Basin, Australia." *Marine and Freshwater Research* 72(5): 601-619.

Crabb P. 1997. Murray-Darling Basin resources. Murray-Darling Basin Commission. Canberra.

CSIRO (2008). Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO. Canberra, Australia, CSIRO: 67.

Dobrowski, S. and S. A. Parks (2016). Climate change velocity underestimates climate change exposure in mountainous regions. Nature communications 7: 12349. https://doi.org/10.1038%2Fncomms12349

DEH (2007). Information Sheet on Ramsar Wetlands (RIS) Riverland South Australia Wetland of International Importance. Department of Environment and Heritage, Adelaide, South Australia.

DELWP (2019). Information Sheet on Ramsar Wetlands (RIS) for Kerang Wetlands Wetland of International Importance. Department of Environment, Land, Water and Planning, Melbourne, Victoria.

DEW (2021). HCHB Southern-Coorong-desired-state-discussion-paper-June-2021.pdf (environment.sa.gov.au).

DEWHA (2009). Information Sheet on Ramsar Wetlands (RIS) for Banrock Station Wetland Complex Wetland of International Importance, 2009-2012. Department of Environment, Water, Heritage and the Arts, Australian Government, Canberra, ACT.

DEWNR (2013). Information Sheet on Ramsar Wetlands (RIS) The Coorong and Lakes Alexandrina and Albert Wetland of International Importance. Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Ecological Associates (2005). Information Sheet on Ramsar Wetlands (RIS) for Hattah-Kulkyne Lakes Wetland of International Importance. Report by Ecological Associates, South Australia, for the Victorian Government, Melbourne, Victoria.

Ecological Associates (2006). Information Sheet on Ramsar Wetlands (RIS) for Gunbower Forest Wetland of International Importance. Report by Ecological Associates, South Australia, for the Victorian Government, Melbourne, Victoria.

EPD (1996). Information Sheet on Ramsar Wetlands (RIS) for Ginini Flats Subalpine Bog Wetland of International Importance. Environment and Planning Directorate, Australian Capital Territory Government, Canberra, ACT.

Gawne, B. and R. Thompson (2023). Adaptive water management in response to climate change: the case of the southern Murray Darling Basin. *Australasian Journal of Water Resources*.
DOI: 10.1080/13241583.2023.2181844

Finlayson, C. M., Davis, J. A., Gell, P. A., Kingsford, R. T., & Parton, K. A. (2013). The status of wetlands and the predicted effects of global climate change: the situation in Australia. *Aquatic Sciences*, 75, 73-93.

Fitzpatrick RW, P Shand, RH Merry, P Marschner, N Jayalath, S Grocke and LM Mosley (2016) Acid Sulfate Soil Assessment and Monitoring of the Banrock Station wetland. Acid Sulfate Soils Report No ASSC_035 (V13), 24th August 2016.

Fu, G., Zou, Y., Crosbie, R.S., Barron, O., 2020. Climate changes and variability in the Great Artesian Basin (Australia), future projections, and implications for groundwater management. *Hydrogeology Journa*l 28, 375-391.

Junk, W. J., An, S., Finlayson, C. M., Gopal, B., Květ, J., Mitchell, S. A., ... & Robarts, R. D. (2013). Current state of knowledge regarding the world’s wetlands and their future under global climate change: a synthesis. *Aquatic sciences*, 75, 151-167.

Kumar, R., R. McInnes, C.M. Finlayson, N. Davidson, D. Rissik, S. Paul, L. Cui, Y. Lei, S. Capon and S. Fennessy (2020). Wetland ecological character and wise use: towards a new framing. *Marine and Freshwater Research* 72(5): 633-637.

Loarie, S.R., P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field and D.D. Ackerly (2009). The velocity of climate change. *Nature* 462, 1052-1055.

Lewis, R., Waycott, M., O’Loughlin, E.J., Urgl, C., van Dijk, K.J., Calladine, A. and Nicol, J. (2022). Distribution and seasonality of the *Ruppia* dominated aquatic macrophyte community and filamentous algae in the southern Coorong. Goyder Institute for Water Research Adelaide, 63pp, Technical Report Series No. 22/09.

Muller, K.L. and N.L. Creeper (2021a). Weir Pool Operations Plan for River Murray Locks 6 to 1. Part One: Long-term Vision and Ecological Rationale for the Deconstructed River Pulse Approach. A report for Department of Environment and Water, Government of South Australia, Adelaide SA 5000.

Nicol, J.M., Weedon, J.T. and Marsland, K.B (2010a). Understorey Vegetation Monitoring of Chowilla Environmental Watering Sites 2004-08. (PDF 3.4 MB). South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000632-1. SARDI Research Report Series No. 499. 87pp.

Nilsson C., Reidy C. A., Dynesius M., and Revenga C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science* 308, 405-408.

MILDRIN, NBAN and NAILSMA (2017). Cultural Flows: A Guide for Water Managers. A report by Murray Lower Darling Rivers Indigenous Nations (MLDRIN), Northern Basin Aboriginal Nations (NBAN) & North Australian Indigenous Land and Sea Management Alliance (NAILSMA), 2017.

MDBA (2012). Sustainable Rivers Audit 2: The ecological health of the rivers in the Murray-Darling Basin at the end of the Millennium Drought (2008-2010). Murray Darling Basin Authority Publication No. 75/12.

