A thriving Murray-Darling Basin in 50 years: Actions in the face of climate change

A series of invited essays exploring the authors' perspectives for the Murray-Darling Basin in 50 years' time after successfully responding to the challenges of climate change.

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Cover – Aerial view of the Murray River around Mildura. fotofritz16, iStock.

Murray-Darling Basin Boundary

Water Act 2007

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ACRONYMS

ABS	Australian Bureau of Statistics
ACT	Australian Capital Territory
AHD	Australian Height Datum (height benchmark)
ANU	Australian National University
ARC	Australian Research Council
ASS	Acid Sulfate Soils
ATSE	Australian Academy of Technological Sciences and Engineering
BDL	Baseline Diversion Limit
BoM	Bureau of Meteorology
BRAT	Blackwater Risk Assessment Tool
BSMS	Basin Salinity Management Strategy
CH_4	methane
CLLMM	Coorong, Lower Lakes and Murray Mouth
CMIP	World Climate Research Programme Coupled Model Intercomparison Project
CO_2	carbon dioxide
CSG	coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAWE	Commonwealth Department of Agriculture, Water and the Environment (2020-2022)
DCCEEW	Commonwealth Department of Climate Change, Energy, the Environment and Water
DELWP	VIC Department of Environment, Land, Water and Planning
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DPI	NSW Department of Primary Industries
EC	electrical conductivity units (salinity measurement - μS/cm)
EHYZ	MDB extremely high yield zone
ENSO	El Niño–Southern Oscillation
EPBC Act	Environment Protection and Biodiversity Conservation Act (1999, Commonwealth)
ESG	Environment, Social and Governance
ESP	exchangeable sodium percentage
FTSE	Fellow of the Australian Academy of Technological Sciences and Engineering
GCM	global climate model
GDE	groundwater dependent ecosystem
GHG	greenhouse gas
GL	gigalitres (10^9 litres)
GMA	Groundwater Management Area
GVAP	gross value of agricultural production
GW	groundwater
ha	hectare
HEVAE	high ecological value aquatic ecosystems
IG	Inspector-General of Water Compliance
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
km/y	kilometres per year (static habitat dispersal rate)
KHV	Koi (carp) herpes virus
LMRIA	Lower Murray River Irrigation Area
LTAAY	long-term average annual yield
MAR	managed aquifer recharge
MBO	Monosulfidic Black Ooze
MDB	Murray-Darling Basin
MDBA	Murray-Darling Basin Authority (2008-present)
MDBC	Murray-Darling Basin Commission (1987-2008)
MDBMC	Murray-Darling Basin Ministerial Council (1987-present)
MDB Plan	Murray-Darling Basin Plan (or the Plan)
ML	Megalitre (10^6 litres)

MLDRIN	Murray Lower Darling Rivers Indigenous Nations
mm	millimetres
MNES	Matters of National Environmental Significance (*EPBC Act*)
N	nitrogen
NAS	non-groundwater-associated salinity
NBAN	Northern Basin Aboriginal Nations
NFF	National Farmers' Federation
nHYZ	northern high yield zone
NOx	nitric oxide (NO) and nitrogen dioxide (NO_2)
NPV	net present value
NRM	Natural Resource Management
NSW	New South Wales
NT	Northern Territory
NWC	National Water Commission
NWI	Intergovernmental Agreement on the National Water Initiative
NWQMS	National Water Quality Management Strategy
OM	organic matter
P	phosphorus
Plan	Murray-Darling Basin Plan
Ppt	parts per thousand
psu	Practical Salinity Unit (ocean salinity = 1g per kg)
PTE	potentially toxic element
QLD	Queensland
R&D	research and development
RCP	Representative Concentration Pathway (greenhouse gas concentration trajectory)
RIS	Reduced inorganic sulfur in sulfidic materials
RMC	River Murray Commission (1917-1987)
SA	South Australia
SDGs	Sustainable Development Goals (United Nations
SDL	Sustainable Diversion Limit
SDLAM	Sustainable Diversion Limit Adjustment Mechanism
sHYZ	southern high yield zone
SILO	QLD Government database of s daily Australian climate data (1889-present)
SLR	sea level rise
SST	sea surface temperature
SW	surface water
teal carbon	freshwater wetland carbon
TN	total nitrogen
TP	total phosphorus
UNSW	University of New South Wales
VHYZ	MDB very high yield zone
VIC	Victoria
WA	Western Australia
Weir pool	The volume of water held behind a lock or weir
WRPs	Water Resource Plans
yr	year

1 FOREWORD

The Murray-Darling Basin (MDB or Basin) is Australia’s second-largest water catchment after the Lake Eyre Basin. It has a long history of supporting and being managed by Indigenous communities including those now comprising Murray Lower Darling Rivers Indigenous Nations and the Northern Basin Aboriginal Nations.

The Basin is a critical Australian environmental and economic asset. It is one-seventh of Australia’s landscape, represents an economically important proportion of Australia’s environmental resources and is a substantive home of biodiversity. It is responsible for delivering a major component of Australia’s Gross Domestic Product. Confounding the enduring health and management of this vital asset is that the Basin traverses four States and the Australian Capital Territory (ACT). This requires effective intergovernmental collaboration.

Effective management of the Basin must take a long-term adaptive view and be intergenerational, requiring:

1) an appropriate balance of environmental, economic, social and cultural outcomes
2) effective inter-jurisdictional collaboration and timely actions
3) a maturity to learn from the past and embrace effective change
4) timely collection, analysis, reporting and sharing of water quantity and water quality data over various time-scales using the latest digital engineering tools
5) transparent data-driven prioritisation of appropriate objectives that consider end users and end uses.

A sustainable river and groundwater system requires health and resilience throughout the whole catchment, from its headwaters to its ocean outlet.

The Australian Academy of Technological Sciences and Engineering (ATSE) is a Learned Academy comprising over 900 Fellows recognised for their expertise and achievements. The Academy seeks to be an independent, non-political source of objective science-based advice achieved through harnessing the skills and experience of its Fellows.

The Academy had previously initiated and published the outcomes of a Symposium it sponsored in October 1989 (ATSE 1989) at the time when the Murray Darling Basin Ministerial Council had initiated the first steps for cooperative management of the Basin environment through development of a Natural Resources Management Strategy. In this current project, initiated through its Water Forum in 2022 when the 2012 Murray Basin Plan was coming under increasing scrutiny, the Academy invited eminent Fellows and other recognised scholars to develop a perspective for the long-term future of the Basin by contributing essays on various aspects of its ecosystem and economy. A 50-year horizon perspective has been sought from each team of authors, taking account of current science-based thinking about the future impacts of climate change.

The essays are thoroughly referenced and have been subject to peer review and revision before acceptance. We had also hoped to include an essay from the Indigenous perspective, however the several Indigenous authors who had agreed to contribute essays to this project, due to their existing and ever-expanding commitments, including to prevailing debates, apologetically had to withdraw. We have therefore sought to provide a referenced Editorial Preface to the essays to highlight some important Indigenous perspectives. The Preface was reviewed by the originally invited Indigenous authors and revised before acceptance.

The essays contain a diversity of views, including views that may not necessarily represent the thinking of all Fellows in the Academy. Appreciating those interpretations of current science will be essential to the future conservation and management of the Basin as an environmental and economic resource for the nation.

The project has been overseen by a Steering Committee comprising Dr John Radcliffe FTSE, Dr Therese Flapper FTSE, Professor Stuart Khan FTSE (Water Forum Chair), Professor Rob Fitzpatrick FTSE (Water Forum Deputy Chair), Dr Tom Hatton FTSE, Professor Rob Lewis FTSE and Dr Peter Derbyshire. Grateful acknowledgement is made to the authors who have contributed to the collection of essays, to anonymous referees who have assisted the authors in finalising their contributions, and to Dr Natasha Abrahams, Dr Hazrat Ali, Edwyn Shiell, Elizabeth Geddes and Adam Huttner-Koros from the Academy's staff in producing the final publications.

Dr John C Radcliffe FTSE and Dr Therese G Flapper FTSE
Co-Chairs – Murray-Darling Basin Essays Steering Committee

March 2024

2 SUMMARY

2.1 Why this 50-year vision matters

The Murray-Darling Basin (MDB or Basin) covers over 1 million km^2. It has many key environmental assets including sixteen Ramsar wetlands, 30,000 wetlands, 85 mammal species, of which twenty are now extinct and sixteen endangered, along with five endangered snake species. There are 367 bird species including 98 waterbird species (35 bird species being endangered), together with 50 native fish, 30 frog and 100 lizard species.

Fifteen bioregions are partly or wholly in the Basin. The Basin provides drinking water for more than 2.3 million Australians in city, regional, rural and remote settings, including people from over 40 different First Nations.

The Basin supports an economy of over $230 billion per annum across recreation and tourism, industrial, commercial, mining and includes Australia's largest agricultural region contributing around 40% of the gross value of Australia's agricultural production from 7,300 irrigated agricultural businesses.

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Located in Australia's south-east, it is a system of 23 interconnected rivers and groundwater spanning 77,000 km, as well as an extensive lake system. The two main rivers in the Basin are the River Murray and the Darling River. The Darling begins in southern Queensland where the Culgoa and Barwon rivers meet. It flows into the Murray at the border of New South Wales and Victoria, and the Murray eventually reaches the sea just to the south-east of Adelaide. The Basin includes most of New South Wales (NSW), some of southern Queensland (QLD), the east of South Australia (SA), northern Victoria (VIC) and all the Australian Capital Territory (ACT).

The Basin is divided into two parts. Water in the northern Basin runs into the Darling River and water in the southern Basin runs into the River Murray. The Coorong estuary, Lower Lakes and Murray Mouth (CLLMM) region comprise Ramsar-listed ecosystems that support ecological, cultural and socio-economic values and is highly vulnerable to hydrological alteration, being at the end of the MDB system.

Active management of the Basin is required to protect its ecosystems, ensuring water is available for future generations. This is coupled with a need to respond to and protect economic, cultural and social aspects of the Basin. As more water has been diverted from the environment since European colonisation, the rivers in the Basin have become less healthy, especially during droughts. Reduced river flow has resulted in more salt in the Basin's rivers, and increased outbreaks of cyanobacteria ('blue-green algae'). When water levels drop, acid-sulphate soils are exposed and blackwater events occur more frequently. There are now fewer native fish, birds and mammals in the Basin than there were before Europeans arrived. At least 20 mammal species have become extinct, and conservation is needed for about half of the Basin's fish species.

2.2 The Use and Development of the Murray-Darling Basin to 2023 - The History

The Indigenous inhabitants living along the MDB traditionally depended on it for their welfare. They harnessed it with fish traps to contribute up to 40 % of the protein in their diets. They have managed the surrounding areas with selective fire management to provide surety of plant and animal resources while living within the capacity of the natural environment.

Since European settlement, the evolution of processes to manage the water resources of the Basin have had a long and chequered history, described in detail by Guest (2017) from which much of this summary has been derived. Guest's account highlights the importance of achieving consensus on political as well as economic and environmental issues.

Captain Charles Sturt came upon the River Murray, named it after Sir George Murray, the UK Secretary of State for the Colonies, and navigated down the river to Lake Alexandrina and its mouth. As an unregulated river with a highly variable flow to the sea, its average annual flow has been estimated to have been 16,000 GL, about two-thirds of the water received by the Basin.

SA was the first colony to use the river, developing it for navigation. By 1854, paddle steamers were carting wool from western NSW and VIC and commerce from the Victorian goldfields to Goolwa and Port Elliot in SA, a development looked upon unfavourably in the colonial capitals of Sydney and Melbourne. In due course, railways were built to recapture the trade from the paddle steamers and SA.

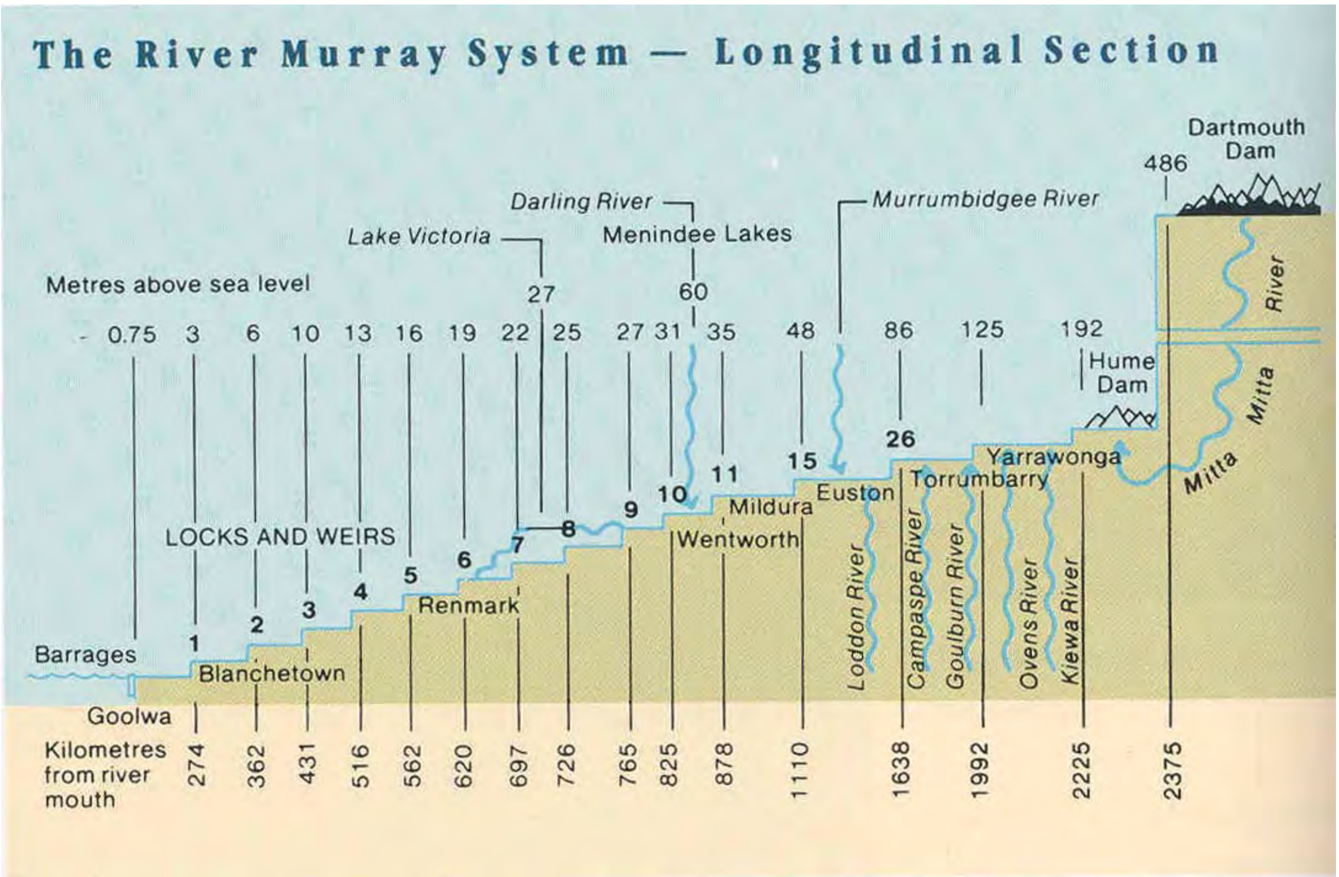
By the 1880s, Victoria was developing an interest in irrigated agriculture but its rights to access the river for water were unclear as the Imperial legislature had put the boundary between NSW and VIC on the southern bank of the river with the result that NSW could claim the water. Periodic conferences and Royal Commissions were instituted between the two States without resolving the issue of their respective water rights for irrigation. The SA colonial government was concerned about increased unreliability of the river for navigation while establishing its downstream riparian water rights, seeking a share of the river water. VIC passed legislation defining water rights as state property, extinguishing British traditional law riparian rights. NSW followed suit. Chaffey Brothers from California secured water rights from the Victorian government in 1886 and developed irrigation land at Mildura (VIC) while also establishing an irrigation settlement at Renmark (SA).

Rights to water became an issue as colonists were developing a constitution for Federation, and in the event, responsibility for water was passed to the newly created States, and control of navigation, in part related to the abolition of colonial customs posts, passed to the Commonwealth. There was provision for a High Court and an interstate commission to adjudicate any unresolved matters. In 1902, a seminal conference with strong irrigator participation and seemingly considerable good will, was held at Corowa, NSW, in sight of the river. The result was a further Royal Commission, jointly established by the three states of NSW, VIC and SA. Principal aims included establishing just water allocations for irrigation and navigation, the provision of water for SA, and the sharing of water for irrigation between VIC and NSW. But negotiations continued for years. By 1915, at the end of the severe 1914 drought, the **River Murray Waters Agreement** was achieved, providing for the construction of a major storage on the Upper Murray, building of Lake Victoria, the construction 26 weirs and locks between Blanchetown and Echuca to ensure navigation, and nine weirs and locks on Murrumbidgee on the Darling Rivers (to be determined by NSW). The **River Murray Commission** comprising water engineers, was established. A Commissioner was appointed by each state and the Commonwealth. The Commonwealth was a financial participant in the works and thereby established a continuing role in the management of the River Murray.

The Hume Dam was built and later expanded, other weirs and locks were completed and the barrages constructed at the Murray mouth to maintain pool level and water quality below Lock 1. By 1934, only 16 of the 35 planned locks had been built; the remainder were abandoned as river navigation was no longer important for commerce and transport. Soldier settlement programs were developed after World War I and World War II. The first of a number of major pipelines for industrial, stock and domestic use was built in 1944 to Whyalla (SA), Several lines were later built to service Adelaide (SA) which became dependent on the River Murray for up to 90% of its water in dry years.

In 1956, the Snowy Mountains scheme commenced to divert the headwaters of the Snowy, Eucumbene and Murrumbidgee Rivers westward through the Great Dividing Range, releasing water into the Murray and Murrumbidgee River for additional irrigation development, electricity generation being a core by-product. But in 1958 the SA Government took out a writ against the Commonwealth, NSW, and VIC over diversion of water in the Snowy Scheme, claiming its water security was at risk. It proposed and had approval to build a dam at Chowilla in SA, creating a reservoir that mostly submerged land in NSW and VIC including the river channel and locks 7, 8 and 9. Later modelling showed that the scheme could not provide salinity dilution flows, it would displace saline ground water into the river and its water would become extremely saline in dry years due to its shallowness. The scheme was abandoned and replaced by building the 4,000 GL Dartmouth dam on the Mitta Mitta River, with SA given an increase in its water entitlement from 1,547 GL to 1,850 GL. The River Murray infrastructure was thus completed as in Figure 1.

Figure 1. Longitudinal Section of the River Murray showing structures, altitudes and distances from the Murray mouth to the Dartmouth Dam. (MDBC 2003).



Concern about rising salinity in the River Murray had been raised from the mid-1960s. Broader environmental awareness was generated during the building of Dartmouth Dam. A meeting of

Ministers held in Adelaide in September 1985 resulted in the evolution of a **Murray-Darling Basin Ministerial Council** involving water, environment and agriculture portfolio Ministers from each of the Commonwealth and Basin states. This led to the creation of the **Murray-Darling Basin Commission** with a remit to deal with land as well as water resources issues. There were two Commissioners appointed from each state chosen with skills across the three portfolio areas at the states' discretion. The new Commission initiated research programs, which underpinned its **Natural Resources Strategy** and its **Salinity Management Strategy**. The latter led to construction and operation of salt interception schemes in SA to offset rising river salinity attributed to poor irrigation management and rising water tables in the upstream states and the consequent diversion of saline drainage water into the river. A further concern was the impact of dryland salinity from land clearing. With awareness of major corporate capital investment occurring in the northern Basin, QLD was invited to join the Ministerial Council and Commission, followed by the ACT which depended on the Murrumbidgee for its water supply.

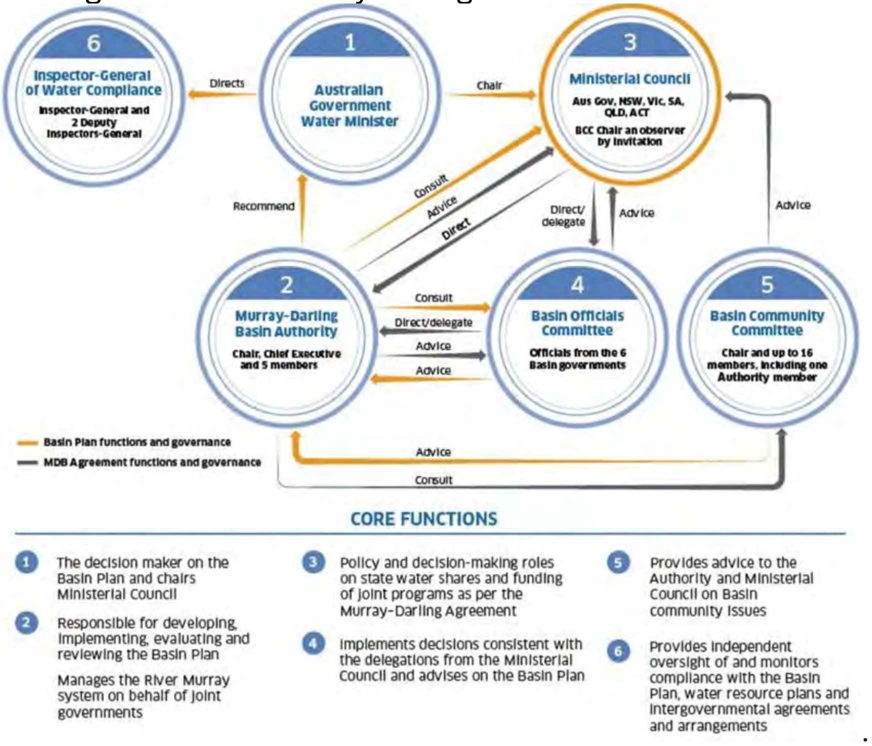
The **1994 Water Reform Agenda** agreed by the Council of Australian Governments separated ownership of land from rights to water which both became independently saleable. In **1995**, a cap was placed on Murray-Darling irrigation, limiting diversions to the volume of water that would have been taken under 1993/94 levels of development. The cap sought to strike a balance between the amount of water available to irrigators, the security of their water supply, and the environment. The 2004 Intergovernmental Agreement on **the National Water Initiative** further defined water entitlements and allocations, increasing water trading opportunities and for the first time also acknowledged aboriginal interests in water. It also recognised the dire state of native fish populations and initiated a Native Fish Strategy that ran from 2003 to 2013 (MDBC 2004)

The year 2002 saw commitment to **The Living Murray** program, which provided recognised environmental flows in the river to maintain river health. The Murray Mouth had first closed to the sea in 1980 and had been regularly dredged to keep it open from the 1990s. The Millennium drought had become so serious by 2006 that concern was being expressed about the future of the Basin. Thinking progressively evolved towards the Commonwealth taking over responsibility for the Basin's water management. After considerable debate among the States and the Commonwealth, the States agreed to refer their powers for Basin water to the Commonwealth and following the passage of The Water Act 2007 and subsequent amendments, the **Murray-Darling Basin Authority** (MDBA), evolved. The chair, an indigenous member and four part-time members are appointed upon advice by the Governor-General. The Authority assumed the roles of the Murray-Darling Basin Commission and its responsibility for previous Murray Waters Agreements. The Authority responds to a new **Murray-Darling Ministerial Council** comprised of Commonwealth and states' Water Ministers. The Ministerial Council advises the Commonwealth Water Minister, who is the final decision maker. The Authority was to develop a Basin-wide strategic plan with sustainable limits on taking surface water and ground water at the level of individual catchments. Water quality objectives, water for essential human needs, trading rules, compliance, standards for catchment plans and managing environmental water were developed. The States remained responsible for **Water Resource Plans** and seasonal allocations.

In 2010, the Authority released the **Guide to the proposed Basin Plan**: Overview - prepared for public consultation purposes, using its best efforts to ensure that the material it presented was current and accurate. The opinions, comments and analysis (including those of third parties) expressed in the document were stated to be for consultation purposes only. The document "*did not indicate the Murray-Darling Basin Authority's commitment to undertake or implement a particular course of action and was not to be relied on in relation to any particular action or decision taken in respect of the proposed Basin Plan*". Unfortunately, it was not well received, being assumed by many to be the Plan being adopted. In one location, copies were spectacularly burnt for media attention. A subsequent broad community consultation process was undertaken, following which, after further States' consultation, a final Plan was accepted by the

Commonwealth, adopted with bi-partisan support and forms part of *The Water Act 2007* as amended.

The detailed plan is accessible at https://www.legislation.gov.au/F2012L02240/latest/text (accessed 23 February 2024). Broadly speaking, it seeks to remove 2,750 GL of water from irrigated agriculture, and return that to the river system, through a mix of government purchases of water licences, and taxpayer-funded infrastructure improvements. The States were to finalise a list of major infrastructure projects designed to deliver environmental water more effectively and efficiently in the southern end of the Basin. It was agreed that 605 GL of the environmental water target would be met through 37 infrastructure projects in VIC, SA and NSW, instead of through further water buybacks. In addition, it was proposed that an 'adjustment mechanism' be explored to deliver an additional 450 GL of environmental water on top of the Plan's 2,750 GL target. Meanwhile, to strengthen regulatory functions, the Commonwealth created and appointed a statutory position of **Inspector-General of Water Compliance** from 2019, located within the Department of Climate Change, Energy, Environment and Water, independent of the MDBA. The structure for the management of the Murray-Darling Basin as at March 2024 is shown in Figure 2.



1. The decision maker on the Basin Plan and chairs Ministerial Council
2. Responsible for developing, implementing, evaluating and reviewing the Basin Plan
   Manages the River Murray system on behalf of joint governments
3. Policy and decision-making roles on state water shares and funding of joint programs as per the Murray-Darling Agreement
4. Implements decisions consistent with the delegations from the Ministerial Council and advises on the Basin Plan
5. Provides advice to the Authority and Ministerial Council on Basin community issues
6. Provides independent oversight of and monitors compliance with the Basin Plan, water resource plans and intergovernmental agreements and arrangements

Figure 2. Structure for managing the Marray Darling Basin and the Plan, March 2024 (MDBA 2024)

The **Murray-Darling Basin Plan** was due for completion by 2024 and for review in 2026 (MDBA 2024). However, it had become apparent that the current Plan will not be achievable by 2024. **Water Resource Plans (WRPs)** are an integral part of implementing the Basin Plan. WRPs in VIC, QLD, SA and the ACT are accredited and in operation. A significant concern for the Authority was the continued slow pace at which it has been able to assess and accredit NSW WRPs. Very little progress has been made in achieving the 450 GL/y target for water efficiency measures, with only 12.2 GL/y, or less than 3%, recovered since 2018, with a further 13.8 GL/y contracted for delivery by 30 June 2024. Little of the 450 GL to be retrieved through water-efficiency projects, will be recovered. As of November 2023, the offset projects were anticipated to deliver between 290 and 415 GL of the 605 GL required. Very little water was getting to floodplains. This means, of the 3,200 GL of water a year to be returned to the environment, only 2,100 GL is likely to be achieved (Pittock 2023). In July 2023, the MDBA advised the Commonwealth Minister of Water Resources that the implementation of the package of supply measures notified by Basin Governments will not deliver the volumetric or environmental outcomes set by the Plan by 30 June 2024 (MDBA 2023).

Following agreement by the Commonwealth and Basin States (except Victoria) on 22 August 2023, a Bill was introduced into Federal Parliament, debated and passed, resulting in the **Water Amendment (Restoring Our Rivers) Act 2023** *(C'wealth).* Its implementation provisions commenced from 8 December 2023. This Act amended the Water Act 2007 and the Basin Plan 2012 to broaden the scope for water efficiency projects. It extends the timeframes so that states can deliver infrastructure projects to meet the 605 GL environmental water target. It provides more flexibility, more tools, and more time to meet the 450 GL target and extends time frames from June 2026 to December 2027. It also sets the rules for water resource plans, which ensure that basin states stay within their sustainable diversion limits. The Act repeals the existing limit on the Commonwealth's water access entitlements purchases which must now meet enhanced environmental outcomes while demonstrating that the purchase is value for money. The Act also seeks to implement some recommended water market reforms and giving enhanced powers to the Inspector General for Water Compliance, who will have an expanded role as data regulator. The Bureau of Meteorology becomes responsible for the development of water market data standards and the collection and sharing of information received from water market data providers. The Act also seeks to improve outcomes for First Nations people, by including a new object "to ensure that the use and management of basin water resources takes into account spiritual, cultural, environmental, social, and economic matters relevant to indigenous peoples, including in relation to their knowledge, values, uses, traditions and customs", provides support to the 40-plus First Nations across the basin to develop cultural flow planning and look at their cultural economies, increase Aboriginal ownership of water entitlements, adds another First Nations representative to the Murray-Darling Basin Authority Board, while also recognizing some of the terminology from the United Nations Direct Declaration on the rights of Indigenous people (DCCEEW 2023).

The provisions of the new legislation go some way to wards addressing issues raised in the following essays. The challenge for the review of the Plan, now extended to 2027, will be to develop a long-term view of what the nation seeks to achieve. This work seeks to assist in that challenge.

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2.3 The Challenges

The Academy's 1989 Symposium strongly supported the introduction of an integrated approach by the Commonwealth and the Basin States towards the adopted Natural Resource Management Strategy. It recommended increased research investment into groundwater, and wetland resources and the conservation of areas of sufficient size with linking corridors to represent the principal Basin ecosystems. Effective communication and the transfer of knowledge from research to practice was highlighted. The symposium recommended high priority to implementing the Basin's Salinity Strategy, an area where considerable progress has since been made. It also recommended extending the then existing system for collecting data on the climate of the Basin and to give particular attention to developing models to predict climate change, a circumstance not provided for in the original 2012 MDB Plan, but which forms the basis of the 50-year horizon view sought from these essays.

The Challenges section draws from across the suite of essays and presents an overview of key challenges. Specific cross-reference to each essay is not provided as much was commonly themed.

The Basin Plan has formidable challenges in achieving any successful implementation of management and other governance and stakeholder engagement. Significantly, it will require adjustment to respond to the impacts of climate change and enable a fair distribution of water between the four Basin States and the ACT. Fair distribution needs to consider balancing outcomes for the environment, industry and communities. The Basin Plan may need to be supplemented with a suite of other actions that can help recover ecological assets and build their resilience to withstand the climate changes.

A 50-year future is impacted predominantly by climate change including warmer temperatures, droughts, floods, severe weather systems and events, and less predictable climate scenarios. This directly impacts *water quantity* characteristics (flow regimes, water levels, availability and scarcity, surface water, groundwater) and *water quality* attributes (salinity, nutrients, dissolved oxygen, sediment, turbidity, metals, toxins, temperature).

Combined, water quantity and water quality climate change outcomes may result in catastrophic impacts including fish kills, cyanobacterial and algal blooms, blackwater events, unsafe drinking water, loss of water availability, damaged and failed infrastructure, terrestrial and aquatic ecosystem failure, species extinctions, and loss of communities and industries. For example, major cyanobacterial blooms have increased in their occurrence, frequency, duration and extent from two in the 1980s and 1990s, to eight in the following 20 years.

In addition to climate change, a 50-year horizon is also challenged by economic, community, environmental, and cultural pressures. Many of these are related to government policy, private sector investment, community-driven aspirations and expectations, equitable water and land rights including distribution to First Nation groups, water licensing and water trading, macro and microeconomics, population demographic shifts, regionalisation policies, social divides, mining and industrial movements and mental health challenges.

These overarching facets can act in concert or competition, conflict or cooperation to generate the resultant outcomes across the Basin in 50 years' time. The suite of essays presented here seeks to invoke data-driven inputs towards decisive *calls to action* to respond, rather than react, in a positive and informed manner to set, implement, monitor and adapt these actions, providing the best opportunities for positive outcomes for the Basin.

Climate change is affecting the hydrological characteristics of the MDB. The future will be warmer with more severe and long-term droughts, more severe floods and more extreme weather events. Temperatures are observably rising in daytime and night-time profiles and there is a marked increase in the frequency of hot years. The Basin has warmed by one degree since 1910 and the warming is expected to continue. Rainfall has shown large interannual to multi-decadal variability affected by the arid and semi-arid nature of much of the Basin. The Basin has experienced several severe droughts of long duration, as well as short-term severe floods. Basin-wide runoff is expected to reduce by 9% by 2030 and 23% by 2070 under a future impacted by climate change, as well as plausibly shifting where it is generated from.

Ongoing worsening social and economic outcomes for regional, rural and remote communities in the Basin could continue. These may be an outcome of water management decisions however it is highly complex to untangle the cause and effect. Trade restrictions, local-to-global supply and demand, transformation of mining and economies of scale are altering the Basin outcomes. There is a risk of inadequate recognition made or examined between environmental water allocation, community redress and the Basin Plan, with climate change adaptation likely to exacerbate this situation.

Agriculture and other industries will remain a fundamental fabric of the Basin and will continue to require water, though they will continually be adjusting in response to new technologies and changed market opportunities and demands. These sectors are seeking to drive economic productivity and to be more sustainable in the 50-year horizon. At the same time, it is plausible that the demand for water will increase given the economic and social need of the Basin. Natural streamflow regimes have significantly altered since European settlement with 24 of its 26 major catchments being modified by infrastructure such as dams, weirs and barrages. There are over 5,000 instream barriers in the MDB which disrupt ecological connectivity such as the movements of fishes. Total water held in storage is over 75% of the historical mean annual streamflow meaning that the engineered impact is very significant. Coal seam gas and coal mining are industries going through substantial change from internal and external forces, and directly impact water resources. They can have both an acute and chronic impact on water flow and quality, depending on management approaches.

The state of soil-landscape ecosystems across the Basin have significantly declined since European settlement. Soil-landscape ecosystems are closely linked to other natural features such as climate, vegetation, geology, hydrology, water availability, and overall ecosystem services and are therefore useful for assessing a 50 year future. Eight adaptive soil-landscape management recommendations are presented based on two scenarios – namely a drying scenario and wetting scenario as soil-landscapes behave differently under each regime. The most significant impacts on soil-landscapes from these two scenarios include acid sulphate soil production, salt leaching and salt concentration, organic matter distribution, production of sodic and saline soils, soil erosion and bank slumping and soil compaction.

Soil-landscapes are substantially impacted by overgrazing, drying and drought, wetting and floods as well as infrastructure related disturbance. To achieve the goal of best “sustainable soil-landscape management” for the MDB in 50 years, we need an integrated approach to implement a seasonal wetting and drying regime to the river and adjacent wetland regulation, which will substantially reduce the many risks related to the prolonged drying and subsequent rewetting, which can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

The ongoing impact of river regulation, along with climate change predictions are expected to continue to degrade ecological outcomes. Reduced availability of water of the appropriate flow regime to support ecosystems impacts not only the environment, but also communities, economic and cultural values. Some of the worst water quality conditions of high salinity, cyanobacterial blooms and elevated nutrient levels occur when River Murray inflows are hampered and lead to catastrophic outcomes for the environment. This may be particularly evident for the Coorong, Lower Lakes and Murray Mouth. The barrages at the downstream end of Lake Alexandrina control the separation of freshwater from estuarine water. They incorporate over 500 individual gates along 7 km and are mostly manually operated. At the same time, climate change will cause sea level rises, which will further stress the barrage system.

Historically, the system would have been more dynamic with higher river inflows and a more extensive connected estuarine reach. The engineered management of the system in this region now operates more as a separation of a dominantly ‘freshwater lake’ from a hard-set change to the estuarine zone. Modelling indicates that the proportion of years with barrage flow exceeding 10,000 GL had fallen from 53% prior to development, to 11 % by 2009. Under the Basin Plan, the proportion is expected to increase to 19% of years. Thus, the Basin Plan is expected to have a positive impact in generating outflows at the Murray Mouth but will still fall significantly short of pre-development outflow conditions.

Essential outcomes of a 50-year vision, providing a sustainable response to climate change for the Basin include:

- A healthy environment, with greater surface flows, stable groundwater reserves, and water flow regimes that support aquatic and terrestrial ecosystems with high quality water.
- Vibrant and resilient regional, rural and remote communities with sustainable economic futures and improved mental health outcomes including a skilled and thriving workforce.
- Indigenous self-determination and engagement, including for cultural water.
- Sufficient water of the right quality allocated to sustain a variety of industries, enabling regional transition, where required, for productive profitable outcomes.
- Reducing the irrigated land footprint and improving sustainable irrigation practices whilst securing domestic food production.
- Technology transformation, innovation and adaptation, infrastructure and automation, for responsive water allocation.
- Producing more from less land, less water and less intensive infrastructure.
- Addressing the Sustainable Development Goals (SDGs) and applying an Environment, Social Governance (ESG) Framework.

A 50-year vision for the Basin that considers and transparently addresses each of these aspects is fundamental to securing a resilient and sustainable future that generates positive legacy for the environment, future generations, ongoing uses and users of the Basin’s natural, physical, social and cultural assets. Based on this future vision, suggestions for which are encompassed in the following essays, we can then take stock and agree actions to be taken now, soon and in the future to secure this vision.