MDBA (2020). The 2020 Basin Plan Evaluation. Vulnerabilities to climate change in the Murray–Darling Basin. M.-D. B. Authority. Canberra, Australia, Murray-Darling Basin Authority: 54.

MDBA (2021). New water infrastructure in the Murray-Darling Basin: Guidance for water managers. Murray Darling Basin Authority, Australian Government, May 2021.

Nahlik, A.M. and M.S. Fennessy (2016). Carbon storage in US wetlands. *Nature Communications* 7, 13835

NASEM (2020). National Academies of Sciences, Engineering, and Medicine; Division on Earth and Life Studies; Water Science and Technology Board; Committee to Review the New York City Watershed Protection Program. Washington (DC): National Academies Press (US); 2020 Aug 10.

OEH (2002). Information Sheet on Ramsar Wetlands (RIS) Fivebough and Tuckerbil Swamps Wetland of International Importance. Office of Environment and Heritage, Sydney, New South Wales.

OEH (2005). Information Sheet on Ramsar Wetlands (RIS) Paroo River Wetlands Wetland of International Importance. Office of Environment and Heritage, Sydney, New South Wales OEH (2007). Ramsar Information Sheet for Paroo River Wetlands, Australia. Office of Environment and Heritage on behalf of the State of New South Wales, September 2007.

OEH (2011a). Information Sheet on Ramsar Wetlands (RIS) Macquarie Marshes Wetland of International Importance. Office of Environment and Heritage, Sydney, New South Wales.

OEH (2011b). Information Sheet on Ramsar Wetlands (RIS) Narran Lake Nature Reserve Wetland of International Importance. Office of Environment and Heritage, Sydney, New South Wales.

OEH (2012). Information Sheet on Ramsar Wetlands (RIS) NSW Central Murray Forests of International Importance. Office of Environment and Heritage, Sydney, New South Wales.

OEH (2013). Macquarie Marshes Ramsar Site: Article 3.2 Response. Office of Environment and Heritage on behalf of the State of New South Wales, March 2013.

Parks Victoria (1999a). Information Sheet on Ramsar Wetlands (RIS) for Barmah Forest Wetland of International Importance. Victorian Government, Melbourne, Victoria.

Parks Victoria (1999b). Information Sheet on Ramsar Wetlands (RIS) for Lake Albacutya Wetland of International Importance. Victorian Government, Melbourne, Victoria.

Pittock, J., Finlayson, C., Gardner, A., & MacKay, C. (2010). Changing character: the Ramsar Convention on Wetlands and climate change in the Murray-Darling Basin, Australia. *Environmental and Planning Law Journal*, 27(6), 401-425.

Prosser, IP., FHS. Chiew, and MS. Smith. 2021. “Adapting Water Management to Climate Change in the Murray-Darling Basin, Australia.” *Wate*r 13 (18): 19. doi:10.3390/w13182504.

QDEHP (2014). Information Sheet on Ramsar Wetlands (RIS) Currawinya Lakes (Currawinya National Park) Wetland of International Importance. Queensland Department of Environment and Heritage Protection, Brisbane, Queensland.

Ramsar Secretariat (2011). Wetland ecosystem services Factsheet 0 – An introduction. Ramsar Secretariat, Gland, Switzerland.

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.

Tweedley, J.R., S.R. Dittman, A.K. Whitfield, K. Withers, S.D. Hoeksema and I.C. Potter (2019). Chapter 30: Hypersalinity: Global distribution, causes, and present and future effects in the biota of estuaries and lagoons. In: Wolanski E., J.W. Day, M. Elliot and R. Ramachandran (Eds). Coasts and Estuaries—The Future. Burlington. Elsevier, 2019. Pp. 523—546.

Verhoeven T. J., Khan S. J., and Evans M. C. (2024). Water quality in the Murray-Darling Basin in response to climate change. In Radcliffe, John C and Flapper, T (2024) (Eds), Challenges and adaptation opportunities for the Murray-Darling Basin in response to Climate Change - A series of essays adopting a 50-year perspective, Australian Academy of Technological Sciences and Engineering, Canberra ACT, Wallace T.A. and J. Whittle (2014) Operations Plan for Chowilla Creek Regulator and ancillary structures V2.1. April 2014. Working Draft. Prepared for Department of Environment, Water and Natural Resources, South Australia, and Murray Darling Basin Authority, Canberra.

Webster, I.T. (2010). The hydrodynamics and salinity regime of a coastal lagoon – The Coorong, Australia – Seasonal to multi-decadal timescales. *Estuarine, Coastal and Shelf Science*, Volume 90, Issue 4, 264-274.

Wedderburn S. D., Whiterod N. S., and Vilizzi L. (2022). Occupancy modelling confirms the first extirpation of a freshwater fish from one of the world's largest river systems. *Aquatic Conservation: Marine and Freshwater Ecosystems* 32, 258-268.

WWF and NPWS (1999). Information Sheet on Ramsar Wetlands (RIS) for Gwydir Wetlands, Gingham and Lower Gwydir (Big Leather) Watercourses Wetland of International Importance. Jointly prepared by World Wide Fund for Nature and National Parks and Wildlife Service for the New South Wales Government, Sydney, NSW.

Xi, Y., Peng, S., Ciais, P., Chen, Y., 2021. Future impacts of climate change on inland Ramsar wetlands. *Nature Climate Change* 11, 45-51.