2.4 The Principles for adaptation

The essays support the need for the following principles to be harnessed as we approach the future management of the Basin.

Consult	Consolidate and make transparent stakeholder and community consultation processes for Murray-Darling Basin Plans, its governance and any reviews. Start by harmonising definitions in legislation in accordance with the National Water Initiative. Include all uses and users such as consumptive, productive, environmental, recreational, cultural, community, industrial.
Monitor	Prioritise the development and implementation of water monitoring using digital technologies to provide timely and consistent volumetric water quantity and water quality monitoring data across Basin states, stakeholders and institutions. Monitor and measure groundwater:surface water connectivity. A single source of data truth that is publicly available.
Model	Centralise, inter-stakeholder and publicly available modelling of Basin attributes including: surface water:groundwater interactions; flow regimes; water quality for various time-series and time-scales; climate change scenarios; uses and users. A single source of risk-based modelled attributes, impacts and outcomes.
Assess	Assess and review impacts including Basin vegetation; fire regimes; aquatic and terrestrial species and geographic range; water chemistry; flow regimes; engineered infrastructure; management actions; population and demographic changes; industry changes. Include sensitivity analysis in the assessment.
Recover water	Use water buybacks as the primary short-term mechanism to deliver the water recovery target component of the Basin Plan. Implement a data-driven hierarchy of water recovery mechanisms (voluntary, strategic or enforced buybacks, on-farm and off-farm modernisation, engineered infrastructure and operation, technology, water pricing and value). Establish Basin-wide criteria and methods to calculate the value of water recovery mechanisms. Deploy the right mechanism in the right part of the Basin for flexible adaptive engineered infrastructure, including the barrages.
Plan	Via the Basin Plan, assign standardised terms and definitions; set minimum flow thresholds for water quantity and water quality targets across time-series and time-scales at ecosystem appropriate geospatial increments. Embed and apply quantified targets. Develop, evaluate and implement comprehensive water quantity and water quality management strategies for Basin futures. Reform water trading and water market mechanisms (consider role of digital technologies). Setting water allocations (sustainable diversion limits), mindful of climate change scenarios, that consider the environment and a sustainable future of the Basin, however being cognisant of regional and rural economics and communities. Connect the Basin Plan intrinsically to socio-economic factors including loss of farmers, regionalisation agenda's, town demise.
Review and improve	Monitor, report and independently assess compliance to the Basin Plan and SMART metrics. Conduct Sustainable River Audits across the Basin at the right time-scale and geospatial increment to inform data-driven decision making. Audit grants, programs and infrastructure investments for impact and outcome value. Enforce in a timely manner.
Resource	Provide bi-partisan secured appropriate level of resourcing including the right people with the right skills; monitoring and modelling capacity and capability; infrastructure; capital and operating finances.
Accept	Ensure community awareness and participation in the development and publication of holistic Integrated Basin Strategies with water to be at their heart. System understanding and system driven actions to be central to investments and policies, with timely and sensitive consideration of current land management, industry, demography, community and social attribute changes, leading to bi-political national agreements.
Commit	Ensure ongoing independent risk-based review and adaptation on a range of time-scales (3, 7, 15 and 50 years) that is bi-partisan, inter-jurisdictional, consulted widely, data-driven and cognisant particularly of climate change. Commit to long-term objectives and implement actions that deliver long-term protections for the Basin.

2.5 Responding to climate change challenges across the MDB

Opportunities that can be gleaned from the essays in response to climate change for the Basin include:

1. Holistic connected interdependent governance that continues, or establishes the following key elements:
    a. Reinstatement of a national body to provide objective unbiased advice on national water management, including MDB issues, independent of Commonwealth and state government departments.
    b. Continue to have a dedicated Commonwealth Minister for Water, which encompasses the MDB, and is under an Environment, not agricultural portfolio.
    c. Continue to maintain the Office of the Inspector-General of Water Compliance. Ensure ability to enforce water theft and water trading offences.
    d. Complete the development and implementation of Water Resource Plans (WRP) and require them to consider long-term interconnected regimes and impacts of groundwater and surface water extractions, as well as dependent ecosystems. Include baseflows and specific rules to enable continual adaptation for climate change, with a requirement for decadal review.
    e. Establish Task Forces with specific objectives and time frames for topical and technical elements. Immediate need is viewed as being water quantity, water quality, cultural water, economic instruments, modelling, satellite and GIS data, water trading and risk assessment.
2. Ensure transparent evidence-based data-driven decision making that includes short, medium and long-term modelling of environmental, economic, social and cultural impacts.
3. Establish, maintain and resource a central data custodian for all water quantity and water quality monitoring data, all modelling and all other relevant data inputs (such as satellite imagery, weather) for driving decision making. Must be publicly available and shared by all stakeholders.
4. Establish, maintain and resource a single central public domain for all consultation, knowledge sharing, information and listing of all funded projects and programs, no matter the jurisdiction.
5. Establish an independent central Water Markets Agency that operates across the Basin, providing standardised definitions, terms, contracts for water trading as well as monitoring and possibly enforcement.
6. Review institutional arrangements that govern property rights at a Territory, State and Commonwealth level for consistency as well as climate-proofing. Seek to mitigate unequitable benefits from institutional governance, including addressing the cultural water rights of Indigenous Peoples.
7. Evolve the Basin Plan:
    a. Include agreed assessment timeframes to be applied to the estimation of water balances and resource condition indicators.
    b. Require climate change and long-term (50 year) impact modelling for water quality and water quantity.
    c. Include integrated land and water management strategies.
    d. Require consideration and modelling of cumulative effects over use, time and location.
    e. Enhance governance and stakeholder representation to include State, Territory, city, regional, rural and remote communities; Indigenous Peoples; Environmental and ecosystem organisations; Commercial, industrial agricultural, mining and manufacturing interests; Associations, industry bodies, not-for-profit organisations. A method of governance to consider appropriate representative contribution.
    f. Robust risk assessment Framework that is multi-dimensional, interdependent and driven by data, considerate of environmental, economic, community, environment, and cultural impacts.
    g. Include ESG Principles to drive the Framework for adaptation and measurement.

3 The Essays

3.1 Editorial Preface

Readers may be aware of the many thousands of years of oral tradition and religious and cultural practice that connect Aboriginal and Torres Strait Islander[i] people to the Basin and its rivers and groundwater systems. Flows of fresh water and healthy aquifers are central to their lives, and sustainable Aboriginal and Torres Strait Islander peoples' management practices embody their responsibilities to maintaining healthy lands, waters and people[1].

As many as 50 distinct Aboriginal nations are part of the Murray-Darling Basin, including the Barkindji (Paakintji), Barunggam, Bidjara, Bigambul, Budjiti, Barapa Barapa, Barkindji, Dhudhuroa, Dja Dja Wurrung, Euahlayi, , Githabul, Gunggari, Gwamu (Kooma), Jarowair, Kambuwal, Kamilaroi (Gomeroi, Gamilaroi), Kunja, Kwiambul, Latji Latji, Maljangapa, Mandandanji, Mardigan, Murrawarri, Maraura, Mutti Mutti, Nari Nari, Ngarrindjeri, Ngemba, Ngiyampaa, Ngintait, Nyeri Nyeri, Tatti Tatti, Taungurung, Wadi Wadi,Wailwan, Wakka Wakka, Wamba Wamba, Waywurru, Wegi Wegi, Wergaia, Wiradjuri, Wolgalu, Wotjobaluk, Yaitmathang, Yita Yita, and Yorta Yorta[2]. The river systems are central to the creation and identity of these peoples[3]. In 2004, about 70,000 Aboriginal and Torres Strait Islander people resided in the Basin, representing 15% of the national population of Aboriginal and Torres Strait Islander peoples and 5.4% of the Basin community[4,5].

Land occupancy and custodianship represented very important responsibilities for these peoples in managing the environment with group or joint rights collectively regulating access to Country[2]. Following the British arrival, taking over and claiming sovereignty over Australia, Aboriginal and Torres Strait Islander peoples were displaced, some being massacred, and their communities lost access to their traditional Country and, by some implications, their further rights to be humans. Aboriginal and Torres Strait Islander peoples also lost access to their vital wetlands, groundwater systems and riverbanks, with the building of European settlements and broad scale fenced grazing lands[6]. Their traditional rights and responsibilities to land were ignored by a lands title system introduced by the early colonists and subsequent Australian governments. More recently, up to 33% of the Basin has been subject to Native Title Claim, but less than 1% of the Basin is owned by Aboriginal and Torres Strait Islander people, largely purchased through the Commonwealth Indigenous Land and Sea Corporation. Most of this land is without rights to water[7].

Australia's water policies, including Murray Waters Agreements, did not take into account Aboriginal and Torres Strait Islander peoples' interests until the *2004 Intergovernmental Agreement on the National Water Initiative.* This oriented national water policy to include environmental, cultural, and social concerns of Aboriginal and Torres Strait Islander peoples and their communities, although these concerns were positioned within a "market environmentalism"[8]. Only 0.08% of the Basin's Sustainable Diversion Limit entitlements is in the hands of Aboriginal and Torres Strait Islander organisations[7]. Aboriginal and Torres Strait Islander peoples and their communities are concerned that there has been no material increase in water allocation for their social, economic, or cultural purpose[9]. Their peoples' values and aspirations will not be met by increased water allocations for the environment, their needs are completely different. A review conducted between 2009-2018 across the NSW MDB, established that the Indigenous Population was 5.4% within the MDB, and they held <1% Land Ownership. The water data found that 55 entitlements across 25 Aboriginal organisations were held, representing 0.2% of Surface water entitlements and 0.022% groundwater entitlements in the MDB.

These entitlements equated to 0.1% of the dollar value of total MDB water. A disturbing finding was that there was a 17% decrease over 10 years in the 0.2% of water ownership.[10]

There has been limited recognition of the need for Aboriginal and Torres Strait Islander participation in decision-making, initially for example with regard to grave sites in the creation of Lake Victoria; followed by the subsequent creation of a formal Indigenous MDBC Community Advisory Committee from 1996; a MDBC MOU with the Murray Lower Darling Rivers Indigenous Nations (MLDRIN) which was established in 1998; and the development of an Indigenous Action Plan, and the Living Murray Indigenous Partnerships Programme with local participation[11]. Aboriginal and Torres Strait Islander peoples are to be invited to provide advice to the Commonwealth Environmental Water Holder when determining environmental flows[2]. *The Water Act 2007* provided for two Indigenous participants in a 17 member Basin Consultative Committee with the most recent Chairperson being Kamilaroi[12]. A former MLDRIN chair has been appointed to the MDBA Board[13].The MDBA also supported the Northern Basin Aboriginal Nations (NBAN) until 2022[14].

Aboriginal and Torres Strait Islander peoples seek additional empowerment. Examples achieved include the *Aboriginal Land Rights Act (NSW) 1973*, and the *Native Title Act 1993 (C'wealth*) which included water bodies within its definition of native title. The *Echuca Declaration*, developed by MLDRIN in 2007 and endorsed by NBAN in 2020, sought to assert sovereignty over traditional lands and resources. The concept of cultural flows was advanced through the *Declaration*, which states:

> *"Cultural Flows" are water entitlements that are legally and beneficially owned by the Indigenous Nations of a sufficient and adequate quantity and quality to improve the spiritual, cultural, environmental, social and economic conditions of those Indigenous Nations. This is our inherent right*[15].

Such cultural flows would provide the capacity of Aboriginal and Torres Strait Islander peoples and their communities to develop economies built on water entitlements that have the same rules and rights as other water users. Aboriginal and Torres Strait Islander peoples in the Basin are looking for greater responsibility for governance of their traditional resources, and that may well require agreements or treaties with Federal, State or Territory governments, the latter in the case of Water Resource Plans (WRPs). Some of these plans are still not yet approved[16]. Some of the WRPs already accredited do not contain or give regard as required in the Basin Plan, to "Indigenous Values, Uses, Objectives and Outcomes of relevant Indigenous Nations". These WRP's include Border Rivers Alluvium, Porous Rock and Fractured Rock. The MDBA overturned the assessment and advice of Indigenous groups' objections by requesting the Federal Minister accredit the plans, which the Federal Minister has done.

Aboriginal and Torres Strait Islander peoples have an expectation of water justice based on Australia's 2009 commitment to the UN Declaration on the Rights of Indigenous Peoples[17]. The work of the Ngarrindjeri Regional Authority in South Australia with the South Australian government provides an example of a successful First Nation led approach to Basin environmental and water management[18]. There is also an anticipation of greater environmental management roles flowing from native title settlements[19].

Well within a 50-year horizon, Basin Aboriginal and Torres Strait Islander peoples will wish to see their demand for cultural water accepted[20]. But they also seek recognition as responsible political entities rather than cultural interest groups[21]. The Federal Government in November 2018 sought to change the ownership of water entitlements by Aboriginal and Torres Strait Islander peoples in

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i – While various collective terms for Aboriginal and Torres Strait Islander people are in common use, the authors have decided to use the phrase *Aboriginal and Torres Strait Islander people* in full wherever appropriate.

the Basin and committed $40 million for purchasing water from the market. These funds were to be shared across nearly 50 Aboriginal Nations of the Basin. At the time of preparing this preface, the funding has been through three different federal departments, Department of Agriculture, Water and the Environment (DAWE), National Indigenous Australians Agency (NIAA) and Department of Climate Change, Energy, the Environment and Water (DCCEEW) but no funds have yet been spent or governance models established. Though the Ngarrindjeri Regional Authority is a successful example of exercising sovereign responsibilities with the support of a non-indigenous government, there is a long way yet to go to achieve their practical exercise of *de facto* Indigenous sovereignty—irrespective of a constitutional recognition of *de jure* Indigenous sovereignty by a non-Indigenous system of law[21].

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MURRAY-DARLING BASIN ESSAY
Essay #1 in a series of nine by Australia's leading water experts

Hydroclimate of the Murray-Darling Basin

Lu Zhang, Francis Chiew and Tom Hatton

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Above: Aerial view of the Murray River around Mildura.
fotofritz16, iStock.

EXECUTIVE SUMMARY

Zhang et al. advocate to develop a long-term hydroclimate management policy that best adapts to the climate change of the next 50 years by minimising the impact on the hydrological characteristics of the Basin region. Around 66% of the streamflow is generated from 12% of the Basin's area. Though MDB is typical of an arid inland river basin with low runoff and high evaporation losses, floods and droughts are very common due to very high spatial and temporal streamflow variability. Also, the Basin has warmed by one degree since 1910 and there is a risk of reduced average runoff (9% by 2030 and 23% by 2070). Zhang et al. also point out that there is an urgent need to invest in research to develop new knowledge and technologies for producing highly efficient projected water availability outputs. If implemented, policymakers will be able to develop future-ready action plans for a healthy and sustainable integrated Basin management system.

As climate change is already affecting the streamflow and degrading water quality, it is important to elevate water quality protection activities and management capabilities to meet future long-term water uses.

Hydroclimate of the Murray-Darling Basin

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Abstract

As Australia's most important river basin, the Murray-Darling Basin (MDB) generates about 40% of the nation's agricultural income and supports important ecosystems with international significance. The agricultural water-use in the Basin accounts for two-thirds of the nation's agricultural water consumption and there is now a consensus that urgent actions are required to address the imbalance between consumptive and environmental water-use. The climate of the Basin varies considerably from the north to the south with about 90% of the Basin classified as arid or semi-arid. The hydrology of the Basin is typical of an arid inland river basin with low runoff and high evaporation loss. As a result, the MDB exhibits very high spatial and temporal streamflow variability with floods and droughts being common features.

Climate change is affecting hydrological characteristics of the MDB and impacting on the environment, economic and social development. The future of the MDB will be warmer and is likely to be drier with more severe droughts, yet the demand for water will increase, presenting major challenges for sustainable water resources management in the Basin.

An understanding of the hydroclimate of the MDB is highly important for developing long-term management policy to best adapt to climate change. This essay provides an overview of the hydroclimate of the Basin in terms of the spatial and temporal distribution of key climate variables and the hydrologic characteristics. It also presents the latest projections of future climate and water availability in the next 50 years and highlights the challenges and opportunities for sustainable management of the Basin. This essay is based on review and synthesis of recent literature on climate change impact on water relevant to the MDB.

1. Introduction

The Murray-Darling Basin (MDB) is Australia's most important basin, covering over 1 million km^2, including parts of four states and all of the Australian Capital Territory (ACT). Agriculture is the dominant economic activity, making up around 85% of the total area, and generates around 40% of the gross value of Australian agricultural production. The MDB uses around two-thirds of the nation's agricultural water consumption. The MDB also harbours some of Australia's most important natural assets and supports a diverse array of ecosystems with international significance.

However, the MDB is also one of the most vulnerable basins in the world, subject to the simultaneous risks of climate change, water over-abstraction and pollution. Projections indicate a hotter and drier future, with more frequent drought periods and extreme weather events (CSIRO, 2012; CSIRO and Bureau of Meteorology, 2015; Potter et al., 2016, 2018). These changes in the Basin's climate and hydrology will have a substantial impact on water availability and river flow characteristics in the Basin (Chiew et al., 2017; Zheng et al., 2019, Whetton and Chiew, 2021), and the social, economic, cultural and environmental outcomes sought by the Murray-Darling Basin Plan (Basin Plan).

The Murray-Darling Basin Authority (MDBA) has been assigned the task of developing a high-level plan for the integrated management of water resources across the whole Basin. A main goal of the Basin Plan is to reduce consumptive water use to a more sustainable level through the establishment of sustainable diversion limits (SDLs). Key elements of the Basin Plan include long-term SDLs, basin-wide environmental watering strategy, water quality and salinity management plan, water trading rules, water resources plans, and monitoring and evaluation. At its core, the Basin Plan seeks to achieve a healthy working Basin and balance all interests. The development of the Basin Plan has been controversial with considerable community outrage and there are concerns that climate change has not been adequately addressed in the Basin Plan, leading to significant public discourse about this issue (Pittock et al., 2015, Alexandra 2016, Prosser et al., 2021). However, the Basin Plan is also designed to be adaptable and includes mechanisms for updating as new knowledge becomes available (Slater 2021). Climate change will be a key consideration in the upcoming review and update of the Basin Plan.

The Murray-Darling Basin Sustainable Yields project pioneered the first basin-scale climate change impact on water assessment through the integration of 23 models of the system's sub-catchments (CSIRO, 2008). It projected that water availability is likely to reduce across the entire Basin under climate change with a greater reduction in the south of the Basin. However, the impacts of climate change on water availability are highly uncertain mainly due to uncertainties in the global climate models. More recently, the CSIRO developed a climate risk management framework (Climate Compass) to support risk assessment and adaptation and planning in Commonwealth government agencies (CSIRO, 2018). Climate Compass has been designed to help management agencies to identify, prioritise and develop plans to manage the risks and opportunities merging from climate change by going through three guided cycles: *Scan cycle*, *Strategy cycle*, and *Project cycle*.

In 2019, the MDBA released a discussion paper on likely climate risks, how they may have changed since the development of the Basin Plan, and the risks and challenges to maintaining a healthy Basin (MDBA, 2019). Currently, the MDBA is undertaking an assessment of how vulnerable Basin Plan objectives are to the likely impacts of climate change, guided by the Climate Compass' 'Scan Phase'. The Commonwealth Government has also established the Water and Environment Research Program (WERP) to enhance knowledge for climate change adaptation. These will help to identify opportunities for adaptation and determine how best to direct future resources and investment.

Given recent advances in climate science and its application to water resources management, this essay provides an update on the current state of the hydroclimate in the MDB and projected changes in key hydroclimatic variables and water availability in the next 50 years. Following this Introduction, Section 2 provides a summary of the spatial and temporal distribution of rainfall and potential evaporation across the MDB. Section 3 describes the spatial and temporal distribution of hydrologic characteristics and water availability across the MDB, followed by projected climate change impacts on water availability in the Basin by 2070. Section 5 discusses the challenges and opportunities for adaptive management of the Basin with longer-term objectives and targets.

2. The spatial and temporal distribution of climatic variables across MDB

The climate of the Basin varies considerably with a sub-tropical climate in the north, arid or semi-arid climate in the west and mostly temperate climate in the south, with approximately 90% of the Basin classified as either arid or semi-arid. High variability is also a key feature of MDB's climate as the weather conditions are strongly influenced by many types of weather systems and their complex interactions.

Temperature

Temperature in the Basin has been increasing since 1910 and the warming has occurred in all parts of the Basin. The Basin-wide average increase over the period of 1910 – 2017 was 1.0 $^{\alpha}$C for daily mean temperature, 0.8 $^{\alpha}$C for daily maximum temperature, and 1.3 $^{\alpha}$C for daily minimum temperature (Whetton and Chiew, 2021). The warming has accelerated in recent decades with 2019 being the warmest on record (Fig. 1). Warming has been observed across the Basin for all seasons in daytime and night-time temperatures. There has also been a marked increasing trend in the frequency of hot years and a decreasing trend in cold years (Whetton and Chiew, 2021). Warming can be mostly attributed to anthropogenic climate change (e.g., greenhouse gases) with a little effect of natural external influences (e.g. changes in solar and volcanic aerosols) (Karoly and Braganza, 2005, Lewis et al., 2014).

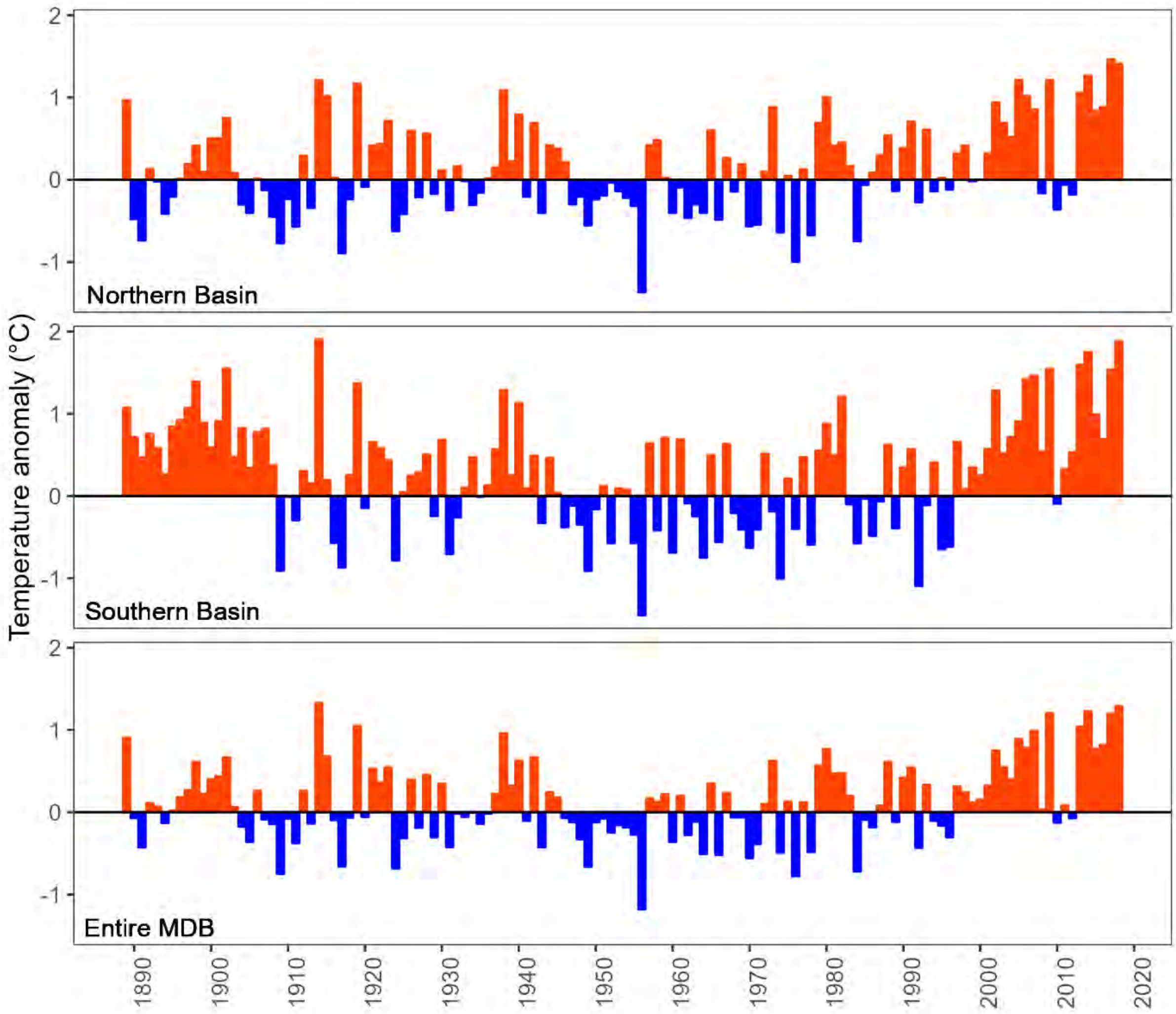

Fig. 1. Annual mean temperature anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Rainfall

Annual rainfall averaged across the Basin is about 467 mm (1889-2018). However, the rainfall exhibits large spatial variation (Fig. 2). The eastern side of the Basin has high average annual rainfall, up to 1,500 mm and in the south, snow falls for several months each winter on the peaks of the Great Dividing Range. The western side of the Basin is typically hot and dry, and average annual rainfall is generally less than 300 mm. Rainfall graduates from summer dominant to winter dominant from north to south. In the northern Basin, rainfall mostly occurs from tropical systems or interactions between tropical and extra-tropical systems (Wright, 1997; Sturman and Tapper, 2005). From December to April, tropical cyclones from the east Australian coast can contribute large rainfall totals to the northern Basin. Rainfall in the southern Basin is mostly extratropical in origin. Cut-off low pressure systems contribute up to 50% of rainfall. Frontal systems also contribute significantly to southern Basin rainfall totals (Pook et al. 2006).

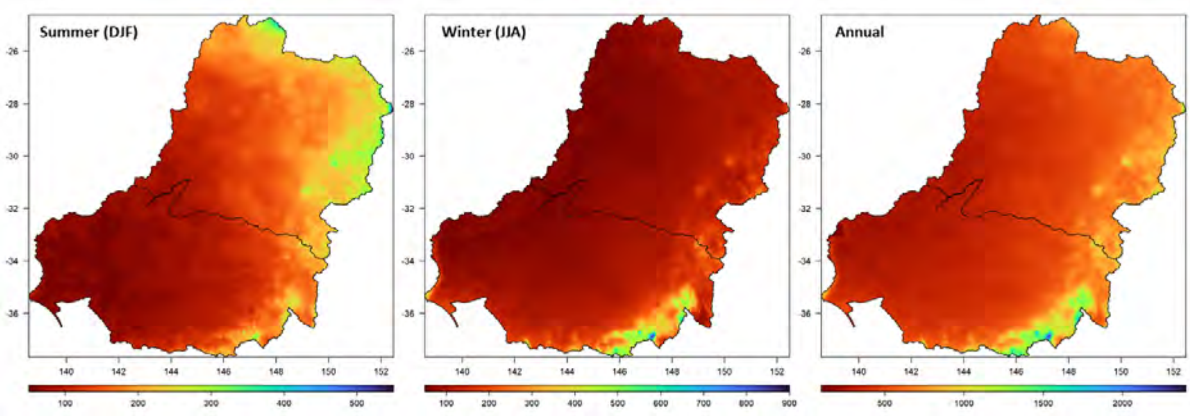

Fig. 2. Spatial patterns of mean annual, summer and winter rainfall in the Murray-Darling Basin (1889-2018) based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Rainfall in the Basin has shown large interannual to multi-decadal variations (Fig. 3). The standard deviation of rainfall is 117 mm and coefficient of variation is 0.25. During the first half of the 20th century, the Basin was relatively dry with rainfall deficits frequently exceeding 100 mm year^{-1} or 20% below long-term average. Over the period of 1900 – 2010, the Basin experienced several dry periods, including the “Federation Drought” (1895-1902), the “World War II Drought” (1937-1945), and the more recent “Millennium Drought” (1997-2010). The Millennium Drought was mainly confined to the southern Basin and was dominated by autumn and early winter rainfall declines stemming from both reductions in the number of rain days and rainfall intensity (Verdon-Kidd and Kiem, 2009). A key feature of the Millennium Drought was the low cool season (April to October) rainfall, which led to unprecedented declines in streamflow in the southern Basin and far south-east Australia as most of the runoff here occurs in winter and early spring (Chiew et al., 2014). This decline in cool season rainfall is evident up to the present (Whetton and Chiew, 2021; DELWP, 2020) and is associated with changes in global-scale circulation. Specifically, the expansion of the Hadley cell (i.e. large-scale atmospheric circulation in the tropics that produces the trade winds, tropical rain-belts and hurricanes) has pushed the cool season rainfall-bearing system further south, a phenomenon which has been partly attributed to anthropogenic global warming (DELWP, 2020; Post et al., 2014; Timbal and Hendon, 2011). As such, this decline in cool season rainfall is likely to persist and possibly intensify in the future.

The Basin has also experienced extreme high rainfall events, resulting in significant flooding and these include the 1956 floods, the 1974 floods, and the 2022 floods. The 1956 flood was the largest flood event in the instrumental record, with major floods in both the Darling River and the Murray River. These flood events significantly impacted properties, businesses and infrastructure in the Basin. Floods are generally more prevalent during La Niña years and negative phases of the Interdecadal Pacific Oscillation (IPO) (Kiem et al., 2003, Johnson et al. 2016).

During La Niña, the Pacific trade winds become stronger intensifying atmospheric circulation across the equatorial Pacific. This causes warm air to rise and increases moisture content and rainfall over much of Australia. La Niña exerts its strongest influence on eastern Australian rainfall during winter and spring. A negative phase of IPO is associated with more frequent La Nina and provides a wet background condition for La Nina. The La Niña conditions developed in the tropical Pacific in September 2020 persisted into 2022, resulting in the first triple-dip La Niña pattern in this century.

The El Niño–Southern Oscillation (ENSO) is the largest single source of interannual rainfall variability in the Basin and is responsible for over 20% of local annual rainfall variations (Nicholls, 1988; Risbey et al., 2009). Seasonal rainfall variations are strongly associated with ENSO events.

Inter-annual variations in Southern Basin winter and spring rainfall are linked to Indian Ocean sea surface temperature anomalies and the Indian Ocean Dipole (IOD). During the positive phase of the IOD associated with cool east and warm west Indian Ocean Sea Surface Temperature (SST) anomalies, low winter rainfall over the southern Basin is likely and vice versa for the opposite phase of IOD (Meyers et al., 2007).

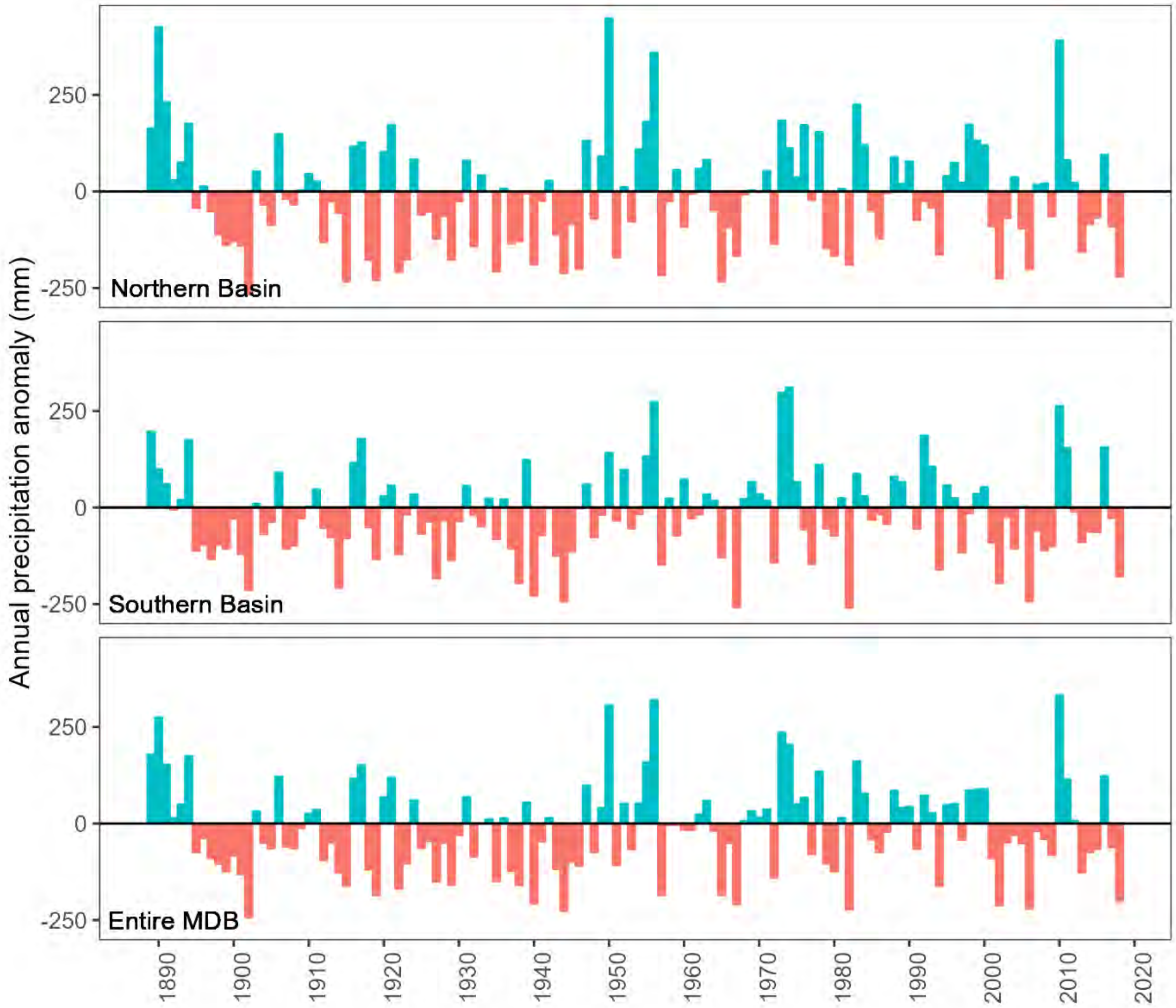

Fig.3. Annual rainfall anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/).

Potential evaporation

Potential evaporation represents the maximal rate of evaporation from a homogeneous surface with ample moisture supply (Brutsaert, 1982). Potential evaporation is generally used to estimate actual evaporation and it is a key climatic variable for water resources management. The mean annual potential evaporation averaged over the Basin is 1,443 mm with a strong gradient - from 1,700 mm in the north to 1,000 mm in the south (Fig. 4) (CSIRO, 2008). Compared with rainfall, potential evaporation exhibits much smaller interannual variability (Fig. 5). Over the period of 1950 - 2018, potential evaporation showed an increasing trend across the Basin (see Fig. 5). However, pan evaporation measurements, representing potential evaporation, showed a decreasing trend over the period of 1975 – 1994 and an increasing trend in more recent time (1994-2016) (McVicar et al., 2012; Stephens et al.,2018; Ukkola et al., 2019). These trends have been attributed to changes in wind speeds and vapour pressure deficit.

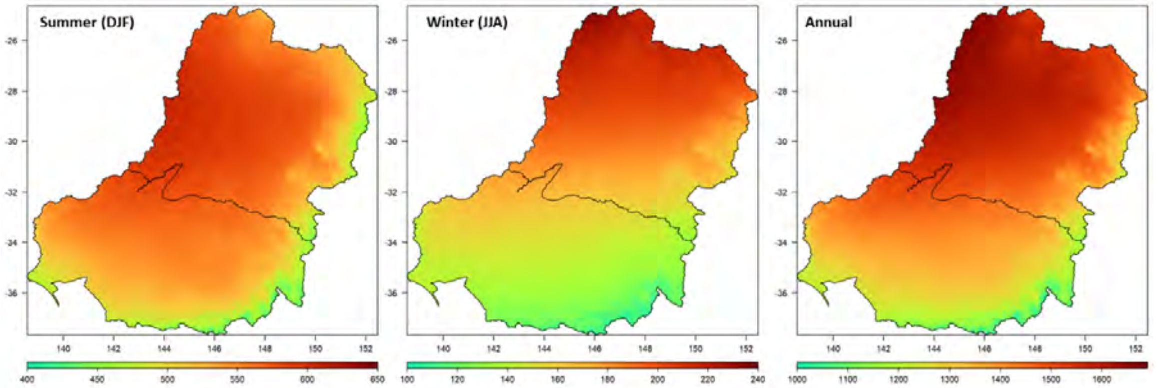

Fig.4. Mean annual potential evaporation in the Murray-Darling Basin (1889-2018) based on the SILO gridded daily climate dataset ([https://www.longpaddock.qld.gov.au/silo/gridded-data/)](https://www.longpaddock.qld.gov.au/silo/gridded-data/).

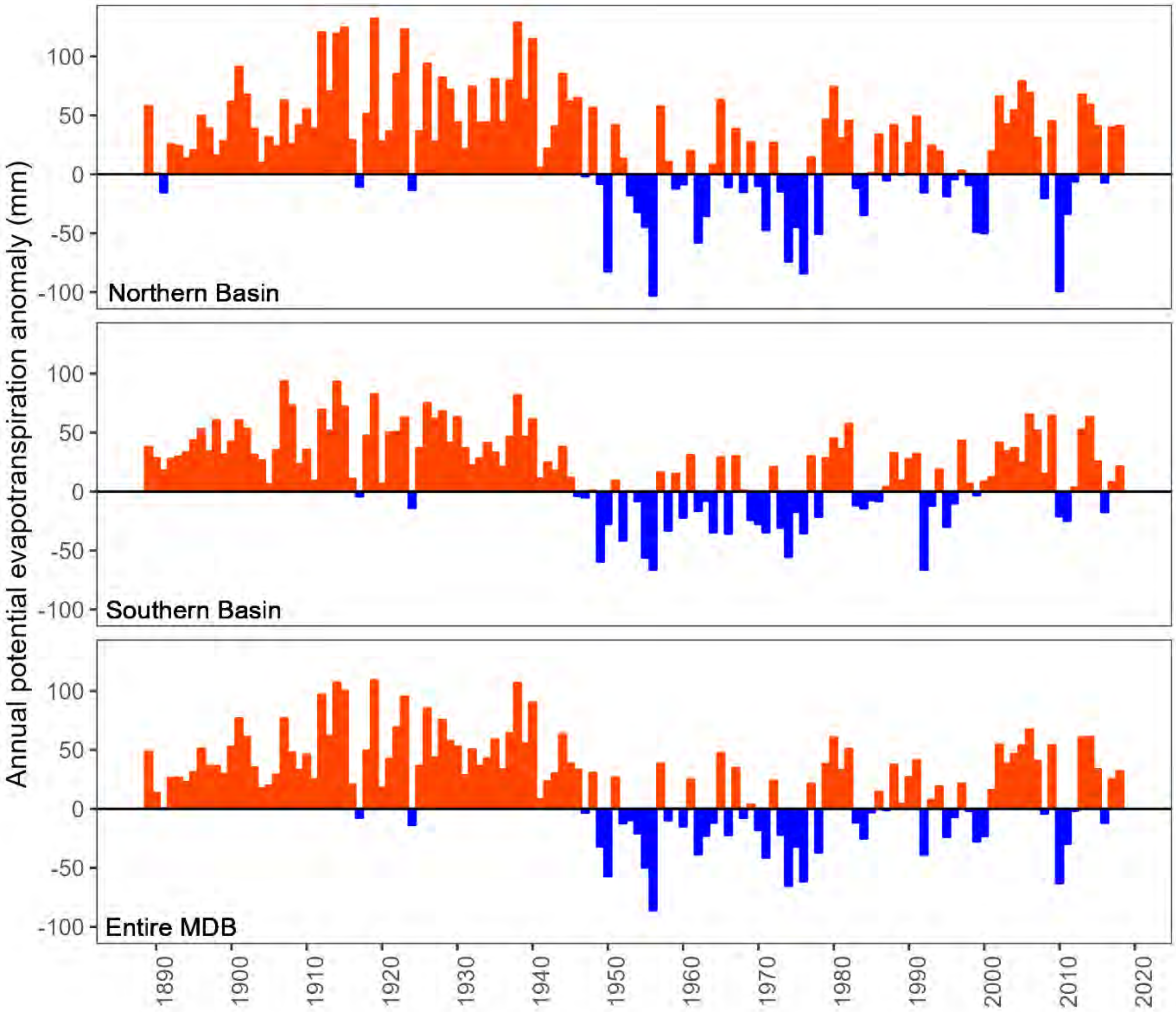

Fig.5. Annual potential evaporation anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on the SILO gridded daily climate dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/)

3. The hydrologic characteristics of the Murray-Darling Basin

The Basin is the most iconic river basin in Australia. It covers a large range of climatic and hydrologic conditions. The hydrology of the Basin is typical of an arid inland river basin with low runoff and high evaporation loss. Despite its arid climate, there are over 30,000 natural wetlands across the MDB including 16 wetlands listed under the Ramsar Convention (see this ATSE essay series on Ramsar Wetlands). The MDB is a complex and interconnected river system. Due to its diverse climate and landscape, and hydrological characteristics, the Basin can be divided into two parts - the northern Basin and the southern Basin (Fig. 6).

The northern Basin includes the Darling River, the Darling Riverine Plain, and the Darling River upstream of Menindee. The northern Basin has a highly variable summer-dominated rainfall regime influenced by monsoonal weather systems. In the Darling system, rivers flow from higher-rainfall areas in the east into more arid regions in the west. The highly variable rainfall means that streamflow in the northern Basin exhibits large seasonal variations with frequent and long periods of very low flows. Hence water availability in the northern Basin is generally less reliable compared with the southern Basin.

The Murray River and its tributaries in the southern Basin flow from the south-eastern highland westward through the dry interior. The rainfall in the southern Basin generally is winter-dominated and the runoff is higher. In particular southern tributaries, including all the Victorian tributaries and the Murrumbidgee River, have their peak flows in the winter period with some minor influences of snowmelt in tributaries draining from the highest elevations of the Great Dividing Range.

Fig.6. Map of the Murray-Darling Basin showing the Northern Basin and Southern Basin. Source: Murray-Darling Basin Authority, https://www.mdba.gov.au/importance-murray-darling-basin/where-basin

As with most inland arid river basins, much of the streamflow in the Basin is generated from temperate headwater catchments on the south-eastern and eastern boundaries of the Basin (CSIRO, 2008). It is estimated that around 66% of the streamflow is generated from 12% of the Basin's area (Fig. 7) (Donohue et al., 2011). Clearly, runoff in the Basin exhibits great spatial variability with the eastern upland headwaters contributing most of the streamflow for low-gradient rivers meandering through arid and semi-arid plains. The northern Basin with summer-dominated flows contributes to high flows in the Darling River. As a result, the MDB shows very high spatial and temporal streamflow variability with floods and droughts being common features.

To reduce risks of extreme floods and droughts, we need better planning to determine future water needs and develop improved flood forecasting systems so that operational responses and water sharing rules can be implemented across the Basin. This has important ecological and water resources management implications.

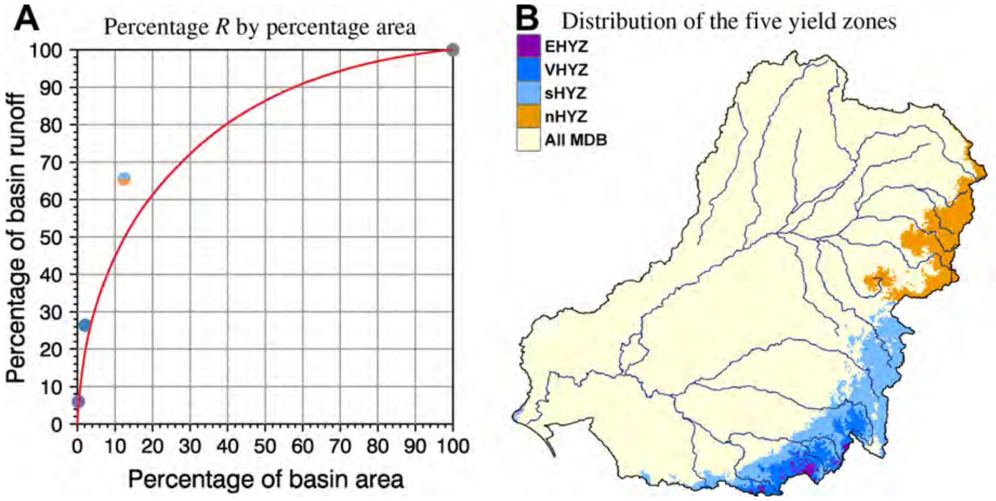

Fig.7. Areal distribution of basin runoff. Plot A shows percentage of basin runoff for a given percentage of basin. The red curve represents values derived by grid cell aggregation. Points represent values for the yield zones calculated using zonal averages. Plot B shows the distribution of the five Murray-Darling Basins Yield Zones: extremely high yield zone (EHYZ), very high yield zone (VHYZ), southern high yield zone (sHYZ), northern high yield zone (nHYZ), and whole Murray Darling Basin (All MDB) (From Donohue et al., 2011).

The MDB is large in area, but small in runoff. Average runoff across the Basin is around 27.3 mm per year, very low compared with other major river basins in the world. The mean annual runoff ranges from less than 10 mm in the west to over 200 mm in the southeast (CSIRO, 2008). Runoff in the Basin also exhibits large temporal variability and is among the most variable in the world (McMahon et al., 2007a, b; Peel et al., 2004; Chiew and McMahon, 2002). Over the period of records, the total streamflow from the Basin varied from 6,740 GL (in 2006) to 117,897 GL (in 1956) (MDB, 2010). As mentioned earlier, the Basin has experienced long multiyear droughts, including the recent Millennium Drought (1997-2010). During the 10-year period (1997-2006), rainfall was up to 20% lower than the long-term average and runoff reduced by over 50% in some parts of the Basin, unprecedented in the historical record (Potter et al., 2010). The cool season (April to October) rainfall has declined since 2001 partly attributed to climate change and resulted in significant reduction in streamflow. This is more evident in the southern basin.

River flows in the Basin exhibit very high interannual variability, where the runoff in a wet year can be more than 20 times greater than a dry year (see Fig. 8). There is also high inter-decadal variability in the rainfall, which is amplified in the runoff, with long wet periods and long dry periods evident in the historical data (see Fig. 8). The interannual variability of streamflow in the Basin is about twice that of basins in similar climate regions elsewhere in the world (Peel et al., 2004). This large streamflow variability is in part due to the arid and semi-arid climate of the Basin and the strong ENSO influence in this region (Chiew and McMahon, 2002). The large variability presents a significant challenge for water resources management, and the strong ENSO-streamflow teleconnection has been used to forecast streamflow several months in advance (Robertson and Wang, 2013; Bennett et al., 2017; Tuteja et al., 2019) potentially helping with the management of this very variable system.

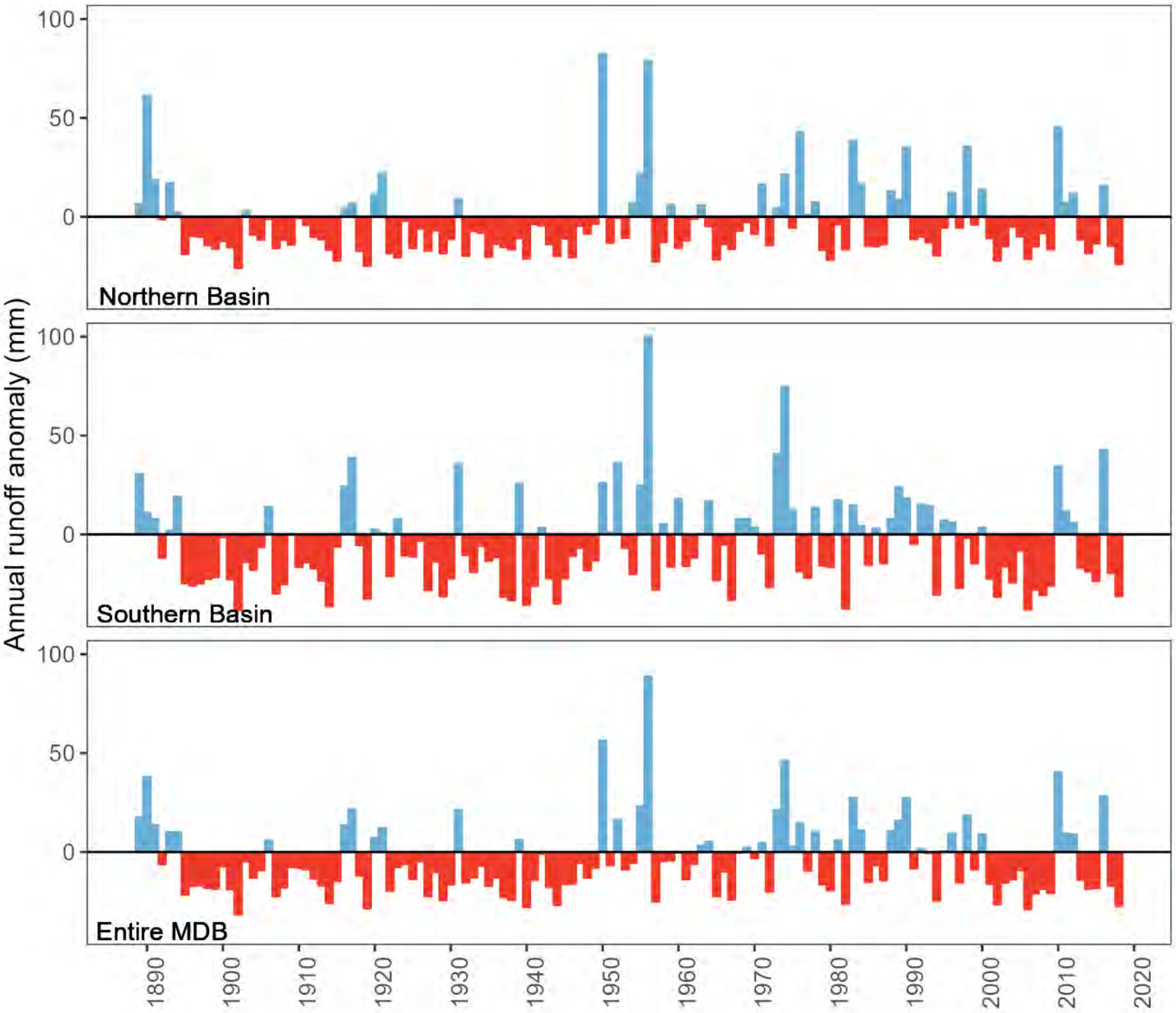

Fig. 8. Annual runoff anomaly (variations from the 1961-1990 mean) in the northern Basin, southern Basin, and entire Basin based on hydrological simulations using GR4J model and climate inputs from the SILO dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/)

There is large variation in the seasonal streamflow patterns across the MDB (CSIRO, 2008). However, the natural streamflow regimes in 24 of its 26 major catchments have been modified by water resources development such as construction of dams and weirs. The total water storage across the Basin is around 22,700 GL (MDBA, 2010), approximately 78% of historical mean annual streamflow. These developments have altered the seasonal streamflow distribution. The southern Basin was developed earlier than the northern Basin and includes the Basin's largest dams. As a result, the MDB is the most heavily regulated river basin in Australia, with significantly altered streamflow seasonality. In particular in the major southern rivers, high winter flows are captured by dams and released in the summer for irrigation, leading to seasonal inversion of flow downstream of major dams. Alterations to high and low flows, as well as the total flow volume, are also common in many catchments. Further downstream, flow seasonality is largely restored but the amplitude of the seasonal variation is greatly reduced due to consumptive water use (CSIRO, 2008). The heavy regulation of streamflow has affected flood- and flow-dependent ecosystems and caused major changes in geomorphological and ecological processes downstream of dams (Kingsford, 2000).

Another important feature of the Basin's hydrology is the complex spatial and temporal patterns of hydrological connectivity between the river channels and their floodplains (Stewardson et al., 2021). The hydrologic connectivity is affected by natural connectivity and the Basin development (i.e. water infrastructure). The level of hydrologic connectivity varies significantly across the Basin with the percentage of flow reaching the Murray Mouth ranging from 3% from the Warrego to 84% from the Murray (CSIRO, 2008). In wet years, rivers flow to the floodplains, lakes, and wetlands, while in dry years more water is lost through seepage and evaporation reducing the hydrologic connectivity. The construction of water supply infrastructure and flood levees has had a significant impact on flow distribution and hydrologic connectivity. It is also important to consider surface water and groundwater connectivity in managing Basin water resources as they are components of one system (see this ATSE series on surface water-groundwater connectivity).

Long-term average runoff depends chiefly on climatic conditions such as rainfall and is expected to change under climate change. However, catchments located in different parts of the Basin are expected to respond differently to climate change and it is important to understand the sensitivity of runoff to climate change.

Basin-wide runoff is expected to change by 2–3% for every 1% change in rainfall (Chiew, 2006), while the runoff sensitivity to potential evaporation is somewhat lower and in the opposite direction (Jones et al., 2006; Donohue et al., 2011). This means that in the high runoff generating catchments in the south-eastern part of the Basin runoff will decrease by 7 mm y^{-1} for a 10 mm y^{-1} reduction in precipitation, and to decrease around 4 mm y^{-1} for the same increase in potential evaporation. It is in these high yielding catchments where runoff is likely to change most under future climate change.

4. Projected climate change impacts on water availability across the Basin by 2070

The Basin has warmed by a degree since 1910 and the warming will continue (Whetton and Chiew, 2021). Climate change will impact water availability in the Basin and affect communities, agriculture, industries, and the environment (CSIRO, 2008; MDBA, 2010). The impact of climate change on water availability and river flow characteristics are generally assessed by combining climate change projections from global and/or regional climate models with hydrological models. The key steps include: (i) selection of greenhouse gas emission scenarios; (ii) selection of global climate models (GCMs); iii) downscaling of GCM outputs to catchment scale climate variables (including robust bias correction); and (iv) hydrological modelling (Chiew et al., 2009).

The impacts of future climate change on water availability in the Basin were assessed by CSIRO (2008). Average annual runoff was projected to decrease 9% by 2030 and 23% by 2070 for the median of the 45 climate scenarios. There is a strong agreement in future rainfall reduction among the GCMs and hence reduction in projected runoff (CSIRO, 2008). However, the range of projected future runoff is mainly due to the large range in the future rainfall projections among the GCMs. The projected change in mean annual runoff ranges from -40% to +10% in the southern Basin mainly due to the projected cool season rainfall reduction. For the northern Basin, the projected change in mean annual runoff ranges from -45% to +30%.

Groundwater contributes 16% of the water used in the Basin, the proportion is much higher in the Darling Basins and during dry periods (CSIRO 2008). Diffuse recharge is the dominant recharge mechanism across the Basin as a whole. Diffuse recharge averaged across the Basin is projected to increase by 5% under the median future climate scenario, increase by 32% under wet climate scenario, and decrease by 13% under dry climate scenario (Crosbie et al., 2010). Such wide ranges of projected changes in runoff and groundwater recharge present challenges for the development of SDLs within the Basin Plan and management of climate change impact.

The climate scenarios and the hydrological projections developed by CSIRO (2008) are consistent with the findings of the latest research (Whetton and Chiew 2021). Fig. 9 shows the projected change (median and the range) in future mean annual runoff across the Basin. Also shown in Fig. 9 are projected percentage change in low flow days and increases in the number of 3-year hydrological droughts (Prosser et al., 2021). The projections are for 2046–2075 relative to 1976–2005 for RCP 8.5. These projections come from hydrological modelling with the GR4J rainfall-runoff model, informed by the climate change signal from the 42 CMIP5 global climate models (GCMs) used in IPCC AR5 (Zheng et al., 2019). The projections can also be interpreted as the change in mean annual runoff for a 2.0°C global average warming relative to the IPCC AR5 1976–2005 reference period (IPCC, 2014). Early CSIRO analysis indicate that hydrological modelling informed by recently released CMIP6 climate projections are similar to CMIP5, i.e. the MDB will be hotter and drier under climate change (Grose et al. 2020, Chiew et al., 2023), and the hotter and drier projections have been consistent through the different generations of IPCC, CMIP and national projections (Prosser et al. 2021, Chiew et al., 2023).

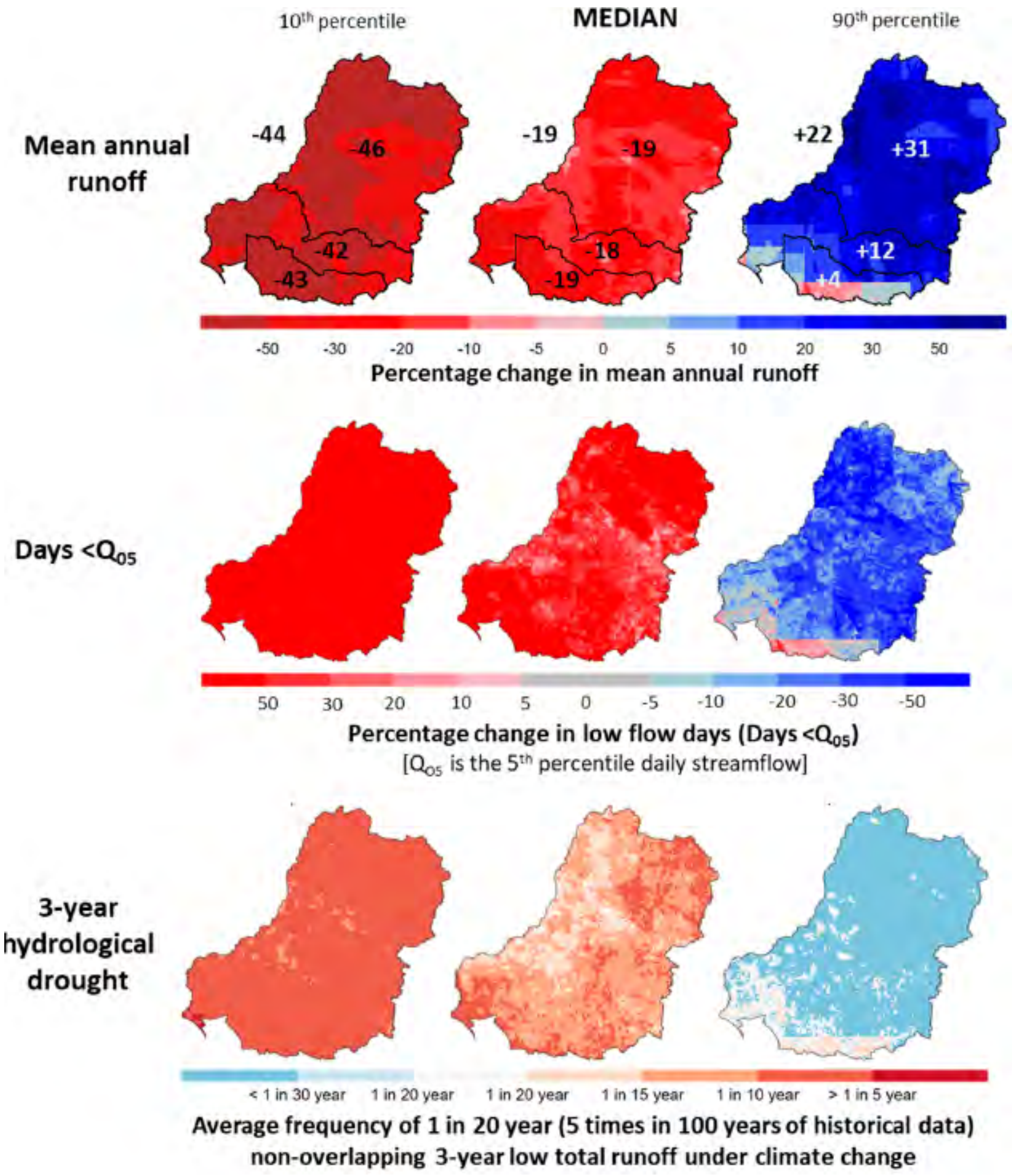

Fig. 9. Projected change in streamflow characteristics for 2046-2075 relative to 1976-2005 for the high RCP8.5 emissions scenario (from Prosser et al., 2021)

The range in the projections largely reflect the uncertainty in future rainfall projections across the 42 GCMs. Most of the GCMs project a drier winter in the future, which is consistent with observations of drier cool season rainfall in the past 30 years, and partly attributed to winter rainfall decline as a result of anthropogenic climate change (Hope et al., 2017; Post et al., 2014). Winter rainfall is therefore likely to decline, and more so further south. The direction of change in summer rainfall is uncertain. The magnitude of extreme high rainfall is expected to increase under climate change (Timbal et al., 2015, Wasko and Sharma, 2015). This will increase the risk of flash floods in built-up areas and small catchments. For large catchments, increases in extreme high rainfall events may not necessarily result in increased flood magnitude due to the effect of antecedent soil moisture conditions and attenuation of river flow (Wasko and Nathan, 2019).

Adaptation options to reduce flood risks include improved flood forecasting, developing temporary levee structures, maintaining floodplains, and water-sensitive urban design (Radcliffe et al., 2017).

Given the large interannual variability in Basin's rainfall, in the near-term (next 20 years), this natural hydroclimate variability will dominate. Further into the future, anthropogenic climate change will shift the averages, as well as the different climate and hydrological characteristics that impact water and related systems. As a result, the change signal in rainfall described above is generally applied to the long historical record (e.g. 1895 to the present), that is, the entire historical record (which encapsulates the range of variability and characteristics), is scaled by the 'delta' change signal, to reflect a future under a warmer world. An alternative approach is a transient simulation providing a trajectory from now into the future. Another important consideration is the choice of baseline hydroclimate for near-term planning, particularly in the southern Basin, where the past 20 years have been considerably drier than the long-term (see Fig. 8).

Zhang et al. (2020) considered seven plausible climate scenarios – the historical climate and six future climate scenarios in assessing the impacts of climate change on streamflow regime. The development of these scenarios was guided by the latest climate science, historical climate and streamflow data, paleoclimate data and projections from global and regional climate models. They showed that:

- A warmer and wetter climate will lead to more favourable conditions with increases of up to 20% in key flow metrics and decreases in the length and severity of low flow and zero flow periods.

- Warmer and drier climate scenarios will lead to less favourable conditions with moderate to large decreases in key flow metrics (e.g. mean annual flow may decrease by 40-50%) and large increases in the length and severity of low flow and zero flow periods. High flow metrics generally show larger percentage reductions than low flow metrics (e.g. freshes decrease by up to 55%).

- An increase in the severity and duration of multi-year droughts can have a significant additional negative impact on flow metrics (e.g. mean annual flow may decrease by up to 70% during the extended drought period). Again, the impact on high flow metrics is generally greater than that on low flow metrics (e.g. freshes decrease by up to 70% during the extended drought period).

The seven hydroclimate storylines provide a range of plausible future climate conditions for the Basin and can be used as a basis for communicating climate change risk on water resources planning and management with stakeholders. These hydroclimate metrics are directly relevant to the flow management tools used in the Basin Plan. The projected changes in these hydroclimate metrics can help the MDBA and stakeholders undertake climate vulnerability assessment with a focus on examining climate change impacts on the objectives and settings in the Basin Plan.

The hydrological modelling discussed here comes from the GR4J daily conceptual rainfall-runoff model. The change signal in the long-term averages presented here, as well as the medium and high flow characteristics, from different rainfall-runoff models are likely to be similar (or relatively much smaller differences compared to the rainfall projections) (Chiew et al., 2018; Teng et al., 2012). However, it is much more difficult to accurately simulate the low flow characteristics, and therefore there is considerable uncertainty in the rainfall-runoff modelling of low flows as well as a larger range in the modelled impact on low flow characteristics (Chiew et al., 2018).

Like practically all climate change impact on water studies, model parameters from calibration against historical record are used here to simulate the future. The modelling therefore only considers hydrological futures from changes in the input climate data. The modelling therefore does not consider potential changes in dominant hydrological processes under higher temperature, enhanced CO_2, and longer dry spells.

Extrapolating hydrological models to predict the future, as is largely the current approach, is likely to underestimate the decline and range in the future hydrological projections (Chiew et al., 2014; Vaze et al. 2010; Saft et al., 2016). There is some research currently attempting to better understand how catchments respond to and recover from long dry spells (hydrologic non-stationarity) and adapt hydrological models to predict the future under changed conditions not seen in the past (Fowler et al., 2018, 2020). Over the last two decades, the science of hydroclimate projections has improved, but uncertainties in the projections will remain.

5. Challenge and opportunity for adaptive management of the Basin under climate change

The MDB has among the most variable hydroclimates in the world, making water resources management particularly challenging. The future will be warmer and is likely to be drier with more extreme weather events like the Millennium Drought and the 2022 floods. These changes pose a threat to sustainable management of the Basin as they are likely to have significant impacts on the Basin's water availability, agricultural production, communities and the environment. It challenges our science and calls for a more integrated and longer-term vision for the Basin with a healthy balance between agricultural water use and environmental water requirements.

Water resources adaptation to climate change is challenging because (i) water is a cross-cutting issue connected to many sectors, (ii) there are competing needs from different water users, and (iii) there is considerable uncertainty in the future hydroclimate projections. To better understand the threat posed by climate change, policy makers require information about plausible future climate scenarios to evaluate the robustness of the water systems in the Basin, so they can plan accordingly. Management of the MDB under climate change will take policymakers and managers into 'uncharted territory' and would require the adoption of more flexible models of water governance and planning that consider multiple future pathways, as well as investment in new science and technologies (Hart et al., 2021).

There is no doubt that climate change is affecting hydrological characteristics of the Basin and impacting on our environment, economic and social development. There is an urgent need to invest in research to develop new knowledge and technologies to manage the risk posed by climate change. To facilitate assessments of climate change impact on water systems, climate scenarios need to be developed with acknowledgement of climate projection uncertainty and should be tailored to specific policy and management issues. This requires climate projections to be relevant and informative at the time and spatial scales of interest.

Climate impact assessments have been traditionally dominated by a "top-down" approach that begins with climate change projections followed by downscaling of GCM outputs and hydrological modelling. A complimentary approach to this model-driven 'top-down' approach begins with gaining an understanding of current exposures of the systems to climate, and then assess how these 'exposures' may change under different climate futures, a so-called 'bottom-up' approach. This approach focuses on identifying potential system vulnerabilities and relationships between the system performance and climate characteristics. *Research in 'bottom-up' approach is likely to yield more policy relevant information in the context of climate change and should be a future priority.* We also need to build stronger partnerships between research communities and management agencies to achieve the expected outcomes for the Basin.

Water resources planning and management needs to take into consideration not only average states of future hydroclimate but also extremes (e.g. increase in extreme high rainfall intensity, changed seasonality with winter rainfall decline, sub-annual dry spells and spatial patterns) with a *longer-term (e.g. 50 years) planning horizon to identify actions that should be taken with development of new technology.* To achieve this goal of sustainable development in the Basin, we need an integrated approach to include economic, social, cultural and environmental considerations at the whole of Basin scale.

What does a Future Ready MDB look like? In 2019, CSIRO ran a forum with 100 participants from diverse backgrounds to explore the future of the Basin through the lens of global trends, physical environment and regional communities and economics. The forum identified five key needs to achieve a future ready MDB with a longer-term vision (CSIRO, 2019):

- Understanding global drivers and their effect on the MDB;
- Engaging with communities to adapt to change;
- Investing in Aboriginal voices of the MDB;
- Strategic investments in new knowledge and technologies; and
- Building a system understanding.

Hart et al. (2021) articulated key priorities for improving the Basin Plan and the policy areas for sustainable water management in the Basin (see Fig.10). They call for more integrated catchment management with emphasis on climate change and community engagement. The Future Ready MDB needs are aligned strongly with the key priorities of Hart et al. (2021). The scientific community needs to work closely with policy makers and local communities towards development of shared vision and a whole-of-system view to support integrated basin management.

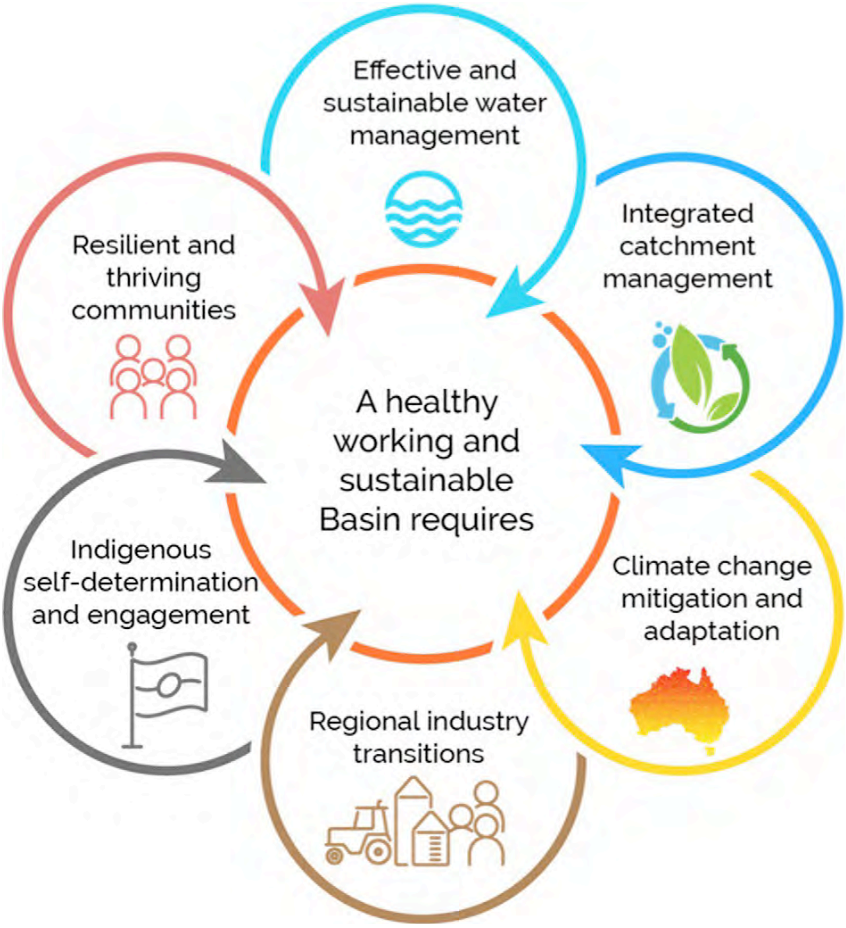

Fig. 10. Diagram showing the areas that need to be linked to achieve a healthy and sustainable working Basin (from Hart et al., 2021)

The historical development and management of the Basin reflects the realities of both coping with, and taking advantage of, the large natural variation in climate. With our growing understanding of how that climate is likely to change, particularly in likely extremes of both drought and flood, life in the Basin will inevitably have to adapt accordingly. This includes recognition that the landscape itself will change, for climate more than management determines the patterns and dynamics of the environment. Where we build, how we value, store and share water resources, what we grow and where, and how we insure or protect assets, livelihoods and heritage will either be anticipated and facilitated by long-term planning and policy or left to react to the changing vagaries of climate. Our understanding of the Basin’s likely climate future merits an approach to planning and policy that gives industry, environmental managers and communities effective anticipation of the changing Basin.

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MURRAY-DARLING BASIN ESSAY

Essay #2 in a series of nine by Australia's leading water experts

Challenges and adaptation needs for water quality in the Murray-Darling Basin in response to climate change

John Verhoeven, Stuart Khan and Megan Evans

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Above: The Darling river at Bourke in drought conditions.
JohnCarnemolla, iStock.

EXECUTIVE SUMMARY

Verhoeven et al. note that as climate change is already affecting the streamflow and degrading water quality, it is important to elevate water quality protection activities and management capabilities to meet future long-term water uses.

They identify six major primary threats, two consequential threats and an emerging threat that can deteriorate the water quality of the Basin. They also make nine interlinked recommendations, based on their analysis using the available hydroclimate metrics, that may lead to mitigation of water use vulnerabilities and threats to future MDB water quality under climate change.

The success of these recommendations lies in the on-going implementation of an expanded MDB Plan, with an integrated effort needed from all levels of the Australian government system, communities, and industries for long-term benefits. However, the reduced future flows predicted under climate change will need to be redistributed to optimise consumptive and environmental uses, while the detrimental effects of flow reductions may be counterbalanced by implementing efficient land management measures in the Basin regions.

Challenges and Adaptation Needs for Water Quality in the Murray-Darling Basin in response to Climate Change

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Abstract

Water quality has a material impact on the effective amount of water available to meet water supply, cultural, environmental, social, and industrial water uses in the Murray-Darling Basin (MDB or Basin). As climate change is already reducing streamflow and degrading water quality, it is important to elevate water quality protection and management to meet future water uses. We describe the current water quality condition of the MDB, identifying six major primary threats; increasing salinity, nutrients, sediments, metals and other toxic chemicals, temperature, low dissolved oxygen concentrations, and two major consequential threats; cyanobacterial blooms and toxins, and blackwater events. An emerging threat is the increasing incidence of pathogens. Water quality condition in the southern Basin is highly variable, with quality generally deteriorating progressively downstream. Long term water quality has also varied over time. For example, major cyanobacterial blooms have increased in their occurrence, frequency, duration and extent, from two in the 1980s and 90s, to eight in the past 20 years, extending for hundreds of river kilometres and having major economic, environmental and social impacts. In contrast, salinity in the River Murray has decreased over the last 30 years, demonstrating the value to water quality of implementing a long-term basin wide salinity management strategy.

We use available hydroclimate metrics to identify water use vulnerabilities and threats to future (50-year) MDB water quality under climate change. We explore adaptation opportunities to mitigate climate change impacts on MDB water quality, and make nine recommendations to address climate change, other anthropogenic impacts, and natural risks to water quality. The interlinked recommendations must all be implemented to effectively safeguard water quality under climate change. This approach requires formidable and on-going implementation by governments, communities and industries, and is built on their participation in a 50-year, integrated, comprehensive process. It requires long-term bipartisan and bilateral agreements at Commonwealth and State governments levels, and resourcing by governments at all levels. We outline a vision of a healthy MDB in 50 years having water quality and related quantity that achieves consumptive and environmental water use objectives identified in the original 2012 MDB Plan. We suggest that predicted future reduced flows under climate change will need to be redistributed to optimise consumptive and environmental uses, while the detrimental effects of flow reductions may be counterbalanced with benefits from the implementation of land management measures.

1. Introduction

The availability and quality of the MDB's surface waters, groundwaters and water-dependent ecosystems is vital for the health and sustainability of the MDB and its communities (adapted from RM Consulting Group Pty Ltd 2020). It provides drinking water for more than 2.3 million Australians; water to sustain 120 waterbird species, more than 50 native fish species and for 30,000 wetlands; water for $22 billion of primary production; and water for recreation-based tourism (MDBA 2022).

Climate change is already impacting the MDB, with increasing temperatures, more extreme weather patterns (floods and droughts) and lower annual rainfalls leading to reducing streamflow and to poorer water quality. Within the MDB, impacts on water quality vary between the northern and southern basins (Figure 1) as a result of differences in climate and climate change impacts over the MDB, in hydrological characteristics, and of differences between the States in water security and availability (dams, river regulation, water licensing and governance arrangements).

The starting point for this essay is CSIRO's Murray-Darling Basin Sustainable Yields Project (CSIRO 2008) which assessed climate change, groundwater extraction and catchment development impacts on MDB water availability and use. Since that assessment, the known status of climate change has been updated by the Intergovernmental Panel on Climate Change (IPCC 2022), and by Zhang, Chiew et al. (2022).

Figure 1. The Murray-Darling Basin and its Northern and Southern Basins

In this essay we describe a basin-scale outlook for the MDB and its water quality in 50 years, and the adaptive policies, management and technologies required to achieve this. We start by describing current water quality conditions, and then climate change challenges for future water quality. We review MDB water policy and management reforms and their implications for water quality. We make nine recommendations to address climate change and other anthropogenic impacts, and natural risks to water quality. Finally, we present two visions within a range of possible outcomes for MDB water quality in 50 years under a changed climate. The visions distinguish between very poor and very good management over that range; a degraded MDB with poorer water quality limiting water uses, or the preferred outlook of a healthy MDB with water quality targeted to meet consumptive and environmental water uses identified in the original 2012 MDB Plan.

2. Current water quality condition of the MDB

Water quality varies widely across the MDB, the result of its many diverse landscapes, of the introduction of European land use including irrigation and the construction of major dams (Walker and Prosser 2021), and of climate and climate change impacts. Walker and Prosser (2021) describe the landscapes which range from mountainous areas in the south-east of the MDB, to vast semi-arid riverine plains. The northern plains, with an area of 650,000 km^2, overlay alluvial sediments up to 200 m thick containing groundwater aquifers. To the south-west, the MDB overlies the 300,000 km^2 Murray Geological Basin containing groundwater aquifers of varying water quality.

2.1 Surface water-groundwater framework

We use a conceptual framework (Figure 2) adapted from Conant, Robinson et al. (2019) to show the surface water (SW) and groundwater (GW) interactions for the MDB. Figure 2 includes the main issues and interdependencies of water quantity, water quality and ecosystems, with particular reference to water quality impacts. Examples of catchment-scale issues are also listed, as SW-GW interactions may extend beyond waterway zones. While our focus is on surface water and groundwater quality, the SW-GW interactions and impacts on water availability (surface flows and groundwater movement) and on ecosystem health are important for MDB water management.

What Figure 2 doesn't show is the more detailed layer at catchment and sub-catchment scales (beyond the scope of this essay) comprising various sources of water, their magnitude and quality, that contribute to surface water and groundwater. These water sources include rainfall, runoff, snowmelt, groundwater recharge and discharge, irrigation return flows, and discharges from towns, mining, and other industries. The risks to water quality of each of these sources varies from catchment-to-catchment, between wet and dry years, and over time with climate and other anthropogenic changes. For example, coal seam gas production in the northern Basin has only recently become a threat to salinity water quality.

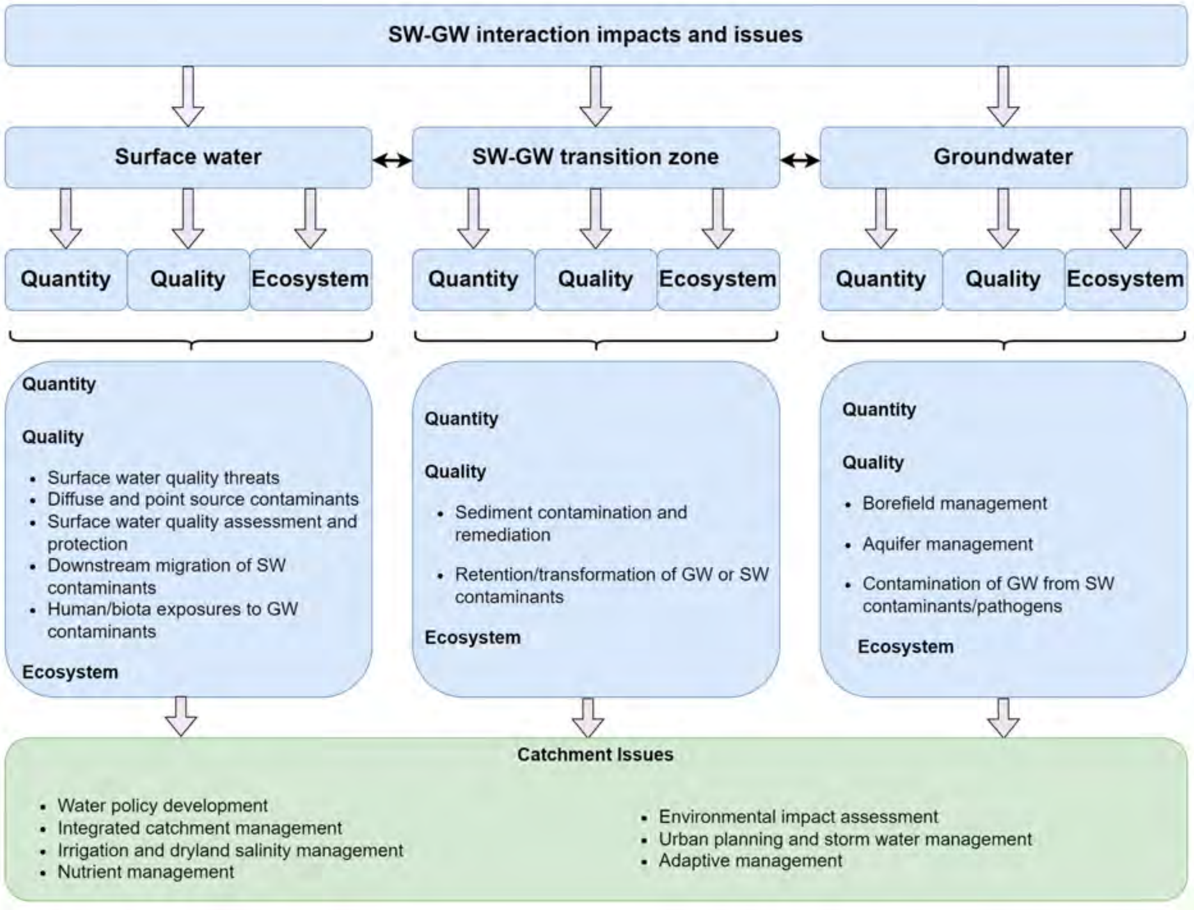

Figure 2: Framework for SW-GW interaction impacts for the MDB, with a focus on water quality (adapted from Conant, Robinson et al. 2019)

Climate over the MDB varies from northern sub-tropical to southern temperate and western semi-arid, and average annual rainfalls range from more than 2,100 mm in the north-east of the MDB to less than 300mm in the south-west (BoM 2020). There are large seasonal differences in streamflow in the unregulated parts of the MDB, with higher flows in late summer–early autumn in the northern Basin, higher flows in late winter–early spring in the southern Basin, and large year-to-year variability across the MDB including lengthy droughts. Details of the MDB hydroclimate including temperature, rainfall, potential evapotranspiration and annual runoff variability are reported by Zhang, Chiew et al. (2024).

Anthropogenic impacts vary widely as a result of surface water and groundwater management by governments. The MDBA and five state and territory jurisdictions operate a large number of water storages, weirs, and waterways, with associated rules for water release; and operate many diversions and extractions for irrigation areas, key environmental assets, cities and towns throughout the MDB. Anthropogenic impacts are also a function of land use practices (Williams, Hunter et al. 2021) resulting in point and diffuse pollution sources, and of the policy and management decisions of governments, communities and industries.

2.2 Water quality policy framework

MDB water quality is governed by legislation and policy instruments including the Commonwealth Water Act (2007), the MDB Plan (2012), and the National Water Quality Management Strategy (1998) (NWQMS). The NWQMS sets out water quality targets in Water Quality Guidelines. The NWQMS also promotes water quality protection by a systematic approach to catchment-based planning and management of water quality, provided by a 'Water Quality Management Framework' (Bennett 2008, Bycroft 2017). A simplified water quality policy framework for the MDB, adapted from the NWQMS, is outlined in Figure 3.

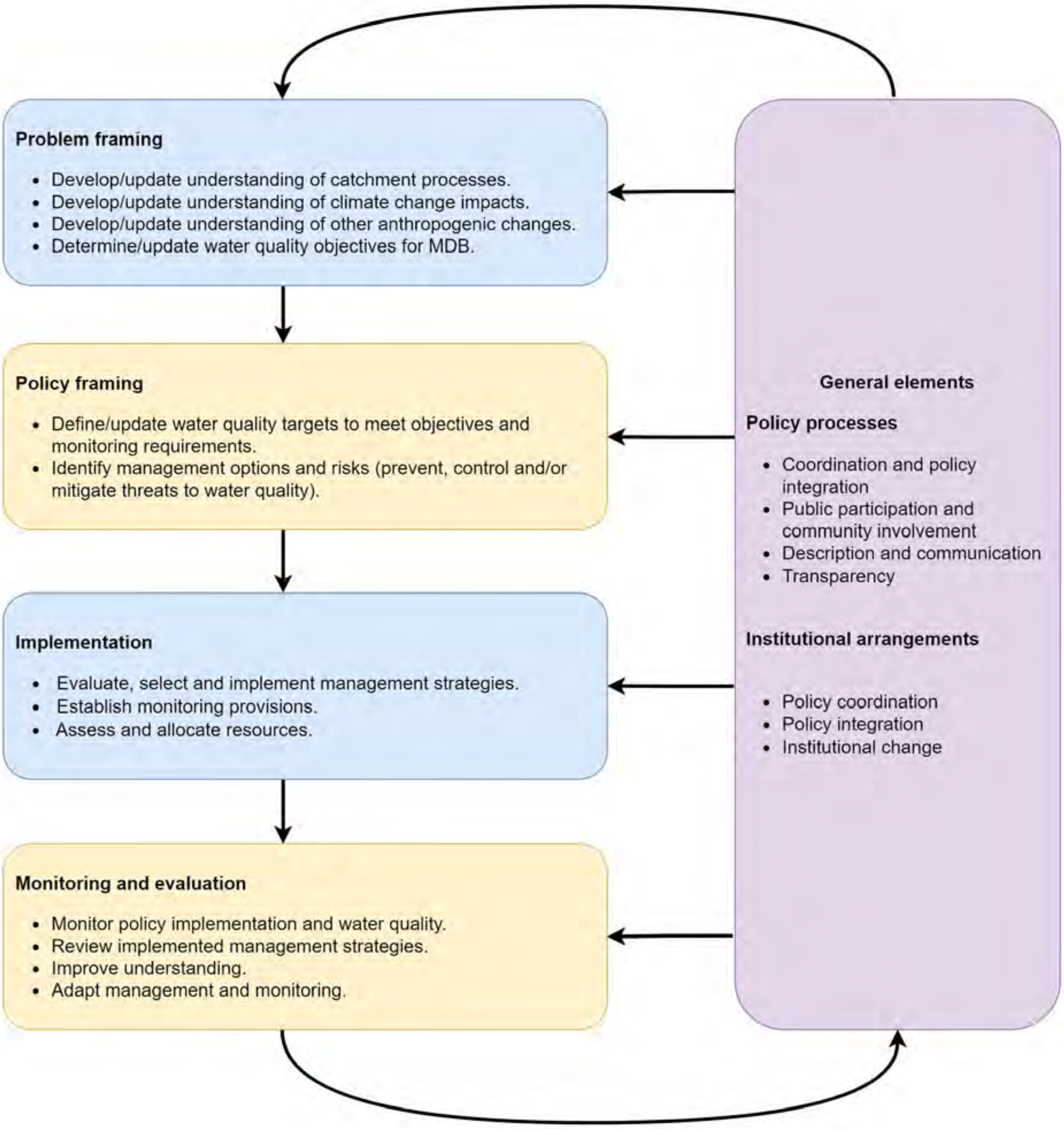

Figure 3: Simplified water quality policy framework for the MDB (adapted from Bennett 2008, Dovers and Hussey 2013)

The MDB Plan aims to ensure the integrated and sustainable management of MDB water resources. The Plan includes objectives and targets to ensure water quality is fit for purpose to meet water supply, cultural, environmental, social, and industrial water needs, and supports risk management of MDB water resources. However, the Plan was prepared under the constraints of the Commonwealth Water Act (2007) which is focused on water quantity. Water quality targets were not designed for enforcement purposes but were set with the expectation that they would be achieved over time.

Setting targets for the large and complex MDB was not straightforward, and not all water quality issues and associated targets could be represented as a single value (RM Consulting Group Pty Ltd 2020). Targets may define a level of risk associated with exceeding a threshold (for example, 95% of the time non-exceedance target for salinity), and/or base flow and event considerations. Furthermore, targets focused on surface water quality, because the SW-GW interaction, whilst recognised, was too complex for groundwater quality targets to be developed. The MDB Plan includes three different types of water quality targets which complement state and local management arrangements: salinity and dissolved oxygen (DO) targets for managing flows, targets for states' water resources plans, and valley salinity targets for long-term salinity planning and management (Table 1).

Table 1: Summary of MDB key water quality targets (adapted from RM Consulting Group Pty Ltd (2020))

Type of target	Description of target
Flow management target	• Flow management salinity targets 95% of the time at five locations in the Murray River, including < 800 EC (µS/cm) at Morgan in South Australia (SA). • DO >50% saturation.
Water Resource Plans (States)	• Irrigation infrastructure salinity targets 95% of the time over a 10-year period. • Sodium adsorption ratio < that which would cause soil degradation. • Water dependent ecosystem targets for 21 Target Application Zones for turbidity, Total Phosphorus, Total Nitrogen, DO, pH, temperature, pesticides, heavy metals, other contaminants. • Cyanobacteria cell counts (<10 µg/L total microcystins; or <50,000 cells/mL toxic Microcystis aeruginosa) or biovolumes (<4 mm^3/L for the combined total of all cyanobacteria where a known toxin producer is dominant, or <10 mm^3/L where known toxins are not present) to meet Guidelines for managing risks in recreational waters.
Long term salinity management	• Median and peak salinity targets 95% of time for 33 valleys.

To help implement the MDB Plan, the MDBA (2022) has operated a limited water quality monitoring program in the southern Basin at 28 sites along the River Murray and across its tributaries in New South Wales (NSW), Victoria and SA from Jingellic above Hume Dam downstream to Tailem Bend since 1978. Water is analysed for electrical conductivity (EC), pH, total phosphorus (TP) and total nitrogen (TN), turbidity, temperature, silica, soluble organic carbon, sulphate and bi-carbonate, chlorophyll and phaeophytin. Phytoplankton sampling is conducted at 12 of these sites. Biswas and Mosley (2019) conducted a comprehensive analysis of the spatial and temporal water quality patterns of data from the southern Basin water quality monitoring program, and the findings of their analysis are included in Section 2.3.

2.3 Current water quality condition

We describe the current water quality condition across the MDB focusing on two primary and two consequential threats: salinity, nutrients (Nitrogen (N) and Phosphorus (P)), the occurrence of cyanobacterial blooms, and blackwater events. Primary threats to MDB water quality include increasing salinity, nutrients, sediments, metals and other toxic chemicals, temperature, and low DO concentrations. Consequential threats include cyanobacterial blooms and toxins, and blackwater events. They result from a combination of primary threats, for example cyanobacteria are stimulated to bloom proportions by nutrients, high water temperatures and slow-moving water having low turbidity.

Salinity is a major issue for the MDB, as high salinity can reduce crop yields, affect plant and animal health, damage the built environment, and impact drinking water quality, including for Adelaide (MDBA 2020a). In the 1980s it was recognised that the cost of salinity to domestic water supply and irrigation users was around $40m/yr and increasing (Blackmore 1995). Under the Basin Salinity Management Strategy 2030 (BSMS2030) and its predecessors, river salinity is being successfully managed through salt interception schemes to prevent groundwater and drainage water from entering waterways, supported by states-based salinity programs. In the southern Basin salinity increased with distance downstream in the River Murray, from a median EC of 40 µS/cm at Jingellic to around 600 µS/cm at Tailem Bend (Biswas and Mosley 2019). Over the longer-term salinity decreased at all monitoring sites. Salinity targets were met for four of the five MDB Plan reporting sites for the reporting period 2014 to 2019 (MDBA 2020b). The EC at Morgan, SA (a major water offtake for Adelaide) showed a decreasing trend below the target of 800 µS/cm resulting from 30 years of applying salinity management measures (Figure 4). The BSMS2030 shows the benefits to water quality of a cost-effective, long-term intervention program with a coordinated basin-wide approach, considering SW-GW interaction, integrating land and water management investments, regulation, and other support by governments working with communities and industries.

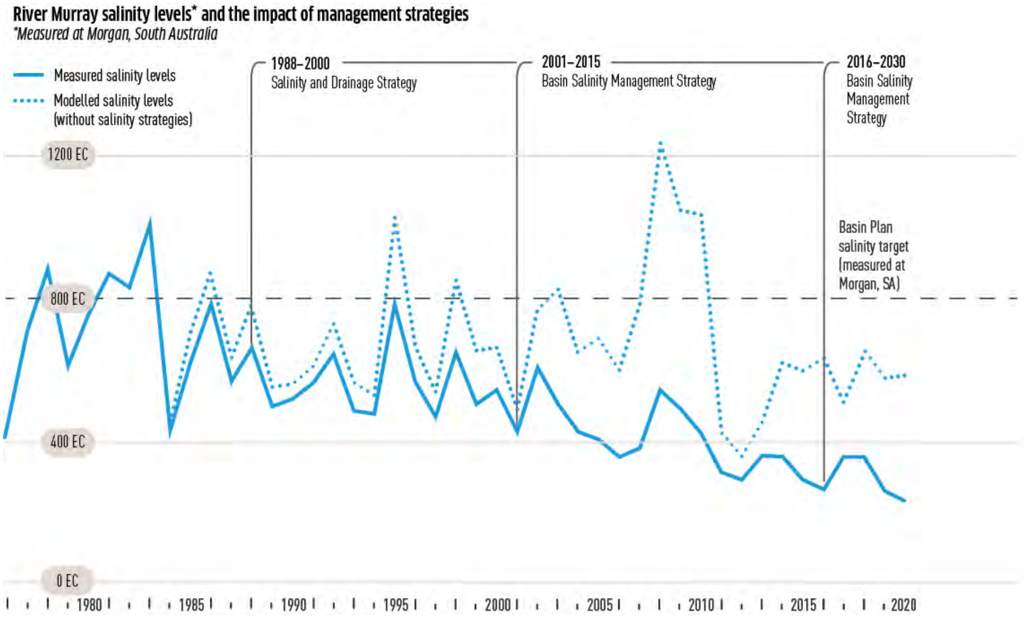

Figure 4: Decreasing salinity in River Murray at Morgan, measured in Electrical conductivity (EC) units (MDBA 2020a) [Licensed under a CC BY 4.0]

Nutrients N and P contribute to water quality and are essential for aquatic organisms. In excess, these nutrients can cause eutrophication by stimulating excessive, nuisance levels of phytoplankton (cyanobacteria, algae and macrophytes). In large numbers these phytoplankton can displace other organisms, smother bed habitats, and disturb aquatic food webs, and in the case of cyanobacteria, can result in toxic blooms.

Nutrient budgets have been modelled by Young, Prosser et al. (2001) in large-scale networks across Australia. The modelling was upgraded using an improved channel network, simulated regulated river flows, improved estimates of sediment inputs and improved regionalisation of hydrological parameters to model nutrient inputs, transport and export for the MDB (DeRose, Prosser et al. 2003). Modelling assessed N and P annual loads in 27 MDB regions for erosion processes including hillslope to stream delivery, gully erosion, riverbank erosion, dissolved runoff, and point sources. The modelling predicted that most P (48%) is transported with suspended sediment, while dissolved N (45%) was predicted to be the largest proportion of the Total N load. Modelling also predicted the amounts of nutrients deposited on floodplains, in reservoir storages, exported dissolved or as particulates, and lost to denitrification, and demonstrated that the MDB is one of nutrient redistribution rather than net export. Predicted mean annual loads were N $8x10^4$ tonnes/yr and P $1.1x10^4$ tonnes/yr. These annual loads were the same as those predicted in modelling studies of major river basins globally by Mekonnen and Hoekstra (2015, 2018), who also found that the MDB's ability to assimilate N had been exceeded by 80%, and to assimilate P had been exceeded by 2200%.

The default water quality trigger guideline for lowland rivers in south-eastern Australia for TN is 500 μg/L and for TP is 50 μg/L (ANZECC ARMCANZ 2000). In the southern Basin, nutrient concentrations increased with distance downstream in the River Murray, with median concentrations of TN increasing from 200 μS/cm at Jingellic to 700 μS/cm at Tailem Bend, and TP increasing from 20 μS/cm to 100 μS/cm (Biswas and Mosley 2019). TN and TP concentrations were highly variable over time. Improved agricultural management practices in recent decades have reduced nutrient loss, and Walker and Prosser (2021) hypothesise that the peak of catchment loss of nutrients may have passed and that loads are reducing. However, there is little quantitative evidence to test this hypothesis; current monthly nutrient monitoring in MDB rivers is inadequate to examine loads transported, particularly during high flow events.

For turbidity, the default water quality trigger guideline for lowland rivers in south-eastern Australia is 50 NTU (ANZECC ARMCANZ 2000). In the southern Basin turbidity was highly variable but generally increased with distance downstream in the River Murray, from a median of 4 NTU at Jingellic and a large increase below the Darling River confluence to 40-50 NTU at Tailem Bend (Biswas and Mosley 2019). There was large variability of turbidity with time at all monitoring sites.

In the southern Basin, water temperatures along the River Murray showed relatively minor changes with an annual variation of around 20-25 ^{0}C and a maximum of around 30 ^{0}C (Biswas and Mosley 2019). The water quality monitoring program did not include analysis of DO, metals and other toxic chemicals.

Under conditions conducive to growth, cyanobacteria can form blooms which can produce toxic scums impacting water supplies, primary production, recreation and environmental quality. Globally, blooms have been responsible for human and animal poisonings (Svircev, Lalic et al. 2019), with 52 human deaths due to cyanobacterial toxins reported in Brazil in 1996 (Jochimsen, Carmichael et al. 1998, Carmichael, Azevedo et al. 2001, Azevedo, Carmichael et al. 2002). Blooms can smother aquatic vegetation, and when blooms die they can make water bodies hypoxic, leading to massive fish kills and invertebrate deaths (Huisman, Codd et al. 2018). Compared with two major cyanobacterial blooms in the MDB in the two decades in the 1980s and 90s, the eight major blooms in the past 20 years showed an increase in the occurrence, frequency, duration, and extent of major blooms extending for hundreds of river kilometres and having major economic, environmental, and social impacts (Table 2).

Table 2: Occurrence of major cyanobacterial blooms in the Murray-Darling Basin

Year	Cyanobacterial bloom event	Details	Reference
1983	Murray River	No details.	Clune and Eburn (2017)
1991/92	1,000 km Darling-Barwon	Timing: 2nd week Nov 91 to mid-Jan 92. Extent: Wilcannia Weir Pool to Mungindi. Species: *Anabaena circinalis* (now renamed *Dolichospermum circinale*). Toxins: Cell counts exceeded 600,000 cells/ml, with toxins.	Bowling and Baker (1996)
2003	Murray River	No details.	(Beavis, Wong et al. 2023)
2006/07	Lake Hume and 150 km in Murray River	Timing: Dec 06 to early May 07. Extent: Lake Hume to Corowa. Species: *Anabaena circinalis, Anabaena flos-aquae, Aphanocapsa sp, and Cylindrospermopsis raciborskii.* Toxins: No details.	(Baldwin, Wilson et al. 2010)
2009	>1,000 km Murray River and tributaries	Timing: Early Mar 09 to early May 09. Extent: Lake Hume to upstream of Euston. Species: *Anabaena circinalis, Microcystis flos-aquae,* and *Cylindrospermopsis raciborskii.* Toxins: Low toxins concentrations.	Al-Tebrineh, Merrick et al. (2012)
2010	500 km in Murray and Edwards rivers	Timing: 5 weeks during Feb-Mar 10. Extent: 500 km in Murray and Edwards rivers, with a small package of bloom infested water moving downstream for 650 km. Species: *Anabaena circinalis.* Toxins: Toxins present.	Bowling, Merrick et al. (2013)
2016	2360 km in Murray River and distributary rivers	Timing: Mid-Feb 16 to early June 16. Extent: 1460 km in the Murray River from Lake Hume to Lock 8 (upstream of South Aust), and 900 km in the Gulpa	Crawford, Holliday et al. (2017)

Year	Cyanobacterial bloom event	Details	Reference
		Creek-Edward River-Wakool River-Niemur River distributary system. Species: Chrysosporumovalisporum occurred for the first time in these rivers. Toxins: No measurable toxins.	
2017/18		“Widespread blooms, especially in the Lower Darling”. No further details.	MDBA (2020a)
2018/19	Menindee Lakes and Lower Darling River	Timing: Nov 18 to Jan 19. Extent: Menindee Lakes and 40 km in Lower Darling River. Species: *Dolichospermum circinale* Toxins: No details. Millions of fish killed as a result of hypoxia triggered by climate and bloom events.	Vertessy, Barma et al. (2019)
2019/20	600 km of Lower Darling River	Timing: June 19 to Mar 20 Extent: Lower Darling River for 600 km. Species, Toxins: No details. Ongoing massive fish kills.	(Stocks, Ellis et al. 2022)

Blackwater events are characterised by high concentrations of dissolved organic carbon (DOC) in water resulting from organic matter washed by floods into water bodies from floodplains and dry water courses. Microbes consuming the DOC also consume DO from the water, resulting in hypoxic water which can cause the deaths of fish and other aquatic animals, particularly with higher water temperatures (Baldwin 2021).

A major blackwater event occurred in the southern Basin in 2000/01 (Beavis, Wong et al. 2023). Another major event occurred over 6 months in 2010-11 along 2000 km of the Murray River and its tributaries, resulting in many fish kills and stressed aquatic animals (Whitworth, Baldwin et al. 2012). The MDBA (2020a) reported two major blackwater events. During the first major event in 2016–17, DO concentrations were as low as 2 mg/L in many reaches of the Murray and its tributaries in the southern Basin, the result of extensive floodplain inundation followed by an unusually warm summer. Hypoxic blackwater was also reported in the Murray in SA, and downstream impacts were mitigated with water releases from Lake Victoria. The second major event occurred following extreme drought in the northern Basin, when Lower Darling River cease-to-flow conditions and hypoxic conditions resulted in disastrous fish death episodes in December 2018 and January 2019 (Vertessy, Barma et al. 2019). A recent major event occurred in February-March 2023 in the Lower Darling River, the result of high temperatures and receding floodwaters (Kingsford 2023).

3. Climate change challenges for future (50-year) MDB water quality

3.1 Climate change threats to water quality

Climate change and other anthropogenic activities, and natural processes including droughts, floods and high temperatures vary across the MDB and threaten already declining water quality. Firstly, rainfall variability spatially and temporally across the MDB is expected to remain high, with dry and wet years. Modelling for the MDB indicates that under a future drier climate scenario annual rainfall could reduce by around 15%, whereas under a future wetter scenario annual rainfall could increase by up to 10% from the present (BoM 2020). Rainfall decline across the MDB, particularly across the southern Basin in winter months, has been amplified in declining winter and annual streamflow. As a result, the annual streamflow for most locations in the MDB has undergone a step decline during the late 1990s, with the magnitude of the decline being greater in the southern Basin (BoM 2020). These trends are projected to continue, resulting in longer and more severe meteorological, agricultural, and ecological droughts, interspersed by extreme weather events such as heavy rainfall with resulting river floods (Grose, McGregor et al. 2021). The occasional large flooding events will wash nutrients, organic matter, and sediments into waterways, resulting in increasing cyanobacterial blooms, blackwater events and higher turbidity respectively (Table 3).

Secondly, rising temperatures across the MDB are contributing to declining soil moisture content trends and declining runoff, particularly in the southern Basin since the Millennium Drought (1997-2009). Optimistically global warming temperature increases may be limited to around 2 °C (IPCC 2022), but this may extend to 2.5 °C in 2050 (BoM 2020). The hotter and dryer regime may increase the occurrence and intensity of bushfires, and the occurrence of dust storms. Finally, snow cover and depth in south-eastern Australia have decreased and are projected to decrease further (Grose, McGregor et al. 2021), resulting in reduced annual spring and summer river flows in the southern Basin.

We used the above-described future changes to climate, and hydroclimate metrics developed in a study by Zhang et al. (2020), to identify MDB water use vulnerabilities and threats to future (50-year) MDB water quality. Their study developed seven climate scenarios, which included warmer climates, dryer, and wetter climates, some including increased length and severity of droughts, to help evaluate MDB water systems, water sharing arrangements and management tools under climate change. We selected the scenario which best described our view of future climate in the MDB; a warmer and drier climate with daily rainfall time series decreased by 10% amplified in mean annual flow decrease of 20%-30%, and with mean annual flow decreasing by up to 40% during the more severe multi-year droughts such as those experienced twice in the last 22 years. The scenario hydroclimate metrics are all climate and flow related, and include temperature, rainfall, potential evaporation (PET), soil moisture index, mean annual flow, overbank flow, freshes, replenishment flows, baseflows, cease-to-flow days, dry spells, and flow sequencing. The outcomes for this scenario are listed in Table 3.

We inferred relative water quality changes from the flow metrics, as water quality parameters were not included in the modelling, to identify threats to MDB water quality under climate change, in Section 3.2. We then developed a vision of water quality for the MDB in 50 years, including adaptation options and strategies to mitigate the climate change threats, in Section 4.

Table 3: MDB-scale hydroclimate scenario storyline from Zhang et al. (2020)

Hydroclimatic metrics	A warmer and drier climate with rainfall decreased by 10% and with more severe multi-year droughts	Category
Mean annual flow - determines water availability and inflows for reservoirs	With a 10% reduction in rainfall and higher PET, mean annual flow will decrease by 20-30%. Dry catchments will show a greater percentage reduction than wet catchments. Mean annual flow will decrease by up to 60% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought.	Large decrease
Overbank flows - inundate floodplains to recover wetland functions and re-establish in-channel habitats	Overbank flows will decrease by up to 30%, decreasing to 60% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought.	Large decrease
Freshes - small-to-medium short duration flows in channels to maintain ecosystem productivity and diversity	Freshes will reduce by up to 30%, decreasing to 50% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought.	Large decrease
Replenishment flows - maintain downstream storages and refill pools and water holes in rivers	Replenishment flows will decrease by up to 30% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought.	Moderate decrease
Baseflows - commonly maintained by groundwater storage, not directly affected by rainfall. Important for aquatic habitat	Baseflows will decrease by up to 15% during the extended drought period because of the 10% rainfall reduction and more severe multi-year drought.	Slight decrease
Cease-to-flow days - occur when the river stops flowing at a specific location. Can lead to loss of connection and habitat	Cease-to-flow days in ephemeral streams will increase. Perennial streams may become ephemeral.	Moderate increase
Dry spells - follow cease-to-flow events and can result in declining water quality and drying out of pools leading to death of plants and animals	Dry spells will increase in length.	Moderate increase
Flow sequencing - the same mean annual flow with different sequences of wet and dry spells can lead to different ecological health outcomes	Flow sequencing will be altered.	Slight change

3.2 Threats and implications for MDB water quality vulnerabilities

Climate change is having a marked impact on the MDB hydroclimate. Our scenario, with a median projection for a 20% decline in mean annual runoff, is of the same order as the 20% of consumptive water being returned to the environment through infrastructure projects and the purchase of irrigation water entitlements (Hart 2016). Current water management initiatives will not deliver the additional environmental benefits sought under the MDB Plan. As a result, all water uses will be vulnerable to further reductions in water flows, to the need for further reductions in consumptive water and to poorer water quality.

As a result of the hydroclimate metrics of flows listed in Table 3, the ability to provide fit-for-purpose water quality for all uses will be more difficult than at present, providing a challenge for the MDB and its management (MDBA (2020c) and BoM (2020)). Drier conditions, increasing temperatures, and changes to flows are already impacting on water quality particularly during periods of low flows. Even if other anthropogenic activities remain unchanged, the threats to future MDB water quality will increase with worsening climate change,

We describe in Table 4 our predicted threats to future MDB water quality, as anticipated under the hydroclimate scenario of Zhang et al. (2020) in Table 3.

Table 4: Predicted threats to future (50-year) MDB water quality and implications as anticipated under the hydroclimate scenario in Table 3 from Zhang et al. (2020)

Water quality issue	Predicted threat to MDB water quality and implications
Primary threats	
Salinity High salinity adversely impacts drinking water quality, agricultural production, ecosystems, infrastructure and industries requiring good quality water (MDBA 2022). Salinity occurs naturally in groundwater, which is mobilised by irrigation, land clearing (dryland salinity) and mining. Since 1988, salinity has been managed through the BSMS2030 and its predecessors by the MDBA supported by state-based salinity programs. The strategies include salt interception schemes, dilution flows to SA to improve water quality in dry periods, water use efficiency schemes and diversion of irrigation returns from rivers (Walker and Prosser 2021). Murray River and end-of-valley salinity targets, monitoring and modelling have supported the BSMS2030, which has been successful in achieving the MDB EC target of less than 800 µS/cm at Morgan SA, shown in Figure 2 (MDBA 2020a).	Climate change induced higher temperatures, 10% reduction in rainfall and more severe multi-year droughts (Table 3).may reduce salt loads in the southern Basin. However, this may be offset as less water will be available to dilute salts, with predicted decreased flows and longer dry spells resulting in less frequent, smaller flushing events, reducing the ability to dilute and flush salts from waterways. Furthermore, increased flooding and groundwater recharge from fewer but high-intensity rainfall events could also increase salinity. In the northern Basin, development of coal-seam gas resulted in saline groundwater being stored in surface water storages, posing a potential long-term salt disposal threat. The major challenge will be to balance SW-GW interactions for salinity including reducing groundwater pumping, rehabilitating saline landscapes, potential environmental flow impacts on salinity and long-term groundwater processes potentially increasing salt loads (Walker and Prosser 2021).
Nutrients Nutrients N and P from farms, stormwater and riverbank erosion entering waterways stimulate phytoplankton growth in waterways causing eutrophication (MDBA 2022). Adverse impacts include growth of toxic cyanobacterial blooms (see below), displacement of other organisms, smothered bed habitats and disturbed aquatic food webs. Nutrients in the MDB are being redistributed rather than exported (DeRose, Prosser et al. 2003). Mekonnen and Hoekstra (2015, 2018) found that annual loads of N and P greatly exceed MDB waterways' ability to assimilate these nutrients. Nutrient monitoring is inadequate to assess if annual nutrient loads are increasing or decreasing (Walker and Prosser 2021).	Climate change induced high-intensity rainfall events may result in greater volumes of nutrients being washed into waterways during larger flooding events, particularly in the northern Basin, contributing to an increase in toxic cyanobacterial blooms. Walker and Prosser (2021) found that more research is required to evaluate the effectiveness of regional scale catchment works to reduce nutrient and sediment accessions to waterways and improve MDB water quality. Furthermore, the ecological basis for nutrient and sediment targets in the MDB Plan is unclear, and setting ecologically meaningful targets and improved monitoring and modelling are required to better manage MDB water quality.

Water quality issue	Predicted threat to MDB water quality and implications
Sediments Sediments flushed into waterways from farms, mining, riverbank erosion, following bushfires or stirred up by carp affect river fauna and flora. Sediments make waterways turbid, reduce sunlight in waterways, reduce the rate of photosynthesis, smother organisms and degrade habitats (MDBA 2022). Sediment budgets modelled by Prosser, Rustomji et al. (2001) were upgraded to improve modelling of sediment inputs, transport and export for the MDB (DeRose, Prosser et al. 2003). Modelling showed relatively high suspended sediment loads in most upland MDB areas, and that sediments are being redistributed in the MDB rather than being exported. Reservoir deposition degrades water quality. Sediment monitoring is inadequate to assess if annual loads are increasing or decreasing (Walker and Prosser 2021).	Climate change induced high-intensity rainfall events may result in greater volumes of sediment being washed into waterways during larger flooding events, particularly in the northern Basin, contributing to turbidity increases. As described above for nutrients, more research is required to evaluate the effectiveness of regional scale catchment works to reduce sediment accessions to waterways, and when setting ecologically meaningful targets. Improved sediment monitoring and modelling are required to better manage MDB water quality.
Metals and other toxic compounds These contaminants are generated by exposure of acid sulfate soils to oxygen as water levels fall in waterways and on floodplains, by historic and current mining and by inappropriate use of chemicals. Acidification in the middle and lower reaches of the southern Basin has been linked to acid sulfate soils (Baldwin 2021). These contaminants kill fish and other aquatic life (MDBA 2022) and are a threat to water quality for domestic, agricultural and other uses.	Climate change induced high-intensity rainfall events may result in episodes of waterways contaminated with metals, other toxic compounds, and low pH. Reduced overland flows and extended droughts resulting from climate change are predicted increase the potential for drying out of southern Basin wetlands and floodplains, leading to increased occurrences of exposure and oxidation of acid sulfate soils. Baldwin (2021) describes management interventions including extensive liming and the delivery of 10s-100s GL of water to keep sediments inundated.
Temperature Temperature variations in rivers resulting from summer heatwaves warming low flows or cold water released from dams harm river fauna and flora (MDBA 2022). Differential heating of water in large storages, lakes and weir pools can result in thermal stratification and promote the growth of toxic cyanobacterial blooms (see below). When stratification breaks down the resulting hypoxic water can result in fish deaths (Baldwin 2021). High water temperatures promote the growth of pathogens including *Naegleria fowleri* with adverse impacts on human health (Bursle and Robson 2016).	Climate change induced temperature increases (Section 3.1) are predicted to increase potential evaporation, and in those regions in the MDB where reduced rainfall is projected, significantly decrease runoff and streamflow, and reduce soil moisture. Higher temperatures will impact physical, biological and biogeochemical processes affecting water quality (Baldwin 2021). Saturated DO concentrations will be lower (see below) and thermal stratification will be stronger. Higher water temperatures will impact organisms in aquatic ecosystems having temperatures already close to the organism's thermal tolerance. Higher water temperatures will increase consequential threats including toxic cyanobacterial blooms and blackwater events (see below). Higher temperatures will also increase the potential for pathogens.

Water quality issue	Predicted threat to MDB water quality and implications
Low DO levels Low DO levels can occur as a result of drought or flood conditions. During drought, sudden changes in weather condition can result in oxygen levels throughout a water column quickly reducing when thermally stratified water bodies with deeper, low oxygen layers mix rapidly with oxygenated surface layers. During floods, large inputs of organic matter creating a blackwater event can rapidly consume the oxygen in a water body for it to become hypoxic (see below). Low DO levels kill aquatic life (MDBA 2022).	Higher temperatures, extended droughts and high-intensity rainfall events resulting from climate change are predicted to lead to more occurrences of low DO levels in waterways.
Consequential threats	
Cyanobacterial blooms and toxins Cyanobacteria are stimulated to bloom proportions by nutrients, high water temperatures and slow-moving water having low turbidity. Their toxins impact water quality for water supplies, primary production, recreation and the environment. Their other environmental impacts are described in Section 2. The occurrence, frequency, duration and extent of major cyanobacterial blooms increased in the MDB over the past 15 years compared with the previous two decades, extending for hundreds of river kilometres and having major economic, environmental and social impacts. Of five major bloom events in the Murray River in the last 13 years, four were related to low stream flows within droughts, and one was related to elevated water temperatures. If temperature was the main cause, it highlights the likelihood of more blooms of this type occurring (Baldwin 2016).	Climate change impacts of higher temperatures, greater intensity rainfall events (with greater nutrient inputs into waterbodies), longer intervening drought periods, longer periods of high evaporation and thermal stratification, reduced mean annual flows, and decreased freshes are predicted to increase the occurrence, frequency extent and duration of cyanobacterial blooms. Under climate change conditions the concentration of cyanobacterial toxins in waterways is expected to increase (Reichwaldt and Ghadouani 2012). The compounding impacts of climate and other anthropogenic changes could be effectively addressed by the development and implementation of a comprehensive MDB cyanobacterial management strategy comprising integrated multi-management approaches operating at local, catchment and MDB scales (Verhoeven, Khan et al. 2023). Management approaches could include preventative measures such as reducing nutrient accessions to waterways, interventions to control the growth of blooms, and mitigation measures such as water supply treatment to remove toxins. Baldwin (2021) identified the need for detailed three-dimensional hydrodynamic models for large MDB wter storages to help manage and prevent blooms.
Blackwater events Blackwater events are characterised by high concentrations of DOC in water resulting from organic matter washed by floods into water bodies from floodplains and dry water courses. They release chemicals to change river water pH and deplete DO in the water following droughts or bushfires. Blackwater events impact drinking water quality (Mobius 2012) and kill fish and crustacea (Whitworth, Baldwin et al. 2012). The climatic conditions that combined to produce blackwater events in the Murray River in 2010-11 (Whitworth, Baldwin et al. 2012) and in the lower Darling River in 2018-19 (BoM 2020) were considered extreme and unseasonal.	Climate change impacts include more regular bushfires, more extreme weather patterns and reduction in the frequency of overbank flows. As a result, organic matter will accumulate on floodplains and only wash into waterways during large floods, resulting in a greater chance of a blackwater event (Baldwin 2021). An intervention to minimise the risk of these events would include more frequent managed flooding to reduce build-up of organic matter on floodplains. The BRAT model gives river and floodplain mangers the ability to assess the risk of hypoxic blackwater formation prior from proposed floodplain watering (Whitworth and Baldwin 2016).

The impacts of the predicted threats (Table 4) occur locally but can also magnify downstream under low flow conditions which can reduce dilution of salt loads, toxins and nutrients, reduce turbulence in waterways, or reduce connectivity (RM Consulting Group Pty Ltd 2020). We predict that the downstream impacts of these threats will be further magnified under future more sustained low flow conditions. Impacts can also magnify downstream under high flow conditions which can increase nutrient, organic matter and sediment loads resulting in increasing cyanobacterial blooms, blackwater events and higher turbidity respectively.

The SW-GW interaction (Figure 2) shows that water quality is also determined by the connectivity between surface waters and groundwater systems. The freshwater lenses that are formed over saline groundwater protect river water quality, and if salt moves into rivers it is diluted and flushed (MDBA 2020c). As connectivity also enables nutrients, pesticides and other contaminants from groundwater systems underlying irrigation areas to move to surface waters, it is important to maintain the relative pressures of groundwater systems so that poorer-quality groundwater does not contaminate better quality groundwater or surface water. We predict that future decreased surface flows and longer dry spells will adversely impact connectivity and resulting MDB water quality. Decreased surface flows will increase the importance of groundwater systems providing baseflows to maintain connectivity. However decreased flows will also increase the demand on groundwater systems for water supply, potentially lowering groundwater pressures and reducing connectivity to surface waters.

An added complexity to predicting long-term water quality and its impact on uses is that the potential for climate change to alter surface water and groundwater chemistry is not fully understood. For example, water for human consumption will be vulnerable both as a result of increases in periods of low-flows and cease-to-flow events, allowing contaminants to concentrate in water sources, increasing cyanobacterial blooms, and as a result of increasing runoff pollution resulting from extreme rainfall/flooding events. Potential changes in water chemistry could alter pathogen composition in raw water. We predict that the impacts of these water quality threats will increase, with higher water treatment costs to address salinity, cyanobacterial toxins, biomass (clogging pumps), taste and odour.

Climate change has “significantly challenged water availability, use and management” in the past decade in extreme climate conditions (MDBA (2020a, 2020b)), These extreme conditions and resulting extreme water quality events are likely to become more common and probably more severe under climate change (Baldwin 2021, Beavis, Wong et al. 2023). Research is needed to improve understanding of how changes in climate conditions and in resulting flow regimes generate water quality threats, and of the management strategies required to address the threats (BoM 2020). Furthermore, as shown in Table 4, it is no longer sufficient to manage just water quantity in the MDB; water quality management is also essential.

4. Adaptation opportunities for MDB water quality

4.1 Review of MDB water policy and management reforms

Water quality presents challenges and opportunities for adaptive management of the MDB, through the integrated use of policy, management, and technology, to reduce uncertainty for various uses and adapt to climate change. The impacts of the Millennium Drought in the MDB and of climate change projections accelerated the development and implementation of water policy and management reforms. These reforms included the development of a MDB Plan, development of consistent regional water resource plans, expenditure of over A$12 billion and environmental watering strategies (Hart 2016, MDBA 2020a, Lawrence, Mackey et al, 2022).

Recent reviews of MDB volumetric water policy and water management reforms have implications for the adaptive management of MDB water quality. While environmental flows are being actively managed as part of the MDB Plan, only small environmental improvements have been achieved at basin-scale (Grafton 2021). Reasons for this include poor definition and establishment of environmental watering targets (Wentworth Group of Concerned Scientists 2021, Colloff and Pittock 2022), and constrained water management and planning resulted in failure to achieve well-timed, effective and efficient use of environmental water (Chen, Colloff et al. 2021).

Five major limitations of water policy and management related to water quality and climate change have resulted in under-delivery of environmental improvements in the MDB. Firstly, insufficient consideration of basin-scale risks, the greatest being no direct allowance of climate change and its impacts on different uses in the MDB Plan (Colloff and Pittock 2022). Secondly, inadequate participatory processes to engage with all relevant stakeholders for all water uses, including consumptive, environmental, recreational and cultural uses, and not just irrigators (Grafton 2021). As argued by Grafton, inadequate participatory processes may lead to perceived or real regulatory capture whereby decision-making for water allocations appears to favour particular interests over the broader public interest.

The third limitation is failures in monitoring and compliance in the northern Basin (Grafton 2021). Fourthly, there is a need for more comprehensive remote sensing, basin-wide modelling and basin-scale water accounting and auditing (Wentworth Group of Concerned Scientists 2021), and to reduce uncertainties in the components of surface water balances (Prosser, Chiew et al. 2021). The final limitation is using a 10-year planning horizon when many decisions have much longer lifetimes, resulting in small incremental changes to water plans while the MDB could be undergoing major transformation as a result of climate change and other drivers (Prosser, Chiew et al. 2021).

4.2 Adaptive management to deliver MDB water quality

Comprehensive volumetric water policy and management reforms for the MDB provided a starting point for improved MDB water management in the 2000’s, but they addressed water quality issues in only a limited way and did not consider climate change. A major change in approach is required to adapt to climate change and to achieve sustainable long-term water quality outcomes and uses for the MDB. We have identified nine steps to deliver MDB water quality outcomes, using the water quality policy framework (Figure 3) adapted from the NWQMS. We commenced with the current water quality condition of the MDB (Section 2) to address predicted climate change threats for future (50-year) MDB water quality (Section 3) and current limitations of water policy and management reforms (Section 4.1). Our nine recommendations (Figure 5) are interlinked, and all must be implemented to deliver a healthy MDB that meets water quality needs of all users.

Problem framing

1. MDB multi-level natural resources risk-based governance framework.
2. Indirect climate change impacts on water quality and quantity.

Policy framing

3. Water quality and quantity objectives and SMART targets.
4. Multiple climate change scenarios.
5. 50-year perspective for climate change.

Implementation

6. Comprehensive, integrated water quality/quantity management strategies for water quality.
7. Integrated land and water management.

Monitoring and evaluation

8. Water monitoring, accounting, modelling and reporting using digital tools.

General elements

9. Policy and institutional arrangements for effective water quantity, water quality and ecosystem management.

Figure 5: Water policy and management recommendations to deliver MDB water quality.

The nine recommendations for the MDB include:

1. SW-GW interactions for the MDB (Figure 2), including the main issues and interdependencies of water quantity, water quality and ecosystems, need to be better understood and formalised in the MDB Plan. As there will not be sufficient surface water of fit-for-purpose quality to meet all the current uses in a future MDB, it will be necessary to implement catchment management measures to complement flow management.
   Develop a multi-level natural resources risk-based governance framework for the MDB to coordinate and integrate land and water management; water volumetric, water quality and ecosystem management; surface water and groundwater systems and their connectivity; in a hierarchy of basin, catchment, and sub catchment plans. The Commonwealth Water Act (2007) and the MDB Plan will need to be amended to formalise the inclusion of water quality and ecosystem management.

2. While the direct impacts of climate change on MDB water quality are generally understood (Table 4), there are gaps in our understanding of indirect impacts.
   Assess climate change indirect impacts on water quality and quantity, including changes to catchment vegetation, changes to fire regimes, and changes to water chemistry. These

impacts have the potential to create new water quality issues and risks to water uses, and their assessment is consistent with recommendations by the MDBA (2020c).

3. **Develop or update water quality and water quantity objectives and specific, measurable, achievable, relevant, and time-bound (SMART) targets** for MDB water uses and evaluate their vulnerability to future changes (Wentworth Group of Concerned Scientists 2021). Water quality targets, related to water quantity and ecosystems, should be consistent across the MDB, across the State and Territory jurisdictions within the MDB, and across water quality management strategies within the MDB. The outcomes and implications of monitoring and modelling should be reported regularly and promptly to governments and communities, to help maintain their commitment and involvement.

4. We assessed the predicted threats to future (50-year) MDB water quality and implications as anticipated under a hydroclimate scenario (Table 3) from Zhang, Zheng et al. (2020). They envisage that other hydroclimate scenarios and associated threats to water quality should also be assessed.
   Assess multiple climate change scenarios, their risks and impacts on water availability and surface water-groundwater connectivity, and options for users' vulnerabilities, to identify and manage the risks of water quality degradation.

5. As described in Section 4.1, 10-yearly planning horizons may not include all the rapidly changing conditions resulting from climate change, or may overstate uncertainties, and a longer-term perspective to risk is required to secure reforms and investments.
   Assess climate change scenarios using a 50-year long-term perspective, to develop actions that should be taken over the next 10-year iteration of the MDB Plan and improve its long-term adaptability, consistent with a recommendation of Prosser, Chiew et al. (2021). .

6. **Develop, evaluate and implement comprehensive, long-term integrated water quality and water quantity management strategies for water quality** issues including cyanobacterial blooms and blackwater events, using the successful approach of the BSMS2030 (Section 2). The BSMS2030 shows the value of long-term bipartisan and bilateral agreements at Commonwealth and State governments' levels, and commitment of and resourcing by governments at all levels, as opposed to incremental policy and management updates, short to medium term catalytic funding, and disagreements between governments on water uses. By contrast, integrated strategies to manage cyanobacteria were developed and implemented in NSW in 1992 (NSW Blue-Green Algae Task Force 1992) and in the MDB in 1994 (Murray-Darling Basin Ministerial Council 1994), but both strategies were subsumed into general departmental operations after around seven years, with resulting loss of focus and resourcing.
   Water quality and water quantity management strategies will need to be implemented over a range of timeframes, spanning decades. For example, a comprehensive cyanobacterial management strategy for the MDB should integrate real-time mitigation measures, waterway management for bloom control over 20-30 years, and long-term (50+years) preventative land and water management measures.

7. **Develop and implement integrated land and water management measures** or integrated catchment management (Blackmore 1995, Bellamy, Ross et al. 2002) to optimise sustainable MDB water quality outcomes. Water quality for some uses such as town water supply is likely to be achieved via one or more pathways including treatment infrastructure and flow management. For other uses such as environmental, given the magnitude of reductions to flows and changes to quality, decisions will need to be made about which species and water dependent ecosystems can be supported. Similarly for cultural, social and industrial uses, decisions may need to be made about which activities can be supported within each use. Decision making could draw on adaptation pathways approaches (Wentworth Group of Concerned Scientists 2021), or conservation planning principles to assist in identifying how and

where environmental assets should be protected (Prosser, Chiew et al. 2021). A dominant theme in the conservation literature is to rationalise and optimise prioritisation, using mathematical algorithms and cost-effectiveness analysis (Wilson, Carwardine et al. 2009). However, decision making is not always rational, with policymakers drawing on many sources of information to make decisions. Many water use decisions (volumetric and quality) are highly complex, and given the size of the MDB, decisions will involve trade-offs between multiple objectives, values and interests (Evans et al. 2017, Evans 2021).

8. As described in Section 4.1, measures are necessary to provide better accounting for uncertainties in the MDB water balance so that they are not disproportionately carried by environmental water uses (Prosser, Chiew et al. 2021), and so that they provide better predictive capacity for water managers to respond effectively to water quality emergencies and to maintain acceptable water quality for its various uses.
   Upgrade water volumetric (resource and extraction) and water quality monitoring, use double-entry water accounting for both quality and quantity, develop a new basin-wide model to replace the various State agency models, conduct independent and transparent reviews and audits, and make water data publicly available (Wentworth Group of Concerned Scientists 2021, Colloff and Pittock 2022).

9. As noted in Section 4.1, there is a need for MDB participatory processes to engage with all relevant stakeholders for all water uses, including consumptive, environmental, recreational and cultural uses (Grafton 2021). The traditional approach has been government-led, with agencies helping the wider community (MDBA 2020c). There is a need to assess if this is the most appropriate approach to combine governments' resourcing of technical assessments, monitoring, modelling and evaluation with community/industry-led visioning, learning and resourcing.
   Assess what policy and institutional arrangements are needed for effective water quantity, water quality and ecosystem management for the MDB. As shown in Figure 3, this includes public participation and community involvement, policy coordination and integration, communication, transparency, and potentially institutional change.

4.3 Visions of water quality for the MDB in 50 years

Under a changing climate, there is a range of possible visions for MDB water quality in 50 years. Based on the hydroclimate scenario in Table 3, current MDB water quality condition (Section 2) and climate change challenges for future (50-year) MDB water quality (Section 3), two competing qualitative visions are presented below: a degraded MDB with poorer water quality limiting water uses, or a healthy MDB with water quality targeted to meet consumptive and environmental water uses identified in the original 2012 MDB Plan. Which vision is realised depends on actions taken by governments, MDB communities and industries as part of the 2026 MDB Plan review.

4.3.1 Vision 1: a degraded MDB

For the hydroclimate scenario in Table 3 which best describes our view of future climate in the MDB, and if current limitations of water policy and management are not addressed (Section 4.1), water quality will degrade from its current condition (Section 2) for three reasons. First, maintenance of currently agreed water sharing outcomes between consumptive and environmental uses will change in favour of consumptive uses if current policy and management settings are not updated (Prosser, Chiew et al. 2021). Second, incremental improvements to water policy and water management in 10-year steps, slow to address concerns described in Section 4.1, will be unable to keep pace with rapid, longer-term 50-year hydroclimate changes and water quality degradation. Finally, continued separate responses to managing water quality and quantity, and to managing water and land, including implementation of separate water resources plans and catchment management plans at a state and not a basin-scale, will result in sub-optimal solutions to address water quality threats.

Under this vision it is expected that the threats to future MDB water quality described in Section 3.2, viewed as extreme and unseasonal in the recent drought, will become more common and severe. Salinity levels may be higher in the southern Basin than at present, and greater volumes of sediments and nutrients N and P are predicted to be washed into waterways during larger but infrequent flooding events, particularly in the northern Basin. The high intensity storm events may result in episodes of waterways contaminated with metals, other toxic compounds, and low pH. There will also be the potential for increased occurrences of exposure and oxidation of acid sulfate soils in the southern Basin. Higher temperatures and more frequent heatwaves will adversely impact the health of aquatic ecosystems and fish species. More frequent occurrences of low DO levels in waterways are predicted.

Increased occurrences of the above primary threats will result in worsening of consequential threats Major cyanobacterial blooms are expected to become a regular occurrence throughout the MDB, increasing in frequency, lasting for longer periods, comprising more species and with higher concentrations of toxins in waters. Blackwater events are predicted to become a more regular occurrence throughout the MDB and increase in frequency.

Given that some ecosystems, primary production, and communities were vulnerable in recent droughts, and that vulnerabilities are likely to increase, it is expected that in future it will not be possible to protect all current water uses. In this vision of the future, the MDB is predicted to support fewer communities, less irrigation and other primary production, fewer and smaller water-dependant ecosystems, less water for First Nations cultural use, and less water-based recreation. This is consistent with findings that some ecosystems will fundamentally change (MDBA 2020c), and that only a minority of wetlands will be protected by environmental watering (Chen, Colloff et al. 2021). Water treatment costs for communities in the MDB, and for Adelaide and other South Australian cities and towns which obtain their water supplies from the MDB, are expected to increase.

4.3.2 Vision 2: a healthy MDB

For the hydroclimate scenario in Table 3, a healthy MDB includes water quality targeted to meet consumptive and environmental water uses identified in the original 2012 MDB Plan. We have selected the 2012 MDB Plan as it describes water quality targets for water uses which are understood and measurable, and to which governments, communities and industries have previously agreed. To achieve this will require formidable and on-going implementation by governments, communities and industries of our nine recommendations (Section 4.2). The suite of recommendations is more ambitious than that described by the MDBA in its preparation for the 2026 review of the MDB Plan (MDBA (2020a) and MDBA (2020c)).

The vision for water quality in a healthy MDB includes salinity levels in the southern Basin which may increase marginally and stabilise as a result of reduced flushing flows, such that the salinity level in the Murray River at Morgan in SA may be between 350 EC and 300 EC. Nutrient and sediment accessions to waterways, and turbidity levels in waterways would both be reduced to around 2012 levels by implementing nutrient and sediment management strategies throughout the MDB. Accession of metals and other toxic compounds to waterways would be reduced by implementing land management measures addressing point and diffuse sources of these chemicals. Higher and low temperatures in rivers would to be reduced by revegetating riverine corridors and mixing waters in storages to reduce thermal stratification respectively.

The occurrence and frequency of major cyanobacterial blooms would be reduced, not increased, from current levels by reducing nutrient accessions to waterways, better targeting flushing flows, and managing conditions in weir pools and other waterways under an overarching cyanobacteria management strategy. Finally, occurrences of blackwater events and of low dissolved oxygen events would be stabilised by managing the accumulation of organic matter on floodplains, and the strategic use of overbank flows.

All nine recommendations need to be implemented to deliver a healthy MDB, and their implementation would address the impacts of our hydroclimate scenario by redistributing the predicted reduced flows to meet optimised consumptive and environmental uses. The recommended actions would counterbalance the reductions in flushing flows and other hydroclimate impacts with benefits from the implementation of land management measures such as reducing the accessions of nutrients, sediments, metals and other toxic compounds to waterways. Finally, the reforms would better account for all components of the water balance to improve predictive capacity for water managers to respond effectively to water quality emergencies and to maintain acceptable water quality for various uses.

5. Conclusions

Under climate change, what were historically extreme climate events in the MDB resulting in major cyanobacterial blooms and blackwater events are likely to become more common and probably more severe. Maintaining the current incremental approach to water policy and management reform will not address all the impacts of climate change and is likely to lead to further degradation of MDB water quality, limiting future water uses.

We have made nine recommendations to address climate change and to achieve sustainable long-term water quality and quantity outcomes and uses for the MDB. Our recommended approach considers SW-GW interactions (Figure 2), all climate change and other anthropogenic impacts and natural risks to water quality and is built on implementing a long-term, integrated, comprehensive participatory process by governments, communities, and industries. The nine recommendations are interlinked, and all must be implemented to deliver a healthy MDB having water quality and quantity needs of all users.

Our approach requires long-term bipartisan and bilateral agreements at Commonwealth and State governments' levels, and commitment of and resourcing by governments at all levels. Our recommendations require elevating water quality protection and management to optimise fit-for-purpose water having different qualities to meet consumptive and environmental water use objectives.

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Australian Academy of Technological Sciences & Engineering

MURRAY-DARLING BASIN ESSAY

Essay #3 in a series of nine by Australia's leading water experts

Surface water and groundwater connectivity in the Murray-Darling Basin: Integrated management of connected resources

Andrew Ross and John Williams

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Above: The gates opening on Lock 11 on the Murray River near Mildura. ncox1585, iStock.

EXECUTIVE SUMMARY

Ross and Williams state that the increased use of groundwater, supporting baseflow to the unregulated rivers, depletion of streamflow due to water extraction and changes in weather conditions are due to identifiable risks (i.e., climate change, irrigation and floodplain harvesting, afforestation, coal seam gas and coal mining) associated with groundwater-surface water connectivity. Drier seasons always worsen these risk factors.

They also mention that improvements and expanded coverage in integrated groundwater and surface water models are essential to develop the integrated management of those resources. These will require enhanced long-term monitoring, assessment and effective management.

Additional investments will be required to improve the accuracy of measurements and the interpretation of monitoring results, and to extend and improve integrated modelling of connected water resources, taking account of the impacts of climate change and cross impacts of extractions."

Surface water and groundwater connectivity in the Murray–Darling Basin: integrated management of connected resources

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Summary and vision

Integrated management of connected groundwater and surface water resources in channels, floodplains, and wetlands is essential in order to achieve optimum use of Murray–Darling Basin (MDB) water resources and storage for human and environmental purposes. Although Australian legislation and policy provides a basis for the management of connected water resources, there are serious weaknesses in the implementation of integrated groundwater and surface water management.

To better identify risks associated with managing groundwater-surface water connectivity due to an increase in groundwater use and climate change requires greatly improved coordination with Basin state governments, giving particular attention to leveraging existing knowledge as well as generating new knowledge to ensure that groundwater policy reform and management is underpinned by the best available science.

In short, to address these risks will require the Basin Plan to be significantly amended in terms of the current risk framework, and in particular, give attention to: a more precise definition of groundwater-surface water connectivity so to clarify the meaning of material impact of significant cross-resource connections; to include measurable indicators of connectivity; and to include targets to measure progress in relation to groundwater-surface water connectivity.

The Basin Plan should be amended to include an agreed assessment time frame to be applied to the estimation of water balances and resource condition indicators, including predictions of drawdown and evaluation of risk of long-term changes in groundwater salinity and water quality.

This extended framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected water resources and ecosystems would facilitate such considerations being fully incorporated in the water resource plans (WRP), which are cornerstones of the Basin Plan.

This would extend current arrangements by requiring the WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks when connectivity is expected to be reduced; and impacts of extractions on an expanded range of groundwater-dependent ecosystems (GDEs) including baseflows, aquatic ecosystems, terrestrial vegetation, and subterranean ecosystems. Implementation of WRPs will be improved by context-specific rules and tools to manage impacts of climate change and extractions, integrated management of water storage and water banking, and long-term measurement and monitoring.

This vision for integrated management of connected groundwater and surface water resources will require the following enabling conditions:

- the volume of connected groundwater and surface water, their uses and their connections, will be measured or estimated and monitored;

- groundwater and surface water planning and allocation will fully account for the impacts of water use on connected resources and ecosystems, and manage these resources to achieve socially acceptable socio-economic and environmental outcomes; and
- the values of groundwater and surface water resources and ecosystems will be determined in consultation with stakeholders, and water users will pay a socially acceptable charge for water use.

1. Introduction

Australia is the world's driest inhabited continent with highly variable climate patterns, rainfall and water supply with recurrent droughts and floods (Productivity Commission 2021). Droughts (and floods) can have devastating environmental consequences such as algal blooms and fish death events (Vertessy et al. 2019).

There are 2.3 million people residing in the Murray–Darling Basin (MDB or Basin) where 40% of Australia's agricultural production is located. Demand for water in the MDB is increasing because of population and economic growth (Williams 2017), but water availability is falling due to climate change (Prosser et al. 2021). The use of groundwater resources is increasing, especially in dry years.

Effective management of connected groundwater-surface water resources throughout the Basin helps to preserve connections between rivers, aquifers, floodplains, wetlands and flows to the Murray Mouth thereby sustaining groundwater and surface water resources in good condition (MDBA 2020a). But the benefits and risks related to groundwater-surface water connectivity have not been effectively accounted or managed in the MDB.

The extent of groundwater-surface water connectivity and steps towards integrated groundwater and surface water management were documented 15 years ago (Evans 2007). Since 2007 there has been some progress towards recognition of groundwater-surface water connectivity in legislation and policy, and improvements in the classification and measurement of connectivity. But planning and management of most groundwater and surface water resources continues to be separated, with limited or no accounting for connectivity and few examples of integrated water management (Lamontagne et al. 2012; Ross 2014, 2018).

In this essay, we define groundwater-surface water connectivity and outline resource connectivity in the MDB. We summarise the impact of extractions on connected groundwater-surface water resources and dependent ecosystems, and driving forces that will affect future groundwater-surface water connectivity in the MDB including climate change, agriculture, irrigation, and coal seam gas (CSG) development. We review the management of connected groundwater and surface water resources and ecosystems and adaptation to change, and discuss improvements in the management of connected water resources, adaptive management strategies and tools. We finish the essay with proposals for improved management of connected groundwater and surface water resources and ecosystems.

2. The nature of groundwater-surface water connectivity in the MDB and implications of connectivity for water resource management

In this section, we set out elements of groundwater-surface water connectivity in the MDB, and outline impacts of increasing water use on connected groundwater-surface water resources and ecosystems. We also introduce a classification of levels of connectivity.

2.1. Elements of groundwater-surface water connectivity

The importance of groundwater-surface water connectivity and integrated management of connected groundwater and surface water resources is recognised in the National Water Initiative (NWI) (Commonwealth of Australia 2004) and the Murray–Darling Basin Plan (MDBP) (Commonwealth of Australia 2012). The objectives of the NWI include ‘recognition of the connectivity between surface and groundwater resources and connected systems managed as a single resource’ (Commonwealth of Australia 2004, Section 23x). Managing connectivity is fundamental to the purpose of the MDBP ‘to manage the Basin as a whole connected system’ (MDBA 2019). Hydraulic connectivity is defined as ‘the ease with which, or the rate at which, groundwater moves: (a) within an aquifer; or (b) between aquifers; or (c) between aquifers and the adjacent or overlying surface water system’ (Commonwealth of Australia 2012, Part 1.07, Definitions).

Adjacent groundwater and surface water resources are usually connected, although the extent and timing of connection is variable (Evans 2007). Surface water and groundwater connectivity can be evaluated according to three criteria (Conant et al. 2019) as illustrated in Figure 1:

1. The dynamics of groundwater and surface water resources, and their potential to interact at the interface or in the transition zone between resources through groundwater and surface water flows and biogeochemical and biological processes.
2. Processes of groundwater and surface water interaction; their spatial patterns and temporal variability.
3. Potential impacts of groundwater-surface water interaction on water quantity, water quality and ecosystems.

Integrated management of connected groundwater and surface water resources is essential in order to achieve optimum use of MDB water resources and storage for human and environmental purposes. The expected outcomes for managing connectivity throughout the Basin include maintaining baseflow, increasing tributary flow, managing return flows from irrigation to groundwater and streams, increasing flows to the Murray Mouth, mitigating salinity and pollution, and maintaining or reinstating, where possible, connection between rivers, their floodplains, and wetlands (MDBA 2020a). To achieve these outcomes, the surface water and groundwater connections and interactions as depicted in Figure 1 provide the foundation for effective integrated water management in the MDB.

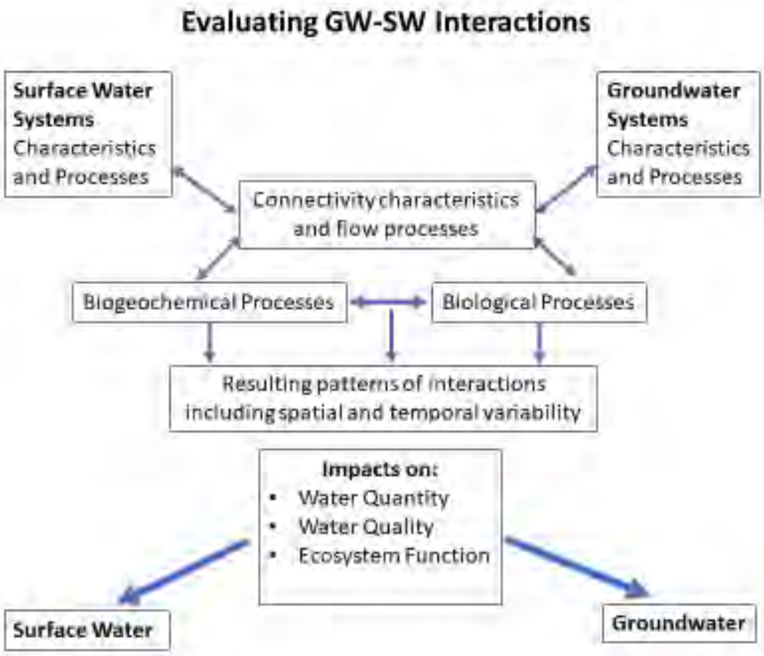

Figure 1. Groundwater-surface water connectivity, interactions, and impacts on water quantity, water quality and ecosystem function. (Redrawn from Conant et al. 2019).

2.1.1. Potential for, and processes of, interaction

Groundwater tends to flow to rivers when the aquifer watertable is higher than the level of the river (gaining rivers). If the watertable is below the level of the river, surface water will tend to flow to and recharge the aquifer (losing rivers). If the aquifer and river are separated by a semi-permeable layer of material (e.g. clay) this will slow the water flow between the two resources (Evans 2007; Jolly et al. 2013). These scenarios are illustrated in Figure 2 below.

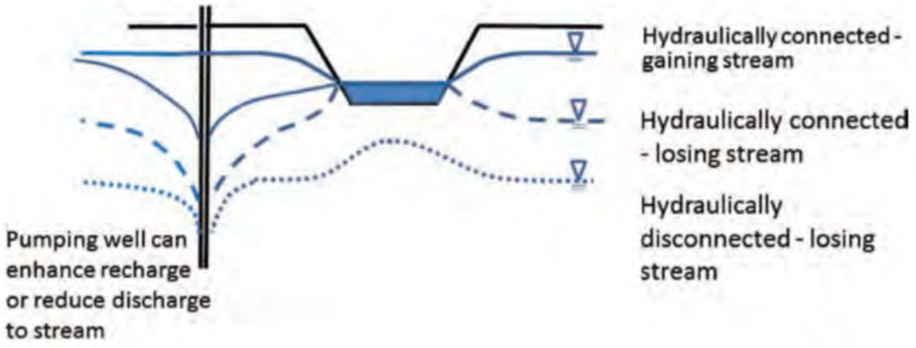

Figure 2. The nature of simple groundwater-surface water connectivity. (Redrawn from Evans et al. 2018).

Groundwater-surface water connections vary spatially along rivers and across aquifers. Rivers may change from gaining to losing, and aquifers may underlie several rivers with different degrees of connection. Groundwater-surface water connections adjacent to a river tend to be stronger and faster than those distant from a river (Jolly et al. 2013), although the nature of the material that the water has to travel through is more important than the distance to the river (Evans 2007).

Gaining and losing rivers at the catchment scale in the MDB were mapped by Parsons et al. (2008) – see Figure 3.1.

Groundwater-surface water connections also vary over time. Surface water responds relatively rapidly to inflows and extractions, often within days or weeks (depending upon the length of the river system). Groundwater systems often respond relatively slowly, and long time-lags are common, extending to years, decades and even millennia (RMCG 2021), and often falling outside the accounting period for state water planning (SKM 2011).

Groundwater-surface water interactions in the MDB occur on a continuum between two endpoints. At one end, groundwater is directly connected to rivers with a 1:1 connection (Evans 2007); at the other end, there is effectively no groundwater discharge to rivers, and instead groundwater discharges to ecosystems (wetland or terrestrial). For example, in mid-river portions of the major rivers in New South Wales (NSW), there is a rapid interchange between alluvial groundwater and overlying surface water, whereas the large groundwater systems of the Riverine Plain are overlain by a semi-confining layer that dampens interaction between groundwater and overlying rivers.

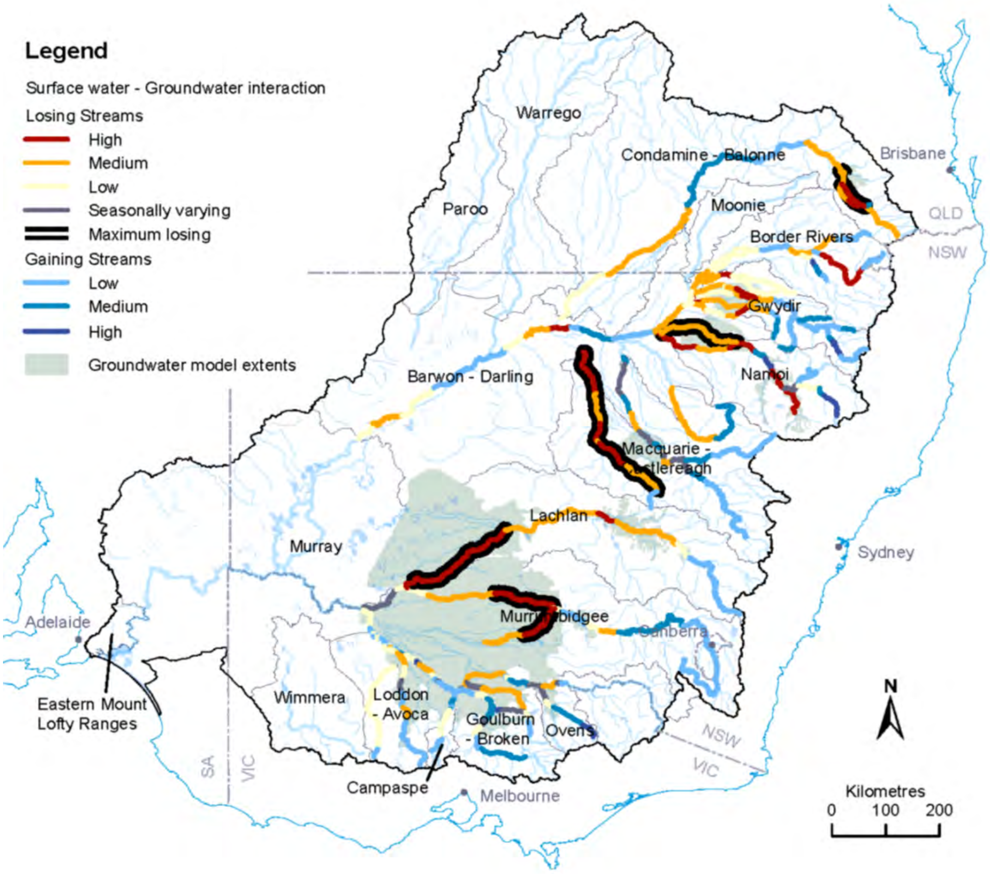

Figure 3.1. Surface water-groundwater connectivity for major rivers of the MDB. (Redrawn from Figure 5.1 of Parsons et al. 2008).

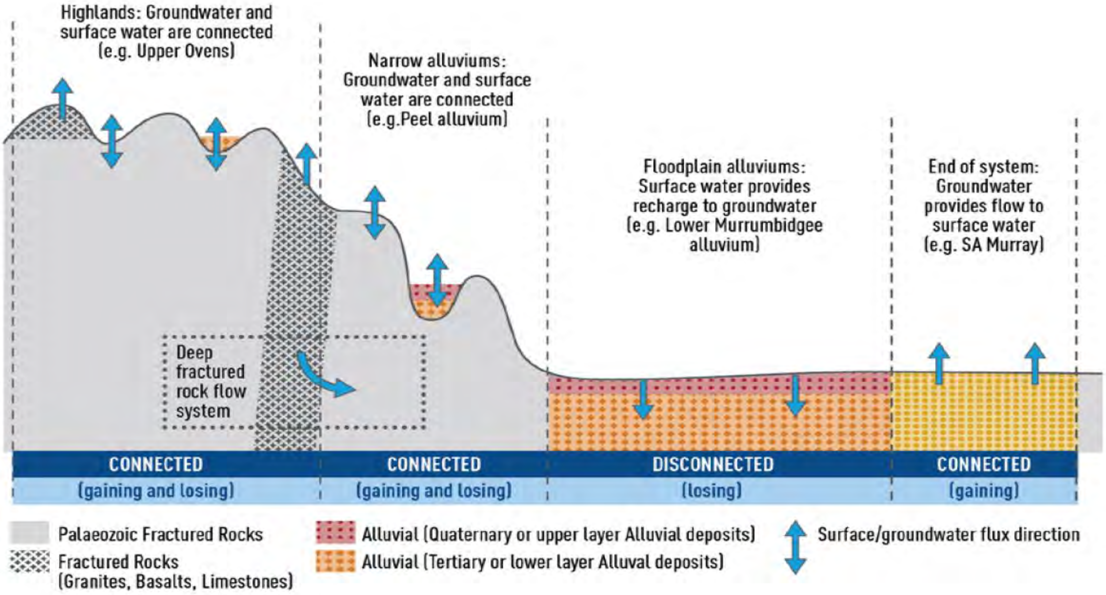

Figure 3.2. Connected systems classification (adopted from Braaten et al. 2001) showing the connectivity between surface and groundwater considering geology and topography (MDBA 2020b).

Figure 3.2 illustrates the river-aquifer connections in the main geomorphological zones in the MDB (Braaten et al. 2001), which can be summarised as follows:

- in upland areas, streams receive flows of freshwater from fractured rock aquifers;
- in mid-sections of larger rivers, high rainfall in narrow floodplains results in shallow watertables with strong river-aquifer connections;
- in the wide semi-arid plains, rivers generally discharge to groundwater systems and freshen the groundwater;
- towards the end of the Murray-Darling system, rivers tend to be neutral or gaining, and the discharge of saline groundwater increases salinity in the lower Murray.

2.2. Human impacts on connected groundwater-surface water resources and their interactions

Groundwater extraction results in a lower watertable that affects surface water flows either by captured groundwater discharge or by induced recharge from surface water. Unless there is a proportionate addition of water from another source, groundwater pumping lowers the flow of groundwater (baseflow) into a connected river or increases the rate at which surface water leaks into a connected aquifer. The relationship between groundwater pumping and river flows is complex, with variable time-lags depending on local geology, topography, vegetation and evapotranspiration (Evans 2007; Hartman 2021).

In alluvial settings where the aquifer and river are closely connected, groundwater pumping has a relatively rapid impact and causes a gradual reduction in streamflow. On flat plains, bores may be located long distances from rivers and the time lags in impacts of groundwater extraction on river flows may be very long. Groundwater pumping from shallow aquifers lowers the watertable and reduces the amount of water available for vegetation and evapotranspiration. Groundwater extraction distant from rivers often impacts on vegetation before streamflow (Evans 2007; Jolly et al. 2013).

The main risks to connected groundwater and surface water resources are from increased extractions, especially in dry years, and climate change (van Dijk et al. 2006). In addition, there are 'synergistic' risks resulting from combined cumulative effects of multiple risks such as lower inflows, declining surface water and aquifer storage, declining water quality, and water supply shortages (Pittock et al. 2023). There has been more attention given to risks to connected groundwater-surface water systems from groundwater extraction than to risks from surface water extraction (Ross et al. 2022).

2.2.1. Estimated impacts of groundwater extraction on connected surface water resources

In 2006, van Dijk et al. cited an estimate of future reductions of surface water resources owing to groundwater extraction ranging between 275 and 550 gigalitres (GL) in 20 years, with a median estimate of 330 GL. Walker et al. (2020a) estimated that the impact from 40 years of growth in groundwater extraction would be up to 580 GL/year, but more likely 100–400 GL/year. On average this represents up to 4% of river flows, using the MDB baseline diversion limit (13,623 GL/year) as an indicator of the available volume of water (Pittock et al. 2023). The impact of groundwater extractions on rivers is much greater than average during low flows (Walker et al. 2020b).

The estimated impacts of increased groundwater extraction are concentrated in a relatively small number of high-impact groundwater management areas (GMA), notably in the Lachlan Fold Belt and the Shepparton Irrigation Region of the Goulburn-Murray GMA (Walker et al. 2020b). Medium to high impacts are concentrated after 40 years, and unlikely within 20 years. However, groundwater extractions are cyclical, with increased extractions during dry periods. After the high levels of extractions during the drought of the 1980s and 1990s, groundwater extractions did not return to the lower levels which existed prior to the drought. This behaviour may be repeated. Therefore, adaptive management is needed to manage the risk that by the time the lagged effects of increased extractions are evident, it will be difficult to reverse them (Walker et al. 2020b).

Also, many groundwater management areas are large, and the spatial distribution of impacts is highly variable. Groundwater extractions can be concentrated in areas of fresh groundwater with high transmissivity, and can cause severe local impacts on environmental flows and ecosystems. These impacts need to be managed by local rules (Walker et al. 2020b).

2.2.2. Impacts of groundwater extractions on groundwater-dependent ecosystems (GDEs)

GDEs can be grouped into three broad classes: (1) terrestrial GDEs, including all vegetation communities that rely on the subsurface presence of groundwater; (2) aquatic GDEs, including riverine baseflows, wetlands and springs that rely on groundwater discharge to surface water; and (3) subterranean GDEs which include aquifer and karst systems (Dabovic et al. 2019).

Groundwater extractions may manifest as reduced streamflow, or other discharge mechanisms, primarily evapotranspiration (Ross et al. 2022). Management of the impacts of groundwater extractions on the quantity and quality of water in shallow aquifers is of vital importance to riverine forests and woodlands dependent on groundwater. Information about these impacts is generally poor, although there has been some progress in understanding the impacts of climate change and land-use change on water yields (Zhang et al. 2018). The impacts of pumping on GDEs are not well understood because of incomplete knowledge about the water needs of GDEs and relationships between watering and different types of GDEs (rivers, wetlands, terrestrial vegetation) (Saito et al. 2021).

2.2.3. Impacts of surface water extractions on groundwater resources

There is a shortage of data and assessments related to the impacts of surface water extractions on groundwater resources. It is easier to obtain estimates of the effects of groundwater pumping on river flow than the impacts of surface water extractions on groundwater. It can be argued that surface water extractions have limited influence on overall groundwater levels in the MDB because most groundwater recharge comes from episodic events (Crosbie et al. 2010), but surface water extractions can have significant local impacts on groundwater levels.

2.2.4. Connectivity between connected water resources and ecosystems in an irrigation zone

Irrigation accounts for about 70% of consumptive water use in the MDB and has a dominant impact on hydrological flows. The interactions between groundwater and surface water in rivers, streams, floodplains, and wetlands are depicted in a systems flow diagram in Figure 4 and illustrated by cross-sectional and oblique view diagrams in Figure 5. Water extraction for irrigation and the return flows from irrigation to groundwater and surface water interact strongly with the flow regimes of Figure 4, and the spatial flooding and drainage patterns in Figure 5, (which are key factors influencing flows to and from groundwater and floodplain wetlands).

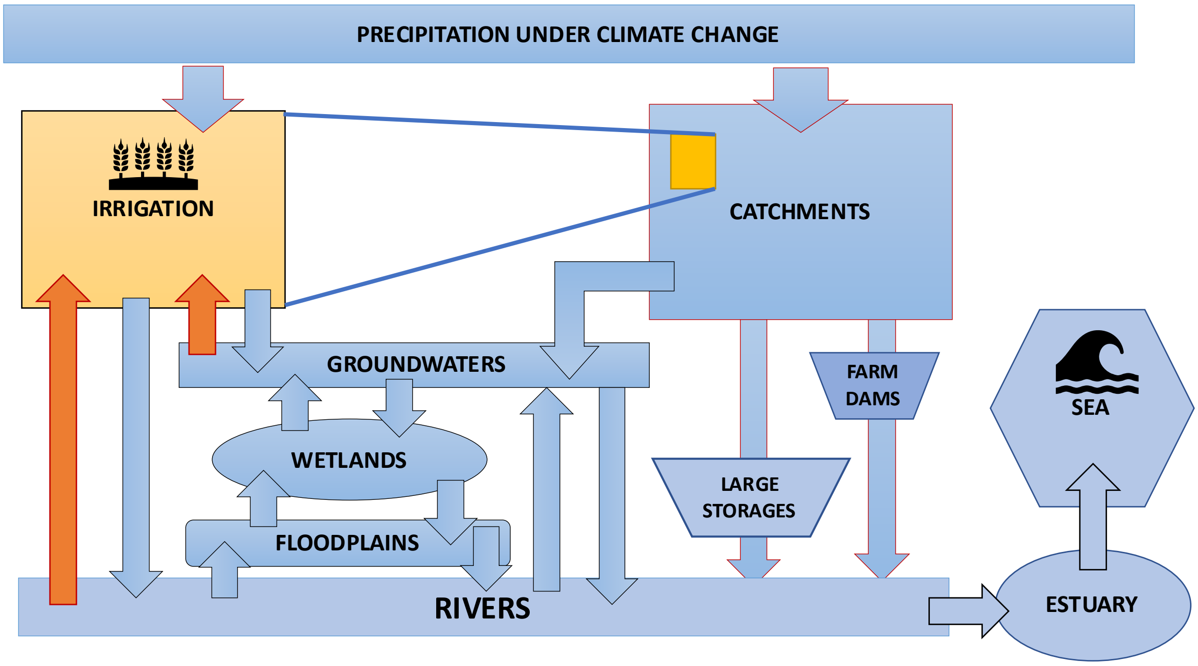

Figure 4. Catchments, farm dams, large storage dams, irrigation areas, rivers, floodplains, wetlands and groundwater connections, management cycles and flows. Consumptive flows to irrigation areas are shown in orange while all other water flows are shown in blue. (Redrawn from Figure 3.01 of Williams et al. 2004).

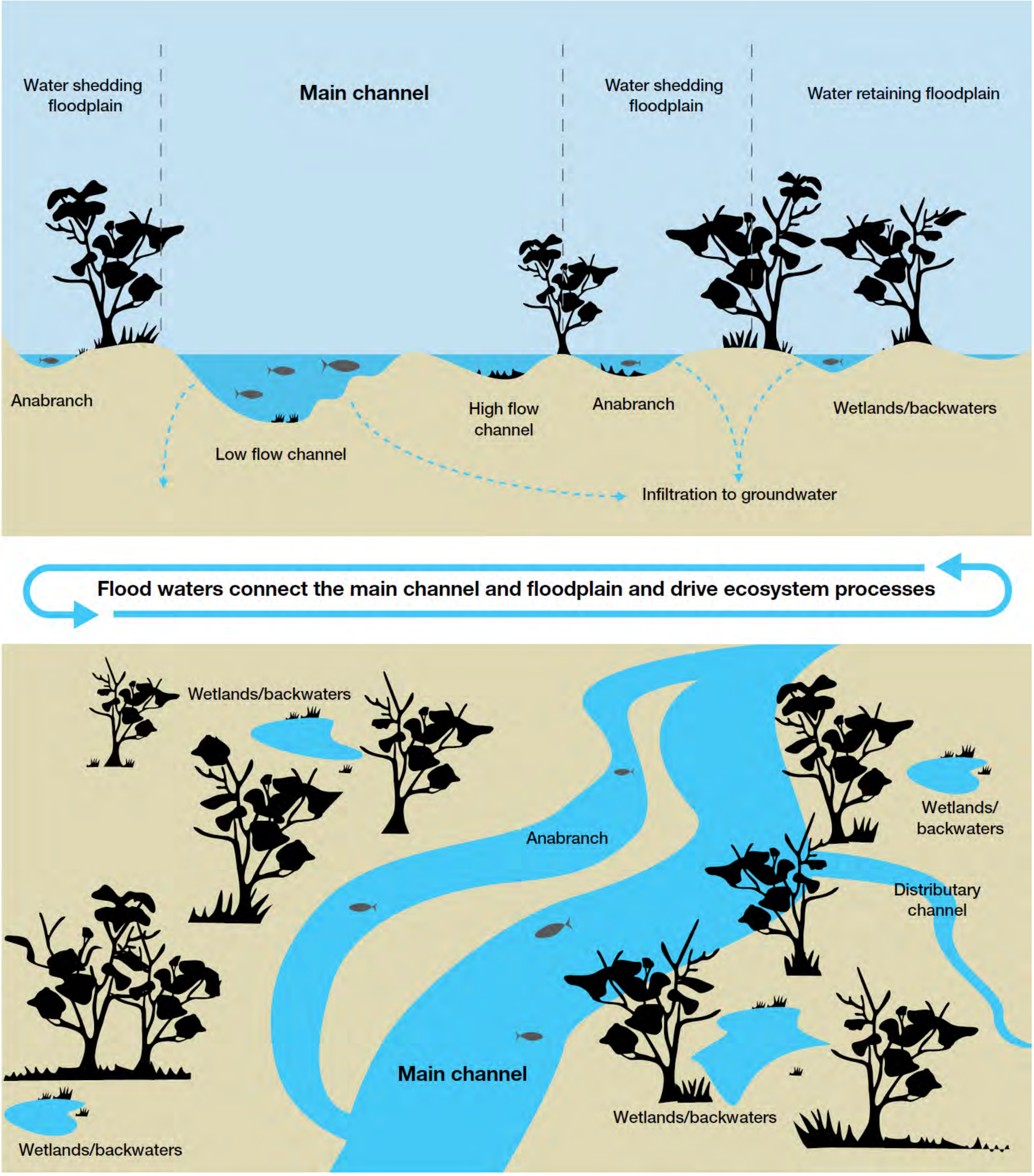

Figure 5. A cross-section and map of surface water connectivity in a riverine floodplain and their connection to groundwater. (From Figure 8.3 of NRC 2009).

2.3. Classification and measurement of connectivity

During the last 15 years, there has been significant development of methods to characterise and measure groundwater-surface water connectivity (Lamontagne et al. 2012). REM (2006) proposed that a definition of surface water and groundwater connectivity should describe the nature, rate, and time frame of the interaction. The definition should be quantifiable and applicable over a range of spatial scales.

The National Framework for Integrated Management of Connected Groundwater and Surface Water Systems (SKM 2011) proposed a three-tier classification of connectivity based on the potential for connection, the time lag between extraction and impact, and other factors important for the management of the system including seasonality and extent of use. In the MDB, the most highly connected systems are the alluvial valleys.

The Murray–Darling Basin Authority (MDBA 2020b) adopted a modified version of this classification as an input for the establishment of sustainable groundwater diversion limits. Connected systems are assessed as high risk when groundwater discharge provides baseflow to the unregulated river reach and groundwater extraction is likely to result in streamflow depletion. Systems are assessed as medium risk where more than 50% of groundwater extraction would have contributed to river flow within 50 years, and as low risk when less than 50% of groundwater extraction would have contributed to streamflow within 50 years. The MDBA considered that extractions to manage salinity and water logging in shallow groundwater systems are low risk to the groundwater system and beneficial to connected surface water.

3. Driving forces and risks that affect water resources and water resource connectivity in the MDB

Major driving forces and risks affecting connected groundwater and surface water resources and impacts of extractions on water resources and dependent ecosystems include climate change, irrigation and floodplain harvesting, afforestation, coal seam gas and coal mining.

Climate change is leading to reductions in rainfall, reduced river flows, and reduced groundwater recharge. Medium to large flows and overbank flows will become less frequent (Prosser et al. 2021) and water quality problems will increase (Beavis et al. 2022).

The most at-risk groundwater systems are sedimentary and alluvial systems dominated by diffuse recharge (Fu et al. 2019).

Demand from agriculture and irrigation for water is projected to increase, especially under dry climate scenarios (Gupta et al. 2020). Increased irrigation efficiency and floodplain harvesting is leading to reduced groundwater recharge and river flows (Williams et al. 2022).

Although the impacts of increased afforestation on MDB water resources has been relatively small, further research and analysis is required on the effects of changes in crop mix and carbon plantings on groundwater-surface water connectivity (Lane et al. 2022).

There are significant uncertainties about the impacts of coal seam gas and coal mining on groundwater-surface water connections, and the cumulative impacts on ecosystems and communities (Williams et al. 2012).

The impacts of these driving forces and risks on MDB water resources are summarised in Table 1.

Table 1. Impact of climate change, changes in irrigation, and coal seam gas extraction on connected groundwater and surface water resources, ecosystems and water quality.

Driver	**Impact of driver on GW-SW connections**	**Impact on connected water resources and water quality**
Climate change	– Reduced GW flow to SW – Reduced SW flow to GW – Reduced GW recharge	– Reduced GW levels and storage – Reduced GW baseflow and contribution to river flow – Deterioration in water quality
Irrigation and floodplain harvesting	– Reduced return flows from irrigation to GW – Reduced SW flow and GW recharge	– Reduced GW levels and storage – Reduced GW contribution to river flow
Coal seam gas extraction	– Changes and reversals in GW flow paths – GW contamination	– Reduced GW contribution to river flow – Deterioration of GW quality

4. Legislation, policy, and adaptive management

The following section reviews current federal and state government approaches for defining and measuring groundwater-surface water connectivity, managing cross-connection impacts of groundwater and surface water extractions, and outlines adaptation to changes affecting connected water resources.

4.1. Legislation and policy related to the management of connected surface water and groundwater resources

The MDBP and state WRPs recognise connectivity between surface water and groundwater resources and require protection and/or restoration of connectivity. They do not, however, clearly define how risks related to connectivity are assessed, or what measures are to be incorporated to address the identified risks (Ross et al. 2022).

4.1.1. Treatment of groundwater-surface water connectivity in the MDBP

The MDBP requires protection and restoration of connectivity between water-dependent ecosystems, ensuring that processes dependent on hydrologic connectivity between the surface and subsurface are protected and restored (Commonwealth of Australia 2012, Section 8.06, (3)(b)(iii)). The MDBP also provides that state WRPs:

- have regard to the management and use of resources which have a significant connection to the water resources of the WRP area (MDBP, Section 10.05);
- set out monitoring and actions to respond to groundwater take (MDBP, Section 10.14);
- have regard to whether it is necessary to have rules that ensure that the operation of a groundwater resource plan '… does not compromise the meeting of environmental watering requirements (for example, base flows)' (MDBP, Section 10.19 (1)).

However, the MDBP does not include a clear definition of significant groundwater-surface water connectivity, or any indication of how significant groundwater and surface water connections will be measured. While the MDBA has had exhaustive consultation with the states to define 'significant hydrological connectivity', a consistent approach between states has not been achieved (Ross et al. 2022). In effect, this leaves the definition and measurement of connections with the Basin states to be managed through state WRPs.

Section 10.19 of the MDBP includes two criteria for significant connection between surface water and groundwater: (i) that water from one resource is physically able to move to the other, and (ii) that activities in one resource may have a material impact on the state of the other. However, there is no guidance on how material impact of *extractions* on connected water resources is to be determined, which creates the risk that some significant impacts will remain uncontrolled (Ross et al. 2022).

Schedule 7 of the MDBP defines targets to measure hydrological connectivity between the river, the floodplain and valleys, but neither the MDBP nor its schedules include targets to measure progress on maintaining connections between groundwater and surface water resources (Commonwealth of Australia 2012).

4.1.2. Management of groundwater-surface water connections in state water resource plans (WRPs)

(a) Definition of hydrologic connectivity, risks related to connectivity and their significance

The lack of a precise definition in the MDBP of groundwater-surface water connectivity and material impact of activities, including extractions, allows MDB jurisdictions to establish varying, inconsistent definitions of connectivity and material impacts. New South Wales established a narrow definition that required 70% of groundwater pumping to be drawn from streamflow within an irrigation season. Victoria has not set a specific threshold.

In addition, there have been differences between the treatment of surface water-groundwater connectivity in surface water and groundwater plans. In the first generation of state WRPs, most groundwater plans recognised that connectivity exists, and a few included measures to address it, but most surface water plans assumed that connectivity does not exist or was not a significant issue (Ross 2014, 2018).

(b) Rules to manage risks related to groundwater-surface water connections at different spatial scales

The MDBP (Section 10.19 (2)) specifies that WRPs for groundwater with a significant hydrological connection to surface water may include rules to prevent impacts on environmental watering requirements. These may include resource condition limits and rules that limit the times, places and rates at which groundwater can be taken.

At the Basin and catchment scales, the risks to connected water resources posed by overextraction are managed by volumetric sustainable diversion limits (SDLs) and allocations. The MDBA considers these risks to be low because more than two-thirds of the groundwater SDL resource units have average annual use levels 50% below the unit SDL (MDBA 2019), although groundwater use can rise substantially in dry years, such as 2019.

Most water management areas in the MDB are relatively large and local cross-connection impacts of extraction on connected water resources are highly variable. Local management rules administered by the states are used to manage high cross-connection impacts of extraction (Stewardson et al. 2021), such as high groundwater extractions near to a river and impacts of extractions on aquatic ecosystems with high ecological value. In practice, most jurisdictional management effort is prioritised towards 'hot spots' with high levels of groundwater 'take' and relatively rapid cross-connection impacts such as larger alluvial systems (e.g. Gwydir, Murrumbidgee, Murray catchments) and narrower alluvial systems (e.g. Upper Ovens and Peel river catchments), where there is empirical evidence of short-term impacts of groundwater take on streams.

(c) Management of variable timescales of groundwater-surface water connections

Management of hydrologic connectivity between groundwater and surface water resources is complicated by the different timescales of the response of surface water and groundwater systems. It is important to take account of the fact that impacts of groundwater extractions on water availability from connected surface water resources may be expressed within a season, within the lifetime of a WRP, or outside the time frame of WRPs depending on geology, topography and vegetation (Evans 2007). When groundwater extractions have a large impact on connected surface water resources with a long time-lag, SDLs and associated local management rules have to be managed adaptively and monitored using resource condition indicators (Stewardson et al. 2021).

Currently, the few WRPs that explicitly recognise groundwater-surface water connections throughout a connected system are attempting to manage short-term seasonal impacts. In the few WRPs where jurisdictions have recognised long-term impacts, such as the Upper Ovens River, they have retrofitted conjunctive water management approaches.

4.1.3. Measurement and modelling

Surface water and groundwater resources with a high level of exploitation, a high potential for connection, and a relatively short time-lag between extraction and impact, experience high impacts from extractions. Between 1999 and 2019, many bores in the highly productive alluvial resources in the MDB were declining, such as the Namoi, Lachlan and Murrumbidgee resources (Australian Government, Bureau of Meteorology 2020). These areas have been thoroughly assessed using models and well data, but there is much less information about the impacts of increasing groundwater extractions in other areas.

Basin Plan modelling has not been updated since 2012 and does not include changes to river operating rules. There is a need for expanded coverage by models and improvements in integrated groundwater and surface water models (Pittock et al. 2023).

4.1.4. Knowledge about groundwater-surface water connectivity and cross impacts of extractions on connected resources and dependent ecosystems

Management of groundwater-surface water connections requires knowledge about groundwater levels and the response of water balances to flows between connected water resources, extractions from these resources, and changes in climate and land use.

There have been some significant advances in knowledge. Connectivity has been estimated using a connectivity factor (Walker et al. 2020a), measurements of hydraulic head (Lamontagne et al. 2012), application of environmental tracers (Smith et al. 2018), and bioregional assessments of cumulative impacts of coal seam gas and coal mining projects.

However, the South Australian MDB Royal Commission (Walker 2019) noted that there remains considerable uncertainty and knowledge gaps in the management of groundwater and GDEs. Connections between groundwater and surface water ecosystems have not been explicitly assessed for each GMA. Management of high ecological value aquatic ecosystems (HEVAE) including GDEs is still being incorporated into state water allocation plans. In Victoria, work was undertaken to develop methods to map the distribution of GDEs on a regional basis (Dresel et al. 2010), and for NSW a state-wide approach is reported in Kuginis et al. (2016). The NSW framework for assessing GDEs illustrates a way forward (NSW Government 2023), and there is increasing appreciation of the importance of protecting GDEs and their function under some components of the *EPBC Act 1999* as reflected in Matters of National Environmental Significance (MNES), but to date this has not been exercised. While there is recognition of the importance of GDEs, there are significant knowledge gaps and uncertainty about the water requirements of GDEs (Saito et al. 2021), especially in dry conditions, and from the impact of coal seam gas and large coal mining developments.

While definition and mapping of priority environmental assets and ecosystem functions are improving, GDEs are potentially at risk from local impacts of extractions that are not regulated within the state water resource planning framework (Ross et al. 2022). Technical input to state WRPs is often insufficient to integrate surface water and groundwater processes to test the range of risks to resources and their connectivity – the Gwydir WRP provides an example – see Section 5.3.

4.2. Adaptation to change affecting connected groundwater and surface water resources

A flexible adaptive management approach is needed to respond to risks and uncertainties arising from impacts of climate change and increasing demand for water on connected water resources and ecosystems (see Section 3). These risks and uncertainties are increased by shortfalls in the baseline knowledge of hydraulic relationships, the immaturity of integrated groundwater-surface water management frameworks, and the likelihood that demand for groundwater resources will increase as surface water availability decreases (Walker et al. 2021).

The National Water Commission (NWC) recommended that future water plans explicitly consider the impacts of climate change on water resources and the environment (NWC 2009, 2014). The Productivity Commission (2018) found that further consideration is needed of emerging risks to Basin water resources from climate change, including impacts on river flows and environmental condition of key Basin assets. Risks from climate change interact with irrigation diversions and floodplain harvesting (Pittock et al. 2023), increasing the cumulative impact of individual risks.

Regional sedimentary and alluvial groundwater systems are especially vulnerable. In these cases, dry scenarios need to include extremes beyond the historical range (Walker et al. 2021).

There has been insufficient consideration of integrated management of groundwater and surface water, and neglect of metering and independent auditing of connected water resources. Unregulated take from floodplain harvesting poses substantial risks (Williams et al. 2022).

National legislation suffers from legal and policy ambiguity in considering cumulative effects of CSG and coal mining (Nelson 2019a, 2019b). The Condamine-Balonne WRP (Government of Queensland 2019) illustrates how the Commonwealth's approach does not deal adequately with the gaps in state law, such as unlimited take of groundwater for CSG activities which pose potentially significant risks to GDEs (Nelson 2021).

5. Discussion: steps towards improved integrated management of connected water resources

Managing and addressing connectivity is perhaps the most significant differentiator between predicting the hydrological response of surface water decisions and groundwater decisions (RMCG 2021). A surface water response largely manifests within days or weeks, but for groundwater, long time-lags are common and can extend to decades in many parts of the Basin. For this reason, connectivity has a relatively high profile in the groundwater-specific components of the Basin Plan. It is given effect through the requirements to consider 'interception activities' and 'significant hydrological connection' in the estimation of SDLs and in the requirements for WRP rules (RMCG 2021).

While Australian legislation and policy provides a basis for the management of connected groundwater and surface water resources, there are serious weaknesses in the provisions for maintaining and improving beneficial connectivity and for managing risks of reduced connectivity or disconnection between these resources. There are a number of steps that can be taken towards integrated management of connected groundwater and surface water resources and ecosystems including:

1. The definition and measurement of groundwater-surface water connectivity.
2. The management of cross-connection impacts of extractions.
3. Improved monitoring and modelling, rules and adaptive measures, including current data analytics and real-time digital technology.
4. Improved knowledge and technical inputs.

5.1. Framework for assessing groundwater-surface water connectivity and impacts of extractions on connected water resources and ecosystems

5.1.1. Framework for assessing groundwater-surface water connectivity and related risks and impacts

The Australian Government, in consultation with state governments, has made efforts to define a common standard for 'significant hydrological connectivity' but a consistent approach between the states has not been achieved (RMCG 2021). It is important to establish a common definition and framework for assessing significant connectivity and the material impact of connectivity in order to ensure that cross impacts of extractions on connected water resources and ecosystems are recognised and controlled.

The MDBP should be amended to include a more precise definition of groundwater-surface water connectivity and to clarify the meaning of material impact of significant cross-resource connections. Measurable indicators of connections between groundwater-surface water resources and ecosystems should be included in the schedules to the MDBP.

An extended framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected water resources and ecosystems in WRPs can be developed building on the existing national framework (SKM 2011). This framework would extend current arrangements by requiring the WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks owing to reduced connectivity; and impacts of extractions on an expanded range of GDEs, including terrestrial vegetation and subterranean ecosystems (Ross et al. 2022). Priorities for maintaining and/or restoring groundwater-surface water connectivity in state WRPs can be established with a reference to this framework.

The extended framework could include:

1. Physical surface water and groundwater environments and the potential for connection between resources.
2. Extent and direction of connection between groundwater and surface water resources.
3. Cross-connection impacts of groundwater and surface water extractions on connected water resources and water-dependent ecosystems, including impacts on river baseflow, terrestrial vegetation and subterranean ecosystems.

4. Impacts on salinity and groundwater and surface water quality.
5. Time lag between extraction and impact.
6. Influence of climatic conditions and level of water resource development on connected groundwater and surface water resources and ecosystems.

5.1.2. Transition to improved integrated management of connected groundwater and surface water resources

It is likely to take some time to coordinate state policies and information to implement the above framework. In order to provide a transition path, the MDBP could be amended to include an agreed assessment time frame to be applied to the estimation of water balances, predictions of drawdown, and evaluation of risks of long-term changes in groundwater salinity and water quality in connected groundwater-surface water systems. This would provide a consistent approach informing ALL planning and regulatory decisions that have implications for connectivity, irrespective of scale, including significant impacts beyond the statutory time period for WRPs (RMCG 2021).

This would be an important step forward from the current status quo which, in the absence of policy-relevant directions, is commonly determined case-by-case or project-by-project resulting in a lack of consistency in the management of connected groundwater and surface water systems. Predicted impacts on SDL units arising from changes in groundwater-surface water connectivity should be considered in the review of the MDBP (RMCG 2021).

5.2. Rules and management approaches to manage connected groundwater-surface water resources and ecosystems

Improved management of risks to connected water resources in a drying and more fluctuating climate can be promoted by rules and tools tailored to specific contexts, and by adopting longer planning and management time frames. The efficacy of different rules and tools to manage the impacts of extractions depends on the hydrological and social context, objectives for managing connected resources, along with both time and space scales of management (Stewardson et al. 2021).

Volumetric limits and allocations in the MDBP and WRPs control long-term impacts of extraction and provide a secure supply for groundwater users, but do not consider spatial hot spots of groundwater drawdown and do not protect local GDEs. Buffer zones limit short-term impacts of abstraction on groundwater level and flow, but it is difficult to determine appropriate zonal boundaries, and buffer zones usually delay rather than prevent long-term impacts. Groundwater response triggers aim to directly control groundwater levels, but their success depends on accurate estimation of the trigger value and appropriate location of the observation wells, and requires costly monitoring (Noorduijn et al. 2019).

The planning period for most groundwater WRPs is too short to account for long-term impacts of changing climate and extractions on connected water resources. The slow movement of groundwater pressure responses means that pumping permitted from the beginning of the MDBP and in decadal WRPs could lock-in undesirable long-term impacts. The planning period for WRPs should be extended for connected systems where there are significant long-term risks and uncertainties (RMCG 2021).

5.3. Measurement and monitoring

Measurement and monitoring of connected groundwater-surface water resources is crucial to enable the MDBP: ‘to establish a sustainable and long-term adaptive management framework for the Basin water resources’ (MDBP, Section 5.02 (1)(b)). Catchment water balances provide an important baseline for the measurement of surface water and groundwater resources, storage and flows. Other important indicators for ongoing measurement and monitoring include river flows, well water levels, salinity, turbidity, and the condition of high value water-based ecosystems.

Inadequate groundwater monitoring and modelling by state agencies pose risks to GDEs from groundwater-surface water interactions, which are not adequately addressed in the implementation of WRPs (Ross et al. 2022). There are ongoing challenges to ensure good consistent data from monitoring bores, which are necessary to correctly interpret water level data and identify machine measurement errors. Technologies of measurement and data analysis are advancing rapidly and need to be applied to the next generation of water management. This will require additional investment in monitoring to improve accuracy of measurement and interpretation (Pittock et al. 2023).

Measuring and monitoring of groundwater-surface water connections can be improved by increased use of new and improved hydrological and chemistry-based approaches. Gravitational measurements are supplementing field observations to improve data on aquifer levels at the regional scale, and small-scale mobile gravitational measuring devices offer additional measurements at the local scale (Chen et al. 2016).

5.4. Improving knowledge and technical inputs for planning and decision making

As water scarcity and risks owing to climate change increase, more thorough and detailed management is required for closely connected and highly exploited surface water and groundwater resources (Walker et al. 2021; Ross et al. 2022).

Currently, insufficient technical work has been done on understanding the cross-connection impacts of groundwater and surface water use and storage on the total consumptive pool, especially in dry climate scenarios. The lower Gwydir groundwater source within the Gwydir alluvium WRP in NSW (Department of Planning and the Environment (NSW) 2019), provides an example of a water allocation plan where it is acknowledged that the connection between surface water and groundwater is occurring – but the level of technical input is less than appropriate. In circumstances such as this, decision-support modelling that integrates surface water and groundwater processes is required and a broader range of use scenarios should be tested.

There are a number of tools that can be used to improve the adaptive management of water resources in response to climate change. These include scenario modelling and planning (to understand potential impacts of climate change under a range of water availability and demand assumptions), soil-vegetation-atmosphere transfer (SVAT) models to estimate reductions in groundwater recharge, and vulnerability mapping to prioritise the most affected resources and regions. Regional sedimentary and alluvial groundwater systems that are already near to the sustainable extraction limit are especially vulnerable. In these cases, dry scenarios need to include extremes beyond the historical range (Walker et al. 2021).

Four key steps are required to enable better adaptation to change and uncertainty, and to improve connected water management in an uncertain future (Williams et al. 2022):

- improved data collection, accessibility and analysis of water and salt balances, and water accounts (Molden 1997) that accurately measure water flows, including return flows, are critical to manage changing water availability in the MDB;
- independent audits of the condition of connected water resources to manage critical risks, such as salinisation and deterioration of riparian environments;
- robust risk analysis to identify cumulative risks from floodplain harvesting, farm storages and irrigation infrastructure subsidies;
- holding key decision-makers accountable for their actions in delivering key objectives of the *Water Act 2007*.

Stafford Smith et al. (2011) identified adaptive measures that reduce decision risk while acknowledging uncertainty, including improved conveyancing and water efficiency, and increased planting of water-efficient crops.

Aquifer storage provides a buffer for managing uncertainty and variability in water supply, and adds to adaptive capacity (Yu et al. 2021). Managed aquifer recharge (MAR) can play an important role in restoring over-allocated groundwater resources, protecting water-dependent ecosystems, and enhancing urban and rural water supplies and storage (Dillon et al. 2016). Water banking in aquifers using MAR is widely practiced overseas, and scientific investigation has documented the potential for water banking in the MDB (Ross 2012; Gonzalez et al. 2020).

6. Conclusions and vision

Integrated management of connected groundwater and surface water resources is essential in order to achieve optimum use of MDB water resources and storage for human and environmental purposes. Although Australian legislation and policy provides a basis for the management of connected water resources, there are serious weaknesses in the implementation of integrated groundwater and surface water management. Therefore, there is an urgent need for policy reform and significant amendments to the Basin Plan. The MDBA has identified that there are many risks to Basin water resources that may not be fully mitigated through state water resource plans (WRPs), which are the cornerstones of the MDBP.

Successful implementation of integrated management of connected groundwater and surface water resources in the MDB requires improved coordination between Basin state governments and a number of legislative, policy and administrative measures. Improved coordination with Basin state governments will be needed to manage risks to surface water-groundwater connectivity owing to increased groundwater use and climate change, giving particular attention to leveraging existing knowledge and generating new knowledge to ensure that groundwater policy reform and management is underpinned by the best available science (MDBA 2019).

A vision for integrated management of connected groundwater and surface water resources includes the following enabling conditions:

- the volume of connected groundwater and surface water, their uses and their connections, will be measured or estimated and monitored;
- groundwater and surface water planning and allocation will fully account for the impacts of water use on connected resources and ecosystems, and manage these resources to achieve socially acceptable socio-economic and environmental outcomes;

- the values of groundwater and surface water resources and ecosystems will be determined in consultation with stakeholders, and water users will pay a socially acceptable charge for water use.

The following legislative, policy and administrative measures are required to manage risks and to implement integrated management of connected water resources. The Basin Plan would need to be significantly amended in terms of the current risk framework, and in particular, give attention:

- to include a more precise definition of groundwater-surface water connectivity to clarify the meaning of material impact of significant cross-resource connections;
- to include measurable indicators of connectivity; and
- to include targets to measure progress towards connectivity.

The MDBP will also need to be amended to include an agreed assessment time frame to be applied to the estimation of water balances and resource condition indicators, including predictions of drawdown and evaluation of risk of long-term changes in groundwater salinity and water quality (RMCG 2021).

In addition, the existing framework for assessing groundwater-surface water connections and cross impacts of increased extractions on connected resources (SKM 2011; MDBA 2020b) will need to be extended to require state WRPs to consider: long-term cross impacts of groundwater and surface water extractions beyond the planning period; long-term risks when connectivity is expected to be reduced; and impacts of extractions on an expanded range of GDEs including baseflows, aquatic ecosystems, terrestrial vegetation, and subterranean ecosystems.

Context-specific packages of rules and tools will need to be developed and included in WRPs to manage local impacts of groundwater extraction on groundwater entitlement holders and GDEs. Adaptive management of extraction limits and rules will need to be undertaken to address uncertainties about local cross-connection impacts, with ongoing monitoring and review. Longer planning periods will need to be established to manage connected groundwater and surface water systems, with significant long-term risks and uncertainties related to impacts of water extractions on connected water resources and ecosystems.

Improved long-term measurement and monitoring will need to be undertaken to monitor trends in connected groundwater and surface water resources and the effectiveness of management measures. Additional investments will be required to improve the accuracy of measurements, the interpretation of monitoring results, and to extend and improve integrated modelling of connected water resources, taking account of the impacts of climate change and cross impacts of extractions.

Improvements in data collection, independent audits of the state of connected water resources, and improved analysis of cumulative risks will enable adaptive management of risks and uncertainty related to connected water resources and ecosystems. Integrated management of water resources and storage and water banking will need to be developed further to improve water security and community resilience and to address the growing risks of severe droughts and floods.

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MURRAY-DARLING BASIN ESSAY

Essay #4 in a series of nine by Australia's leading water experts

Riverine ecosystems and health: Soil-landscapes

Robert Fitzpatrick, Luke Mosley, Brett Thomas and Erinne Stirling

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Above: The Murray River wending its way through eucalyptus forest. Auldist, iStock

EXECUTIVE SUMMARY

Fitzpatrick et al. overview the state of soil-landscape ecosystems across the Basin and their significant decline since European settlement. Soil-landscape ecosystems are closely linked to other natural features such as climate, vegetation, geology, hydrology, water availability, and overall ecosystem services and are therefore useful for assessing a 50-year future. Eight adaptive soil-landscape management recommendations are presented based on two scenarios — a drying and a wetting scenario — as soil-landscapes behave differently under each regime. The most significant impacts on soil-landscapes from these two scenarios include acid sulphate soil production, salt leaching and salt concentration, organic matter distribution, production of sodic and saline soils, soil erosion and bank slumping and soil compaction.

Soil landscapes are substantially impacted by overgrazing, drying and drought, wetting and floods, as well as infrastructure related disturbance. To achieve the best "sustainable soil-landscape management" for the MDB in 50 years, we need an integrated approach implementing a seasonal wetting and drying regime to the river and adjacent wetland regulation. This will substantially reduce the many risks related to the prolonged drying and subsequent rewetting, which can lead to the redistribution and accumulation of environmental hazards within a soil profile and the floodplain.

Riverine ecosystems and health: soil-landscapes

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Abstract

Soil-landscape ecosystems in the Murray-Darling Basin (MDB) are closely linked to other natural features such as climate, vegetation, geology, hydrology, water availability, and overall ecosystem services. A soil-landscape is an area of land with unique landform features and characteristic soil types, which further encompasses various ecosystems and their processes. Consequently, soil-landscapes are one of the most appropriate, integrated conceptual, and practical concepts for developing long-term sustainability assessment and management policy to best adapt to climate change in the MDB.

This essay focuses on a 50-year vision for MDB soil-landscapes, focussing on wetlands and floodplains, by reviewing and synthesising recent literature on how soil-landscape degradation is modified under the influence of changing climate. An overview of recent advances is presented in our understanding of the key soil-landscape processes from extreme: 1) soil drying caused by prolonged drought conditions (and the impacts of increasing bushfires) and 2) wetting caused by extreme flooding. These processes have resulted in a wide range of soil-landscape degradation issues, namely: soil erosion, acidification, salinisation, clay dispersion/sodicity, waterlogging, soil compaction, production of noxious gases, monosulfide accumulation and disturbance.

Eight adaptive soil-landscape management recommendations to reduce risks of extreme droughts and flooding on soil-landscapes have been developed using two generalised soil-landscape transect diagrams, for the drying and wetting scenarios, and include:

Drying Scenario	**Wetting Scenario**
Slow the lowering of water levels where practical and promote the extension of colonising plants to increase plant productivity and thus soil organic matter content, which will improve soil structure, stabilise banks and reduce soil erosion.	Increased topsoil and subsoil supply of water, which will increase plant productivity and thus soil organic matter and nutients leading to improved soil structure, reduced risk of erosion and improved stream water quality,
Careful exposure (i.e. limiting extent and exposure time where practical) of hypersulfidic material (pH>4) with Reduced Inorganic Sulfur (RIS) to oxygen (air), which will allow oxidation to occur and reduce the quantity of accummulated RIS and minimise acidification risk (i.e. formation of sulfuric material: pH <4).	Leaching of salts deeper in the soil profile and washing away surface salts reduces soil salinity and sodicity, which reduces salt loads and improves downstream water quality.
Controlled drying, which will cause salts to leach out of saline soils leading to reduced salt loads in the longer-term 50-year hydroclimate changes leading to soil-landscape degradation.	Controlled exposure (via Weir Pool Lowering) and inundation (via Weir Pool Raising) of hypersulfidic material, which will reduce the accummulation of reduced inorganic sulfur (RIS) through improved redox cycling.
Use environmental and irrigation water where possible to prevent deep cracking and salinisation of clay soils and maintain plant cover.	Control inundation and flow rates were possible to prevent development of hypoxic blackwater events and scouring of sediment and monosulfidic black oozes (MBOs).

To show how the major soil-landscape processes impact on negative and positive outcomes from drying (drought) and rewetting (reflooding) scenarios, an interrelating flow diagram is used.

To achieve the goal of best “sustainable soil-landscape management” for the MDB in 50 years, we need an integrated approach to implement a **seasonal wetting and drying regime** to the river and adjacent wetland regulation, which will substantially reduce the many risks related to the **prolonged drying** and **subsequent rewetting**, which can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

Our 50-year vision for MDB soil-landscapes is that they be adequately restored based on the eight adaptive soil-landscape management recommendations so they can be maintained as sustainable and robust environments, providing for the socio-ecological and economic needs of future generations in the face of the challenges of climate change.

1. Introduction

This essay explores a 50-year vision of soil-landscapes in the Murray-Darling Basin through a lens of our changing climate and its influence on soil-landscape degradation. We use 'soil-landscapes' as the environmental unit of interest herein as it is an integrated conceptual and practical concept for developing long-term sustainability assessment and management policy to best adapt to climate change in the MDB. A 'soil-landscape' is an area of land with unique landform features and characteristic soil types, which further encompasses various ecosystems and their processes (Conacher 2009; WCED 1987). In the MDB, the following major soil-landscape degradation changes have emerged as a threat for sustainability of ecosystem functions: soil physical changes (soil erosion, structural and textural decline) and chemical changes (acidification, salinisation, and element oxidation or reduction). Already existing degradation processes are further being compounded by climate change and unsustainable land management practices.

This essay provides a summary update on the current state of the soil-landscape science in the MDB with a focus on projected changes in key wetting-drying variables for the dominant soil-landscapes in the next 50 years. We first provide a summary of the distribution of the main physiographic provinces, regions, and soil-landscapes in the MDB. This is followed by projected climate change impacts of several key temporal soil-landscape characteristics across the MDB from: (i) drying caused by prolonged drought conditions, and (ii) wetting caused by extreme flooding. Finally, we discuss the future challenges and opportunities for adaptive soil-landscape management to reduce risks of extreme droughts and flooding.

2. Physiographic provinces, main regions, and soil types of the MDB

The MDB is divided into the following six major physiographic provinces as shown in the physiographic map in Figure 1a. This indicates areas with similar landform histories that can be related to similar soil types in accordance with the Australian Soil Classification (Isbell & NCST 2021; Figure 2), geology and climatic impacts:

- Central Lowlands (37%): Kandosols, vertosols, and sodosols, overlying sandy, clayey, and stony plains with low sandy hills.
- Kosciuszkan Uplands (10%): Rudosols, chromosols, kandosols, tenosols, and sodosols overlying moderately high mountains and detached hills with intervening alluvial valley floors.
- New England–Moreton Uplands (7%): Chromosols, rudosols, ferrosols, and sodosols over mainly undulating granitic plateaus and metamorphic ridges and shale lowlands.
- Macquarie Uplands (6%): Kandosols, sodosols, chromosols, and rudosols overlying mainly granitic and basaltic tablelands with detached hills in the west.
- Murray Lowlands (37%): Calcarosols, vertosols, sodosols, rudosols, and hydrosols which contains over 30, 000 wetlands including 16 wetlands listed under the Ramsar Convention.
- Gulfs Ranges and Fitzroy Uplands (<3%): Rudosols, tenosols, kandosols, and sodosols.

About 85% of the MDB comprises four Australian Soil Classification soil orders (Figure 2; Isbell & NCST 2021), namely: sodosols, kandosols, vertosols, and calcarosols as described in more detail in Table 1. The soil types and associated physiographic provinces have distinct physical and geochemical characteristics that impact on erosion (Pain et al. 2011), cracking and exposure of acid sulfate soil materials (Fitzpatrick et al. 2017a), hydrological, and river/stream water quality processes (Murray–Darling Basin Commission 2008).

The role of agriculture in the MDB and the influence of salt on the MDB's soils and waters mean that its soil-landscapes are often considered through a framing of salt retention and movement. Soil-landscapes are considered key assets of the MDB under the Basin Plan as they are highly dependent on water resources and stores of ‘salt loads’ in the four main regions shown in Figure 1b. According to Hart et al. (2020) ‘salt loads’ across the MDB can be divided into the following four main regions: Southern Uplands, Riverine Plains, Northern Basin, and the Mallee Region (Figure 1b). The relative water flow contributions and salt loads from these four regions is shown in Figure 3.

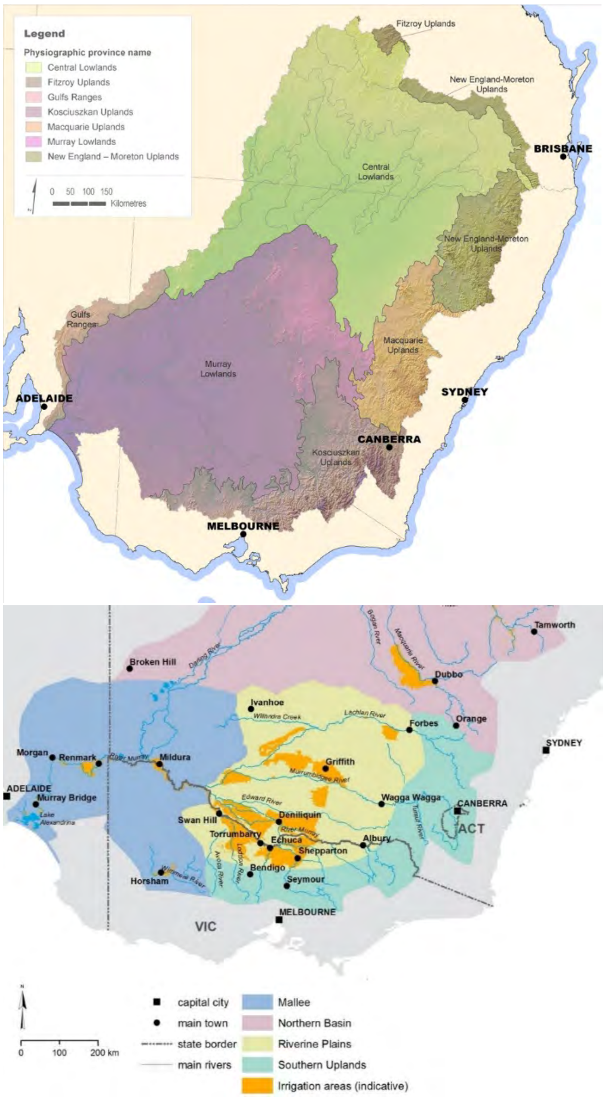


Figure 1a. Map above showing physiographic provinces of the MDB (from Australian Water Resources Assessment, 2012); Figure 1b Map below showing the four main regions in the MDB (Source MDBA 2008)

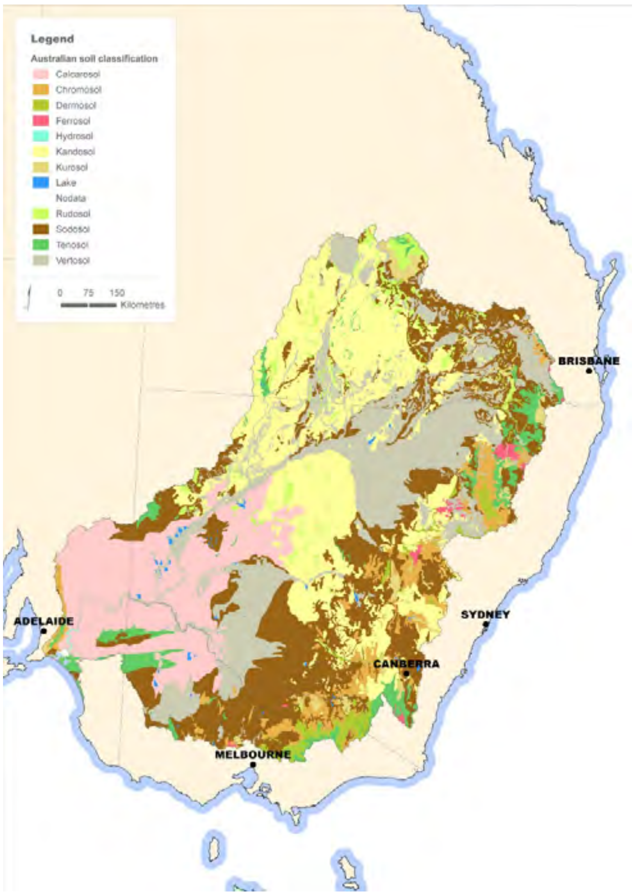


Figure 2. Soil type (Australian Soil Classification in accordance with Isbell & NCST, 2021) distribution in the Murray-Darling Basin from Australian Soil Resource Information System website www.asris.csiro.au

These average contributions of flow and salt loads to the River Murray salinity at Morgan show that the great bulk of the salt (approximately 70%) in the River Murray comes from the Riverine Plains and the Mallee, while the Southern Uplands contribute most of the flow. As such, an explanation for this can be linked to the distribution of the soil types with dominant Sodosols, Calcarosols and saline Hydrosols occurring in the Riverine Plains and the Mallee (Figure 2). In contrast, Kandosols with low salinity dominate across the Southern Uplands and Northern Basin.

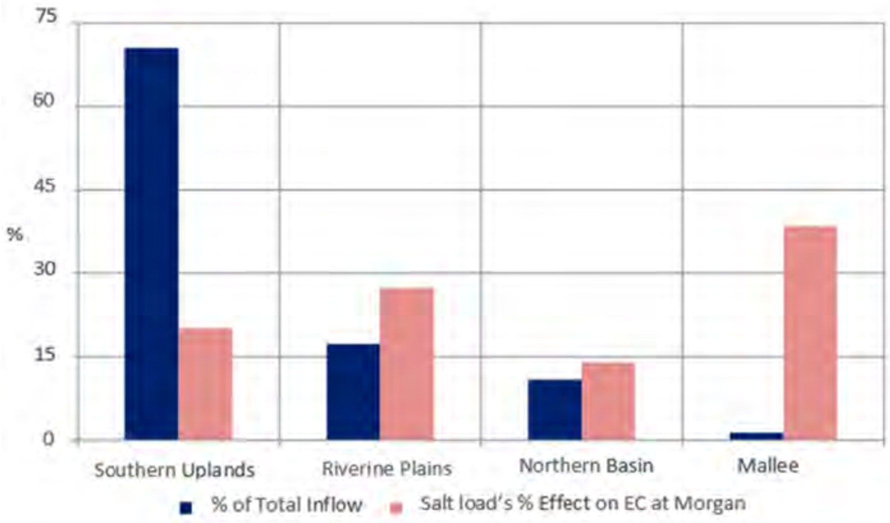


Figure 3. Average contributions of flow and salt loads to River Murray salinity at Morgan. See Figure 1b for locations of the main four regions (after Hart et al. 2020).

Table 1: Soil orders found in the MDB, their percentage coverage, dominant occurrence, land use, characteristics, and agricultural potential.

Soil type	%	Occurrence (Figs 1b & 2) and Land use	Characteristics	Agricultural Potential
Sodosols	24	South, southcentral as well as eastern parts (Mallee & Riverine plains). Used for dryland cropping and horticulture.	Soil with a strong texture contrast between the (upper) A and (lower) B horizons and possessing a high (>6%) exchangeable sodium percentage (ESP) in the B2 horizon. These soils have a relatively impermeable, sodic and clay-enriched subsoil.	Due to their potential for clay dispersion and structural instability, they are susceptible to tunnel and gully erosion as well as dryland salinity if vegetation is cleared. They also have poor water holding capacity and infiltration when dispersed.
Kandosols	23	Dominant in northwest and widely represented in the southeast of the region (Northern Basin and Southern Uplands). Mostly used for grazing.	Soils in which the B2 horizon structure is massive. May have a loamy to clayey texture. Often very deep (>3 metres). Do not have: (i) strong texture contrast (ii) colour change, or (iii) carbonate throughout their profile.	Low to moderate agricultural potential with moderate water holding capacity and chemical fertility. When grazed, these soils are susceptible to surface soil degradation, such as hardsetting and crusting even under low grazing intensities.
Vertosols	22	Stretched around the southcentral (Riverine Plains) to north-central part (Northern Basin). Mainly used for	Brown, grey or black soils with high clay contents (>35% throughout) and are highly structured with slickensides and open cracks at some time in most years.	Highly fertile and have a large water-holding capacity. However, they require a significant amount of water before water

		dryland agriculture and horticulture.		becomes available to plants and to prevent deep cracking which can damage farm infrastructure.
Calcarosols	15	Dominant in the lower parts of the MDB (Mallee). Mostly used for dryland crops and horticulture.	Have high calcium carbonate content, which occurs as soft or hard white fragments, or as solid layers. Often shallow with low water-holding capacity. Does not include deep sandy profiles.	Low to moderate agricultural potential and often have high salinity and pH levels. Alkalinity and boron toxicity may cause issues.
Hydrosols	10	Dominant soil types in the lowest lying and poorly drained positions in the floodplain (Mallee and Riverine Plains). Also found under evaporation ponds.	Soils where the major part of the profile is inundated for prolonged periods (2-3 months) in most years. Common soil subgroups are saline soils and acid sulfate soils, which may occur in saline lake deposits, lake beds, clay pans as well as in lagoons and swampy areas where organic matter has accumulated (may be buried).	Occur in over 30,000 natural wetlands across the MDB including the 16 wetlands listed under the Ramsar Convention (see part VII of this ATSE series on Ramsar Wetlands) - despite the fact that about 90% of the MDB is arid and semiarid. Shallow water tables are commonly saline and may need to be managed to prevent impacts on root zone.
Tenosols, **Rudosols,** **Dermosols,** **Kurosols,** **Ferrosols,** **Chromosols**	0.5 to 4	Minimal representation in the MDB. Rudosols occur mainly in higher parts of landscapes. Chromosols are largely associated with abandoned alluvial tracts in the east.	Rudosols: soils with no to limited pedological organisation. Tenosols: soils with only weak pedological organisation. Dermosols: non texture contrast soils in which the B horizon is structured Ferrosols: non texture contrast soils with high free iron. Kurosols: texture contrast soils in which the B2 horizon is strongly acidic. Chromosols: texture contrast soils in which the B2 horizon is not strongly acidic nor sodic.	Rudosols and Tenosols often have shallow, rocky and poorly developed soil profiles that are not optimal for agriculture. Kurosols generally have very low agricultural potential due to high acidity (pH < 5.5) in the subsoil and low chemical fertility.

3. Climate change impact on soil-landscapes of the MDB

Indigenous peoples in the MDB have recorded creation stories about the remarkable climate changes that occurred both when the sea level began rising 18,000 years ago and when the current sea level stabilised about 5,000 years ago. The creation stories and oral traditions of indigenous people have been passed down from generation to generation, especially about the detailed knowledge of nurseries such as wetlands or reed beds, which were much more extensive in the past. For example, the Ngarrindjeri people believe the land and water is a living body and that they are a part of its existence (Ngarrindjeri Tendi et al. 2007). In the Ngarrindjeri Nation

Yarluwar-Ruwe plan (Ngarrindjeri Tendi et al. 2007) it is stated: “The land and waters must be healthy for the Ngarrindjeri people to be healthy. We say that if wetlands/nurseries die, our Ngartji (totem or special friend) die, then Ngarrindjeri will surely die.”

The MDB has experienced a drying climate for the past 40 years and has also been in drought for much of the last 20 years (Bureau of Meteorology, 2020) with more recent climate modelling indicating that this trend will continue (Reisinger et al. 2024). Projections indicate a hotter and drier future, with more frequent drought periods and extreme weather events, including more extreme flooding events (e.g. CSIRO, 2012; CSIRO and Bureau of Meteorology, 2015; Pittock et al. 2015; Pittock, and Finlayson 2011; Chiew et al. 2023; Prosser et al. 2021; Zhang et al. 2023; Walker et al. 2021; Whetton et al. 2021).

Observations from the Millennium Drought provide insight into how fluctuations between inundation and subsequent extreme drying, events associated with periodically flooded soils, are major drivers of temporal differences in biogeochemical processes occurring in MDB floodplain soils (e.g. Fitzpatrick et al. 2009, 2017a, 2018; Mosley 2018; Stirling et al. 2020). For example, the alteration of subaqueous (submerged) and waterlogged soils due to drying causes physical, chemical, and biological changes that may have major interactive effects on soil properties (Figure 4). However, some soil-landscape changes in the MDB are cyclic and recover during the transition back to subaqueous phases, while others result in permanent or irreversible changes as drained phases.

Maintaining a sustainable use of soil-landscape properties for a 50-year future in the MDB is reliant on a wide variety of interdependent elements. Soil-landscape degradation is strongly dependent on soil-landscape drying (droughts) and wetting (reflooding) cycles as shown in Figure 4 and discussed in Sections 4 and 5. To mitigate soil-landscape degradation threats we make adaptive soil-landscape management recommendations to reduce the risks of extreme droughts and flooding in Section 6.

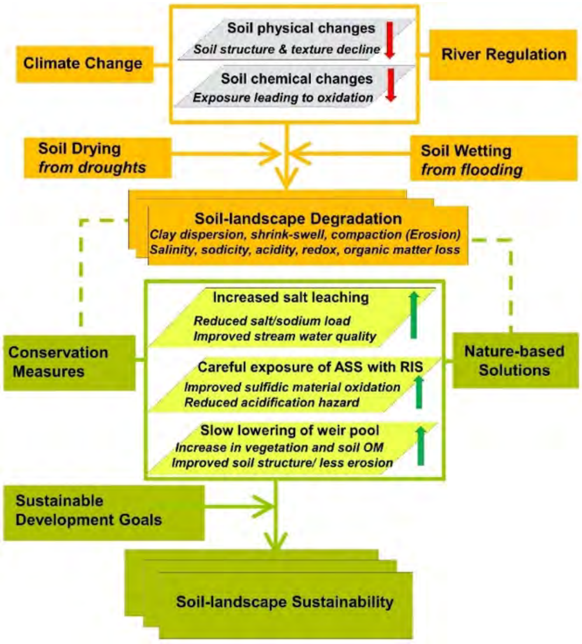


Figure 4. Framework for climate change and water regulation impacts on soil physical and chemical changes and soil-landscape degradation from soil drying (droughts) and wetting (flooding) and future sustainable management opportunities involving conservation measures and nature-based solutions. Where: Red down arrow implies negative outcomes; Green upward arrow implies positive outcomes; ASS = Acid Sulfate Soil; RIS = Reduced Inorganic Sulfur in sulfidic materials; OM = Organic Matter.

4. Climate change threats from prolonged drought on soil-landscape drying

The Millennium Drought (1998-2010) caused widespread lowering of water levels in lakes, wetlands, and the river channel leading to broadscale soil-landscape drying in the MDB (Fitzpatrick et al. 2009). Soil drying from exposure or drainage of formerly submerged soils and sediments due to prolonged drought conditions has also led to physical, chemical, and biological soil changes that have had further interactive effects on other soil properties. These are outlined below.

4.1 Soil physical changes: decline in soil structure and texture

River regulation and land use change across the MDB has led to the following landscape degradation processes with consequences that affect soil erosion, salinity, and soil formation within wetlands:

- Removal of native vegetation for dryland agriculture has increased groundwater recharge leading to rising saline water tables, secondary salinity, and salt storage within floodplains (Figure 5).
- Changed hydrology due to land use change have allowed salt efflorescences, sodic soil dispersion, and removal of surface soil layers by wind or sheet erosion which then form scalds and exposed hardpans (Figure 6).
- The loss of vegetation and organic surface soils within the floodplain has led to soil sealing in some areas and increased surface run-off (Figure 5).
- Tillage, logging, stock pugging, grazing pressure, and vehicle trafficking creating densipans (hard cemented layer of very fine silty sand) or introducing oxygen to saline discharge areas with hypersulfidic material (e.g. Fitzpatrick et al. 2009), which has resulted in affected areas with expanded erosion, salinity and sulfuric material (Figure 7 (c)).
- Prolonged drying of vertosols can form deep cracking, which increases oxygen penetration depth into hypersulfidic material to rapidy form sulfuric material (Figure 7 (c)).
- Sedimentation within the weir pool and behind weirs, blocking banks, levee banks, and drains resulting in burial of natural organic bottom sediments and raising of sill levels (Figure 8).
- Fine sediment deposition during flood events increases erosion potential (by water and wind) during prolonged droughts due to lowered water levels and sediment exposure.

4.1.1 Saline and sodic soil landscapes

Saline (or salt-affected) soils are those with large amounts of soluble salts, such as NaCl. Saline soil-landscapes in the MDB form under different environmental conditions as shown in Figure 5 and have the following hydrology defined saline land categories (Fitzpatrick 2008): (i) non-groundwater-associated salinity (NAS), or dry saline land or transient salinity, which is not hydrologically connected to a saline water table (see Figure 6 for more detail; Rengasamy 2002); (ii) deep NAS or 'salt bulges', which occur well below the root zone of former native vegetation (usually >2 m from soil surface); (iii) primary (natural) Groundwater Associated Salinity (GAS) or dryland salinity is caused by rising saline groundwater and salt accumulation in soils due to evaporative water loss in saline seeps and (iv) secondary (anthropogenic) Groundwater Associated Salinity (GAS) caused by rising saline groundwater and salt accumulation in soils due to evaporative water loss in saline seeps.

Saline soil-landscapes in the MBD have generally developed since European settlement due to extensive land clearing and the subsequent replacement of deeply rooted native vegetation by shallow rooted, water-inefficient annual crops and pastures. Evapoconcentration in previously vegetated and inundated soil-landscape surfaces has increased soil surface salinity, leading to salt scalds and the precipitation of salt efflorescences (Fitzpatrick 2008) with the following categories defined by hydrological and geochemical environments: (i) Alkaline (sodium carbonate dominant, pH >9), Halitic (sodium chloride dominant) and Gypsic (gypsum / calcium sulfate dominant). Highly soluble salts (such as NaCl and gypsum) precipitate out of solution as the water evaporates, creating surfaces that are inhospitable to most organisms (Fitzpatrick 2008; Stirling et al. 2020).

Across the MDB, salinisation of floodplain soils is considered a major factor in the declining health of floodplain trees (Hart et al. 2020; Walker et a. 2021, 2023). There has been extensive vegetation death in many areas with dieback being a function of the combined effects of rising saline groundwater and river regulation; salinisation dieback is exacerbated by the effects of drought.

Soil salinity induced by climate change refers to a significant increase in the concentration of soluble salts in the soil column caused by various climate change aspects including increasing air temperature and evaporation rates, changing rainfall patterns, rising sea level, and accelerating droughts.

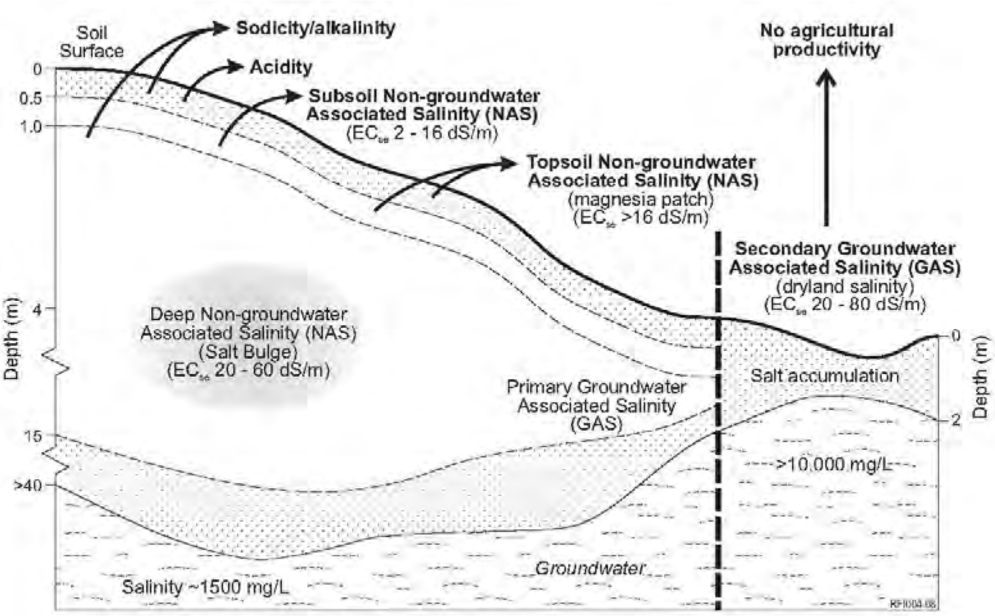


Figure 5. Schematic cross section showing various categories of saline land as defined by hydrology (after Fitzpatrick 2008)

When sodosols in the MDB (Figure. 6) are subjected to drying and wetting cycles, they are affected by the following key processes (Fitzpatrick et al. 1994; Fitzpatrick 2008; Rengasamy et al. 2010):

- **Soil physical changes** due to:
    - Textural changes associated with clay dispersion, desiccation, shrinking and swelling, compaction and transport (e.g. erosion and deposition processes);
- **Soil chemical changes** due to:
    - Soil structure and physical changes that influence oxygen diffusion (e.g. sodicity causing waterlogging), organic matter decomposition, soil redox conditions and transport of nutrients, salinity, alkalinity, acidity and toxic elements.

Wetting and drying cycle driven processes are influenced strongly by soil texture and mineralogy, affecting how a specific soil profile (or wetland) may be impacted by flooding or drying through space and time. For example, sodosols have a dense structure and high strength when dry, are particularly susceptible to waterlogging with low oxygen availability, and have slow water infiltration through the subsoil (B horizons) resulting in perched water tables. These soils are usually strongly alkaline and often contain toxic concentrations of boron and salt, which, alongside the physical restraints, restricts root growth. Sodosols react completely differently on flooding or drying when compared to deep sandy loam soils with no physical, chemical or drainage issues.

Sodification of soils is a substantial risk in soils exposed to saline groundwater seeps during dry periods (Figure 6). On return to 'normal' conditions (i.e. exposure to rain or fresher channel water) the lower salinity water causes sodic clays to disperse. Clay dispersion degrades the water quality (via turbidity and salinity) of run-off and receiving waters, and can remove seed banks and seedlings by erosion of the lighter textured suface soils (A horizons) due to lateral water movement when water cannot infiltrate into the subsoils (B horizons) (Rengasamy et al. 2010). Drying of already sodic soils further increases soil EC and exchangeable sodium percentage (ESP) via increased saline groundwater inputs and evapoconcentration (Mosley et al. 2017).

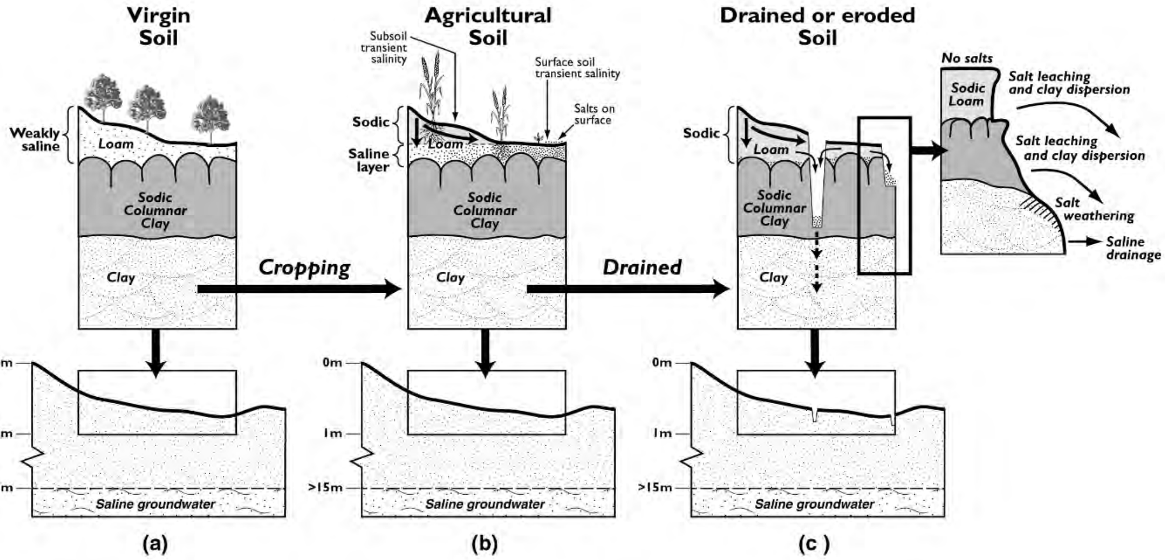


Figure 6. Soil-regolith model showing salt transport and erosion processes leading to formation of subsoil and surface soil transient salinity (not associated with the saline groundwater tables). NOTE: Sodic duplex soil (sodosol) is used here as an example but these processes also do occur in gradational soils or in soils with thin A horizons directly overlying saprolite (after Fitzpatrick 2008)

When shallow surface NAS soils are drained, soils are leached and salt efflorescences on the soil surface are dissolved (Figure 6 (b)). Salt crystals develop at depth in sodic soils where salt is leached through the subsoil clay layers on edges of gullies or drains (Figure 6 (c)). This causes stream banks to erode by salt weathering and if these processes are expresed on the surface of the soil, bare eroded saline scalds are evident (Fitzpatrick 2008; Rengasamy et al. 2010).

In alkaline soils, sodicity typically increases alongside clay content with depth. Sodicity in non-saline soils causes collapse of fine soil structures and the development of massive structures, which on drying causes the soil to have high strength (Rengasamy et al 2010), a process which reduces turbidity upon reflooding but also prevents root penetration. Dispersed sodic soil horizons are inhospitable to plant roots, can be poorly draining, and are highly susceptible to erosion when disturbed (Bethune and Batey 2002). On drying, the massive structure can restrict the uptake of water and nutrients due to waterlogging.

4.1.2 River bank slump and tunnel erosion

River banks along the Murray River and Darling River slump during soil drying and water level lowering through over steepening of the bank (bank toe erosion), or through the removal of water pressure from the pool (drawdown effect). Over steepening of the bank may occur where flow patterns cause scours to form at the channel margins and drawdown slumping is generally associated with poorly draining soils. Soil erosion caused by bank slumping has negative effects on water quality and can damage or destabilise nearby infrastructure (Hubble et al. 2014).

There is a risk of bank adjacent tunnel erosion and subsequent topsoil instability during changed subsurface soil drainage. Soil profiles at risk of tunnel erosion are those in which there is subsurface lateral water flow such as that caused by an impermeable subsoil horizon (e.g. in sodosols).

4.1.3 Soil compaction

Compaction of soil profiles under drying conditions occurs when pores that are usually filled with water empty and the weight of overlying soil ‘crushes’ the gas-filled voids. Compaction can significantly reduce profile drainage capacity, plant establishment, and soil structural stability, leading to increased risk of soil erosion (Stirling et al. 2020). Dewatering of organic matter rich horizons can lead to irreversible soil compaction as moisture and organic carbon is lost and voids are crushed by the weight of overlying materials. Compaction in this scenario may decrease organic matter decomposition rate due to limited oxygen exposure of the inner profile surfaces (Stirling et al. 2020). Compaction or the formation of hardpans or toxicity may also limit plant establishment in newly drained landscapes (Fitzpatrick et al. 1996; 2017a).

4.1.4 Vertosol (cracking clay) landscapes

Prolonged drying of vertosols forms large and connected pores and cracks that allow rapid infilration of fluids into the profile. Vertic soils within the Lower Murray Irrigation Area (LMRIA) are particularly susceptible to deep cracking, with cracks as large as 3.5 m deep observed at sites in the Lower Murray as a result of the Millennium Drought (Mosley et al. 2014; Fitzpatrick et al. 2017a). Cracking substantially increases oxygen penetration depth into the soil profile and increases the soil extent exposed to oxidising conditions. There is a substantial risk at sites where sulfide minerals (RIS materials) coexist with shrink/swell clay soils due to the potential for severe acidification if these materials are oxidised. Cracking can also cause severe damage to farm infrastructure.

Prolonged exposure of normally inundated or saturated vertosol soils may also exacerbated the development of saline sodic soils through the increased salt concentration from salt evapoconcentration. The inherent surface evaporation rate of exposed soils is constrained by water movement through the profile and therefore by soil texture and structure. Increased salinisation and sodificiation reduces soil water infiltration rates and therefore reduces recharge by rainfall, meaning the landscape has less capacity to flush floodplain salts.

4.2 Soil chemical changes: Exposure leading to oxidation

Soil exposure and the periodic draining of wetland soils in the MDB are major drivers of spatial and temporal differences in soil properties that affect the structural, textural and biogeochemical processes taking place (Fitzpatrick et al. 1996; Fanning et al. 2017). Periodic exposure of typically wet soils to air:

- Increases oxygen diffusion into the soil profile, increasing soil redox potential, leading to changes in pH, mineralogy and organic matter,

- Increases release and mobility of acidity and potentially toxic elements (PTEs) to porewaters and the environment, and
- Oxidises soil organic matter, thereby affecting carbon (CO_2 and CH_4 gas) emissions and nutrient cycling.

These processes are largely influenced by soil microbiology as microbial communities change from anaerobic dominated communities to aerobic dominated communities (Jayalath et al. 2016; Kölbl et al. 2017, Fanning et al. 2017; Stirling et al. 2020). Periodic exposure prevents the accumulation of materials that may pose a significant environmental threat under prolonged exposure events (as observed during the Millenium Drought).

4.2.1 Exposure of acid sulfate soil landscapes with hypersulfidic material

Acid sulfate soils (ASS) is the name given to soils in which sulfuric acid may be produced, is being produced or has been produced. Acid sulfate soils with hypersulfidic material (pH >4) contain sulfidic minerals (principally iron sulfides, such as iron pyrite FeS_2) and are formed under waterlogged (anaerobic) conditions and pose no problem if left undisturbed and saturated. If disturbed and aerated, ASS with hypersulfidic material can rapidly transform to sulfuric material (pH <4) and become 'the nastiest soil in the world' (Dent and Pons 1995). An estimated 16 million ha of acid sulfate soils in Australia is encountered in inland environments such as the MDB (Fitzpatrick et al. 2011).

Under more 'normal' conditions, such as prior to draining natural wetlands for agriculture on historic floodplains in the MDB, natural wetlands cycled between wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles. These periods of wetting and drying would have prevented an excessive build-up of hypersulfidic material by both chemical and physical processes.

The subsequent post-European **construction of locks, barrages and levee banks** in the MDB has allowed accumulation of hypersulfidic material (pH >4) in subaqueous (saturated, waterlogged) soils (Figure 7 (a)) due to:

- Artificially stable water conditions in many wetlands for over 80 years that has resulted in considerable build-up of hypersulfidic, hyposulfidic and monosulfidic materials due to permanent waterlogging (i.e. lack of regular drying cycles to oxidise or "burn off" pyrite that has formed naturally).
- The evaporative concentration of sulfate (i.e. source of sulfur for pyrite formation) from groundwater-connected river salt loads during the period of stable pool level.
- The lack of natural scouring and seasonal flushing of wetlands.
- A plentiful supply of organic matter from aquatic vegetation (e.g. *Phragmites Australis* and *Typha* sp.).

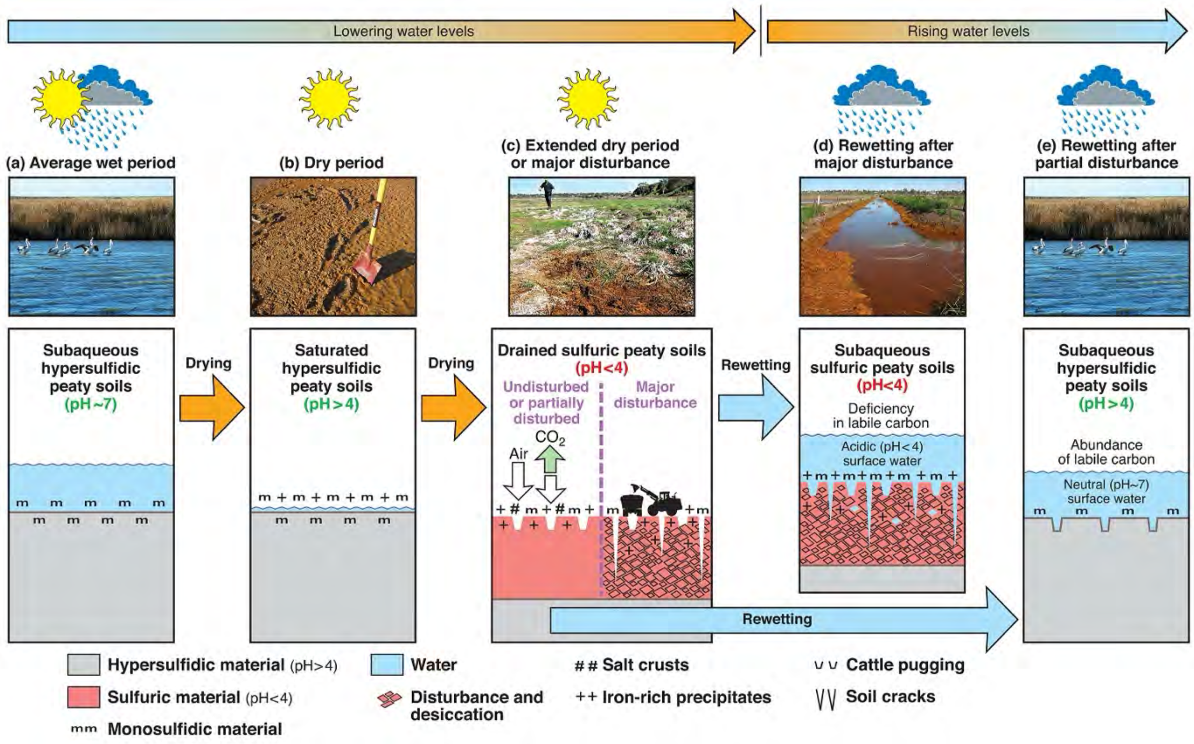


Figure 7. Conceptual model illustrating transformation processes of acid sulfate soil materials caused by drying (droughts) and rewetting (flooding) conditions (modified from Fitzpatrick et al. 2018).

Both natural (e.g. Millennium Drought, Figure 7 (b)) and anthropogenic processes caused by humans (e.g. excavation of wetlands) and cattle (e.g. pugging, Figure 7 (c)) cause these soils to dry. Drying and exposure results in the decline of the water table and exposure of the hypersulfidic material to air or oxygen, which induces oxidation of iron sulfides (FeS_2) and the formation of sulfuric acid or sulfuric material as shown in Figure 7 (c) (Fitzpatrick et al. 2009, 2017a; 2018; Fanning et al. 2017; Shand et al. 2009; 2010). Exposure allows microbially mediated oxidation of reduced inorganic sulfur (RIS) in hypersulfidic material and subsequent release of acidity (H+), which transforms hypersulfidic material (pH>4) to sulfuric material (pH<4). The initial form of acidity occurs as soluble or readily exchangeable acidity (i.e. sulfuric acid) in the soil profile pore waters. Secondary minerals, such as jarosite, sideronatrite and schwertmannite may also form within soil profiles, which act as 'stored' acidity (i.e., they are sparingly soluble and may produce acidity upon dissolution during re-wetting; Fig. 7 (d)) (Fitzpatrick et al. 2017b; Trueman et al. 2020). This 'stored' acidity in secondary minerals continues to be important as the Fe^{3+} in both jarosite and schwertmannite can undergo further hydrolysis and subsequently result in the release of acidity into the surrounding environment down the hydraulic gradient of the sulfuric acid sulfate soil source.

Evapo-concentration of saline acidic seepage containing dissolved Fe and Al will concentrate both soluble and retained acidity at the surface (and near surface to the capillary fringe of soil peds and columns) in the form of Fe or Al hydroxysulfate minerals and salt crusts or efflorescences (Fig. 7 (c)), such as jarosite and natrojarosite (Fitzpatrick et al. 2018, Creeper et al. 2015a,b; Mosley et al. 2017). Prolonged drying can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

The following wide range of environmental hazards are generated by the oxidation of hypersulfidic material:

- Severe acidification of soil and drainage waters (<pH 4 and often <pH 3) (Figure 7 (d)),
- Mobilisation of metals (e.g. iron, aluminium, copper, cobalt, zinc), metalloids (e.g. arsenic), nutrients (e.g. phosphate), and rare earth elements (e.g. yttrium, lanthanum), deoxygenation of water bodies (Figure 7 (c) and (d)),
- Production of noxious gases (e.g. H_2S) and CO_2 (Figure 7 (c)) (Hicks and Fitzpatrick 2008).
- Scalding (i.e. de-vegetation) of landscapes (Figure 7 (d)).

The degree of acidification in MDB soils and water is partially determined by the substrate's acid neutralising capacity (ANC), which is determined by the content of organic matter, alkaline minerals, and clay particles in the soil environment (Fitzpatrick et al. 2009, Shand et al. 2010). ANC buffers against changes in pH by reacting with excess H^+ ions to form new compounds or by scavenging H^+ out of solution due to negative surface charges. Armouring of carbonate ANC material by coating with oxides, clays and organic residues may make it 'unavailable', reducing the effective acid neutralization capacity. The generation of sulfuric acid and formation of acidic minerals such as jarosite has been found to prevent (or delay) soils with sulfuric material in the MDB from returning to 'normal' during restoration (e.g. Mosley et al. 2014a,b; Fitzpatrick et al. 2017a).

4.2.2 Accumulation of monosulfidic soil material during drying

Formation of monosulfidic (FeS) material and finely divided organic matter is common in acid sulfate soil affected drainage channels, such as drains and waterways behind floodgates and barrages (Cheetham et al. 2012, Mosley et al. 2014a, Mosley et al. 2019, Thomas et al. 2019). Buildup of these materials is commonly called 'monosulfidic black ooze' (MBO). Hazards associated with monosulfide accumulation and disturbance include deoxygenation of water, severe acidification and the release of potentially toxic elements (for example metals and metalloids such as arsenic), and high levels of nutrients (Bush et al. 2004, Mosley et al. 2014a,b).

4.3 Airborne impacts

Odours and dust are the prominent airborne impacts of drying in normally inundated soil-landscapes. Drying anaerobic soils may release hydrogen sulfide and malodorous organic S compounds that naturally form by microbial metabolic processes when sulfur and organic matter are present (e.g. Hicks and Fitzpatrick 2008; Fitzpatrick et al. 2009). Complete desiccation of surface soils and loss of cover vegetation has led to raised dust in the Lower Lakes region, due to wind erosion of bare soils or salt efflorescences (Fitzpatrick et al. 2018). Soil particles susceptible to wind erosion are generally the most valuable particles in the soil, with high nutrient and organic matter concentrations. In addition to downwind human health concerns, downwind water bodies may experience decreased water quality (sedimentation/eutrophication) while the source site experiences an effectively irreversible loss of topsoil (Marx et al. 2009, Javadian et al. 2019).

4.4 Animal and human behaviours

Exposure of previously inundated wetland areas can lead to changed animal and human behaviour, potentially resulting in soil disturbance by livestock, people, vehicles, and local fauna. Pugging, wallowing, and vehicle use while moist will negatively affect surface soil structure and therefore leave soils more vulnerable to soil erosion once dry/desiccated (Fitzpatrick et al. 1996). Compaction from animal and vehicle use may also change profile drainage, reducing a profile's capacity to drain freely under gravity (Steward et al. 2012).

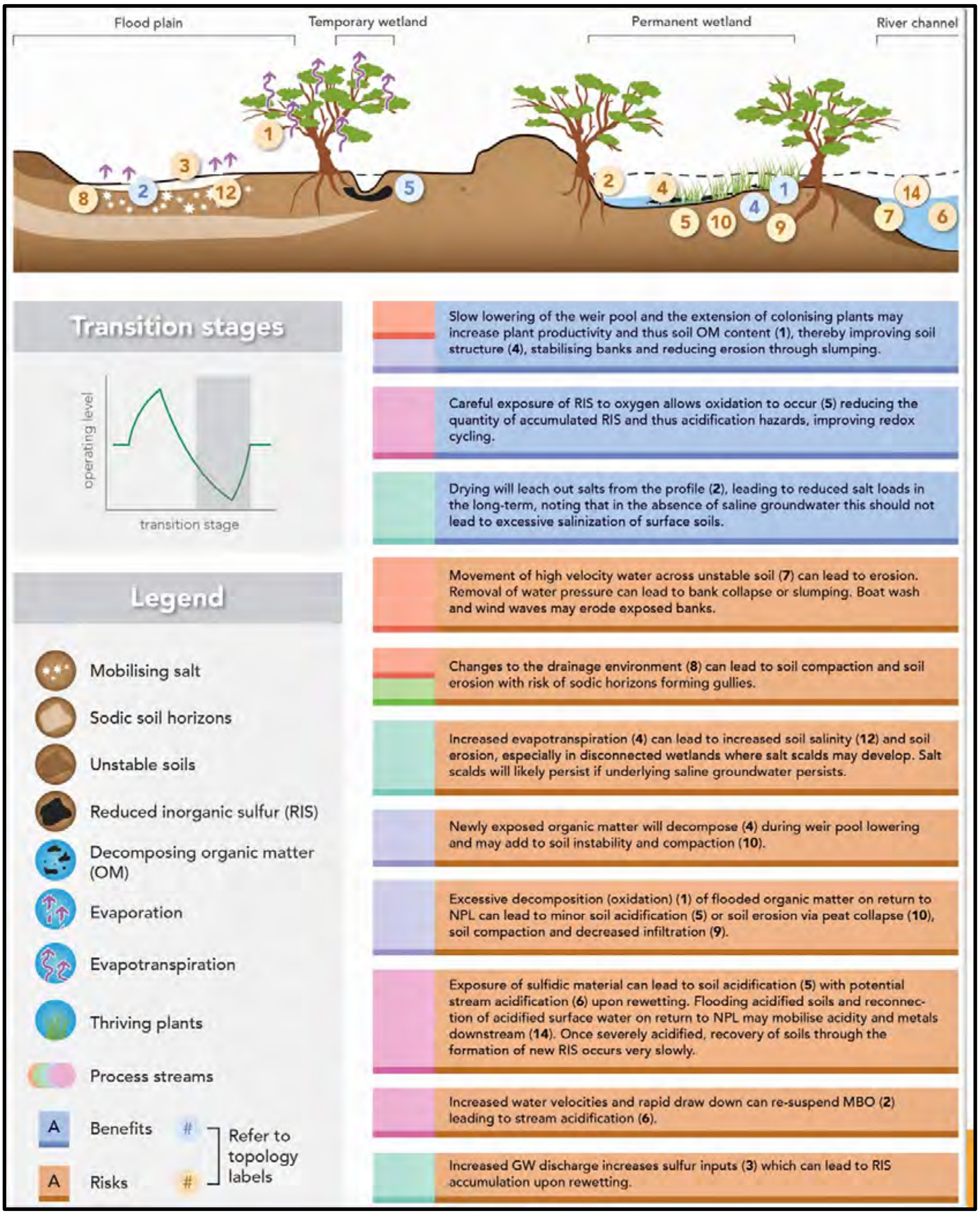
4.5 Bush fire impact on soil-landscapes

Exposure and drying of saline wetland soils during prolonged drought conditions followed by the so called "mega bushfires" in 2019-20 (Lane et al. 2022) resulted in the permanent or irreversible conversion of some minerals into new minerals under a range of temperature conditions (Fitzpatrick et al. 2014). Following this severe bushfire in the MDB, coarse soil fractions comprising hard, ceramic-like fragments were formed within clayey soils with high organic matter (e.g. burn peaty clays). These soil types have been identified in Australian soils and has led to the introduction of "burnt soil materials" in the Australia Soil Classification, now classified as "fusic material". Extremely high temperature fires (>800°C for more than 1 hour or 600°C for 80 hours) were shown to melt salt-rich saline acid sulfate soil types to form masses of glass-like groundmass. These solid masses reduce the chemical, physical, and consequently biological characteristics of soil condition. Fire in such areas leads to permanent soil loss by soil erosion.

4.6 Summary of soil-landscape threats from drying caused by prolonged drought

The following eight predicted threats/risks to future (50-year) MDB soil-landscapes as anticipated under the drying hydroclimate scenario caused by prolonged drought conditions is shown in the generalized soil-landscape transect conceptual model (Figure 8):

1. Unstable soils (decline in soil structure and texture as noted in Section 4.1) can lead to soil erosion, river bank collapse and slumping.
2. Drainage of sodic soils can lead to soil compaction and erosion forming gullies (as noted in Section 4.1.1; Figure 6).
3. Increased evapotranpiration can lead to increased soil salinity (as noted in Section 4.1.1; Figure. 5) and soil erosion (as noted in Section 4.1.1; Figure. 6).
4. Newly exposed organic matter will decompose during weir pool lowering and lead to soil instability and compaction (as noted in Section 4.1.3).
5. Excessive oxidation of flooded organic matter on return to Normal Pool Level (NPL) can lead to minor acidification and soil erosion via peat collapse (as noted in Section 4.2.1, Figure 7 (c)).
6. Exposure of hypersulfidic material leads to the formation of sulfuric material with potential stream acidification upon rewetting and mobilisation of metals (noted in Section 4.2.1, Figure 7 (d)).
7. Increased water velocities and rapid draw down can re-suspend monosulfidic material (MBO) leading to stream acidification (noted in Section 4.2.2, Figure 7 (d)).
8. Increased Ground Water (GW) discharge increases sulfur inputs, which can lead to RIS accumulation upon rewetting (as noted in Section 4.1.4, Figure 5).



Slow lowering of the weir pool and the extension of colonising plants may increase plant productivity and thus soil OM content (**1**), thereby improving soil structure (**4**), stabilising banks and reducing erosion through slumping.

Careful exposure of RIS to oxygen allows oxidation to occur (**5**) reducing the quantity of accumulated RIS and thus acidification hazards, improving redox cycling.

Drying will leach out salts from the profile (**2**), leading to reduced salt loads in the long-term, noting that in the absence of saline groundwater this should not lead to excessive salinization of surface soils.

Movement of high velocity water across unstable soil (**7**) can lead to erosion. Removal of water pressure can lead to bank collapse or slumping. Boat wash and wind waves may erode exposed banks.

Changes to the drainage environment (**8**) can lead to soil compaction and soil erosion with risk of sodic horizons forming gullies.

Increased evapotranspiration (**4**) can lead to increased soil salinity (**12**) and soil erosion, especially in disconnected wetlands where salt scalds may develop. Salt scalds will likely persist if underlying saline groundwater persists.

Newly exposed organic matter will decompose (**4**) during weir pool lowering and may add to soil instability and compaction (**10**).

Excessive decomposition (oxidation) (**1**) of flooded organic matter on return to NPL can lead to minor soil acidification (**5**) or soil erosion via peat collapse (**10**), soil compaction and decreased infiltration (**9**).

Exposure of sulfidic material can lead to soil acidification (**5**) with potential stream acidification (**6**) upon rewetting. Flooding acidified soils and reconnection of acidified surface water on return to NPL may mobilise acidity and metals downstream (**14**). Once severely acidified, recovery of soils through the formation of new RIS occurs very slowly.

Increased water velocities and rapid draw down can re-suspend MBO (**2**) leading to stream acidification (**6**).

Increased GW discharge increases sulfur inputs (**3**) which can lead to RIS accumulation upon rewetting.

Figure 8. Generalized soil-landscape transects describing the distribution of the main soil types during the progressive stages of drying caused by prolonged drought conditions. Where: WPR = Weir Pool Raising, WRL = Weir Pool Lowering; NPL = Normal Pool Level. (modified from DEW 2021).

5. Climate change threats from prolonged flooding on soil-landscape wetting

Wetting of previously dry materials in several MDB wetlands caused physical, mineralogical and biochemical processes to proceed where they had previously been water limited (Fitzpatrick et al. 2017a,b; Stirling et al. 2020). Although these processes are not independent, typical soil biochemistry changes that occur as a soil profile is rewet or resubmerged include (Ponting et al. 2021):

- Depletion of oxygen that leads to anoxia, increased hydrogen sulfide and methane concentrations, nutrient availability and increased phytotoxins (e.g. sulfides) in the 'reduced' soils,
- As soil redox potential decreases the speciation and mobility of redox sensitive metals (e.g. Fe, Mn) and metalloids (e.g. As) are altered (e.g. Potentially Toxic Elements (PTEs) and manganese and iron hydroxides undergo reductive dissolution and may accumulate to levels that are toxic to plants,
- Sulfate is reduced, generating sulfidic materials (FeS, FeS_2) and alkalinity (increasing pH) while PTEs may be immobilised due to precipitation of metal sulfides, and
- As oxygen is depleted, dissolved organic matter (DOM) increases and nitrate is reduced to ammonia by some soil microorganisms to become the main form of plant available mineral nitrogen.

During flooding, these biochemical processes will primarily occur at the oxic-anoxic interface and in the anoxic soil layers. The kinetics of these processes are of great importance because the location of the oxic-anoxic interface is subject to change due to floodwater/re-filling residence times and fluctuating water table levels, meaning the effect of flooding is not easy to predict (Ponting et al. 2021). Chemical reduction processes will often occur in a known sequence in the soil profile, a so called 'redox ladder', and are also influenced by the availability of organic matter (Kolbl et al. 2017).

5.1 Soil structure and textural changes

Soil texture and structure interact with each other to determine soil pore size and connectivity; soil pores control water movement through the profile, with light textured soils (i.e. sands) or soils with large or well connected pores allowing greater saturated hydraulic conductivity rates (i.e. water movement through already wet soil) and heavy textured soils (i.e. clays) or soils with small or tortuous pores allowing greater unsaturated hydraulic conductivity (i.e. water movement into and through dry soil). As such, processes affected by water movement, such as mobilisation of acidity and accumulation of precipitates such as sulfur minerals or salts will vary throughout the reach and may require contrary management approaches during drying after flooding (e.g. Mosley et al. 2019).

5.2 Vertosols (cracking clay soils)

While most soils will swell to some degree when wetted from dry, soils containing substantial proportions of shrink/swell clays (Vertosols) have the greatest increase in volume. Vertosols in the LMRIA and elsewhere in the MDB develop *Gilgai* (Kamilaroi and Wiradhuri word meaning small water hole or depression that has been adopted into modern soil science (Aquatic Ecosystem Health Science Integration and Capacity Building Group 2013)) microrelief in response to an excess in water availability (Fitzpatrick et al 2017a, Arnold et al. 2020). This process effectively has the effect to 'bury' RIS and oxidation products, lowering the potential for re-oxidation and surface water impacts during subsequent drying (i.e. improved with each wetting and drying cycle). In summary, this process has positive implications ASS management as it assists to re-establish conditions conducive to RIS reduction at a lower position in the soil profile (Fitzpatrick et al 2017a).

Vertosols have a high moisture holding capacity that can support vegetation later into a dry summer compared sandy soils. Rewetting Vertosols will wash surface debris such fine self-mulching clay and organic matter into the cracks, increasing the speed with which the soil reincorporates itself.

5.3 Saline sodic soils

Re-inundation of saline-sodic soils presents a risk of dispersion, particularly as the flood water (or rainwater) typically has a lower ionic strength or salinity than the soil porewater (Rengasamy 2002, Rengasamy et al. 2010). Dispersion of sodic soil causes clay aggregates to dissolve as water fills the interlayer spaces and force clay particles apart, filling pore spaces with unstructured clay particles and significantly reducing hydraulic conductivity (Rengasamy 2002). Dispersed clay in the water column also decreases water quality through increased turbidity (Rengasamy 2002, Rengasamy et al. 2010). Clay dispersal at the soil surface poses an acute barrier to movement (vehicles/animals) and will form a hard-setting soil crust on drying (Fitzpatrick et al. 1994, 1996). Changes in water movement through the soil profile and decreased plant germination due to hardsetting surfaces further increase the risk of soil erosion (Mosley et al. 2017).

Inundation of saline sodic soils with freshwater with low calcium or magnesium content does not provide remediation of sodic soils, but rather leaches sodium cations leaving soil prone to structural collapse (Fitzpatrick et al. 1994). Inundation that inputs fresh water into the soil profile recharges shallow groundwater with fresh water, dissolves solid salt crystals, and provides a mechanism for salt export. However, irrigation and drainage with River Murray water has been shown to reduce soil salinity and sodicity in Vertosols in the LMRIA (Mosley et al. 2017).

5.4 River bank slumping

There is an increased risk of bank slumping and topsoil instability during re-flooding where soils have previously been eroded during water level lowering. Soil erosion caused by bank slumping has negative effects on water quality and can damage or de-stabilise nearby infrastructure (Hubble et al. 2014, Bovi et al. 2020). Furthermore, flooding, even at relatively low velocity may cause soil erosion in unvegetated sites where stream flow is concentrated and underlying soils are poorly structured and not massive. Shallow water velocities can lead to erosion of surfaces with a slope of at least 3.5% (e.g. Thomas et al, 2019, Wong et al 2016). Relatively minor erosional events may lead to gully formation in sodic or otherwise unstable soil profiles (Figure 6).

5.5 Changes in soil structure by wetting

Compaction that occurred under drying conditions may be irreversible where organic carbon was lost from organic horizons, where voids were crushed by the weight of overlying materials, or where the loss of soil mineral structure has occurred (Stirling et al. 2020, Fitzpatrick et al. 2017a). However, soil compaction may recover to some extent following inundation where increased moisture causes swelling of clays and the decomposition of organic matter generates soil vapours or allows aggregate formation. To this end, soil structure has been found to improve as organic matter is incorporated into the profile, which is further enhanced by the re-establishment of wetland vegetation increasing litter deposition and root growth.

Re-flooding and maintaining stable weir pool levels and groundwater levels reduces the storage capacity of soils within the catchment because saturated soils have severely limited air-filled porosity compared to non-saturated soils (Thomas et al. 2019). Rewetting of texture contrast soils with poorly structured B horizons may result in waterlogging as the dry subsoil horizons pose a substantial barrier to vertical water movement.

5.6 Reflooding leading to oxygen depletion and decreased soil redox potential

Inundation of acid sulfate soils that contained sulfuric materials (pH<4) in several wetlands in the MDB rapidly (i.e. within a few weeks) induced anoxia in the soils, particularly in soils with heavy texture and high organic matter contents with abundant labile carbon as shown in Figure 7(e) (Kölbl et al. 2017; Yuan et al. 2015, Jayalath et al. 2016, Fanning et al. 2017, Lee et al. 2021). Anoxic conditions generate carbon dioxide, nitrous oxide and methane, thereby adding to GHG emissions (Mosley et al. 2021). Nitrous oxide and methane production typically exists in a balance wherein the redox conditions for one are not suitable for the other; wet soils can cycle between producing these two gases in a diurnal rhythm (Stirling et al. 2020). As soil redox potential decreases in flooded wetlands, the speciation and mobility of redox sensitive metals and metalloids (e.g. PTEs) is altered and manganese and iron hydroxides undergo reductive dissolution, which can accumulate to levels that are toxic to plants.

The prime consumer of oxygen in wet soils is microbial organic matter decomposition and, while decomposition is necessary to release plant available nutrients, rapid decomposition of organic matter can lead to deoxygenation of both soils and water as has been observed in the Chowilla Floodplain region (Murray-Darling Basin Commission 2006).

The capacity for a wetland to capture organic matter is influenced by topography and water retention time with shallow wetlands and floodplains likely to provide more ecological benefits than deeply incised channels due to their greater horizontal area affected by changing water levels such as in the Nelwart Lagoon. Actively revegetating such wetlands with shoreline plants that extended into a lagoon floor can aid RIS formation by providing an additional source of labile organic matter and alkalinity (Shand et al. 2010) as shown in Figure 7 (e).

In soils with sulfur salts present (in the soil itself or dissolved in the water), anoxia typically leads to both abiotic and microbial sulfate reduction and the production of RIS materials (Fanning et al. 2017). Under optimal conditions, RIS starts forming within days of saturation; however, meaningful accumulation of RIS takes at least weeks-months (e.g. Jayalath et al. 2019). Re-establishment of reducing conditions and RIS production consumes acidity and generates alkalinity, thereby having a positive impact on improving pH of surface waters or by removing acidity by storage in reduced minerals such as pyrite (Figure 7(e)). Sulfate reduction is enhanced in the presence of low molecular weight organic matter or labile carbon, which is an energy source for microorganisms.

5.6.1 Acid sulfate soil materials during re-flooding

Reflooding a wetland following a period of managed drying (or prolonged drought) has potential to mobilise acidity (soluble and stored forms), salinity and or metals to the receiving environment (e.g. Simpson et al. 2010) as shown in Figure 7 (d). In highly acidified acid sulfate soil wetlands, reflooding has led to surface water acidification and a heightened risk of ecological damage through persisting periods (i.e. years) of low pH, increased metal mobilisation and off-site transportation of acidity and metal(loids) (Baker et al. 2013; Creeper et al., 2015a,b; Mosley et al., 2014b; Shand et al. 2009, 2010). Acidification can develop quite quickly (weeks) under suitable ASS conditions in many River Murray wetlands (Thomas et al. 2019a,b).

During reflooding, acidity and oxidation products may be mobilised by the in-flowing waters, either by surface run-off or by lateral through flow, potentially resulting in acidification of surface and near surface water (e.g. Wilson et al. 1999; Mosley et al. 2014a,b); however, the degree to which acidity will be mobilised (to surface waters) is specific to the soil and hydrological characteristics of each wetland. During reflooding of permeable sandy soils, acidity may be displaced downward, deeper into the profile by advective piston flow, where it may persist for many years (Creeper et al. 2015a,b; Mosley et al. 2017). In the absence of piston flow, a diffusive flux of acidity from the soil to surface water may result in surface water acidification. In less permeable clayey acid sulfate soil diffusion may not be sufficient to acidify surface waters during reflooding (Creeper et al. 2015a,b; Mosley et al. 2017).

Where subsurface transport of acidic water does occur, the acidic water will interact with a range of different soil materials that may neutralise the acidity and adsorb many of the substances that were mobilised during initial rewetting. During transport into surface waters, mixing with waters of differing pH, alkalinity and concentrations of suspended solids may also result in neutralisation of acidity and precipitation or adsorption of metals (Simpson et al. 2010). These observations indicate that inputs of dissolved metals from re-wetted acidic soil systems to the River Murray may be expected to be lower if acidic waters are transported through large masses of soil before reaching the river system (Simpson et al. 2010).

5.6.2 Resuspension of monosulfidic soil material during flooding

Rapid drawdown during weir pool lowering may re-suspend MBO if increased channel water velocity causes scouring (Mosley et al. 2014b, Thomas et al. 2019a,b). During managed inundations or weir pool lowering, relatively high water velocity within creek channels may generate sufficient turbulence (scour energy) to disperse soil crusts and mobilise monosulfides and organic matter (i.e. if the critical sediment shear stress is exceeded by moving water) (Thomas et al. 2019a,b). Values for critical bed shear stress (Newtons per square meter, $N\ m^{-2}$) indicate that shear stress values >0.04 Nm^{-2} are sufficient to re-suspend fine organic rich materials (Thomas et al. 2020). Resuspension can lead to latent acidification and complete consumption of dissolved oxygen in the water column (Bush et al. 2004, Cheetham et al. 2012, Mosley et al. 2014a,b; Sullivan et al. 2018).

During managed (or natural) floodplain inundations the highest in-stream velocities occur during the early phases of inundation, prior to tail waters becoming sufficiently elevated to reduce the hydraulic gradient and drive a decrease velocity and scour energy in these creeks. During weir pool manipulations, water velocities will increase marginally in the main river channel, but will not exceed flows under normal conditions. Weir pool lowering has the potential to marginally increase water velocities in anabranch creeks that flow around weirs, if the head difference across the weir is increased, but velocity increases are not expected to be sufficient to cause scouring. In contrast, in-stream regulators, culverts or drainage restrictions are likely to have higher velocities for short distances, and these structures may accumulate monosulfides behind them during periods of low water level (Mosely et al. 2019, Thomas et al. 2019a,b).

Shallowing of lagoons during river water level or weir pool lowering has potential to expose monosulfidic sediments, or to bring them to the near surface, where they will then be susceptible to scouring and re-suspension by windblown wave action (or seiche). These sites present a water quality risk to the lagoon and ultimately to any connected waterbodies down hydraulic gradient (such as the main river channel).

5.6.3 Excessive organic matter decomposition in the water column

While organic decomposition is a vital ecological process occurring in wetlands, rapid decomposition strips oxygen from the immediate environment and may kill adjacent aerobic organisms. Litter decomposition and mobilisation of DOC can lead to rapid (within days) hypoxia through bacterial respiration and stratification (Hladyz et al. 2011, Whitworth et al. 2012, Vithana et al. 2019). The risk of hypoxia after flooding is influenced by temperature, water volume, water exchange, and the quantity of organic matter entrapped by the waterbody. The highest risk environments are shallow waters with low exchange rates, high water temperatures (>20°C), and large quantities of dissolved organic carbon. As little as one month of plant litterfall can be sufficient to cause a hypoxic event if water conditions are appropriate (Mosley et al. 2021).

Forested sites tend to carry a higher risk of post-flood hypoxia; these sites can remain hypoxic for several months after inundation (Mosley et al. 2021). As water flows through a floodplain, oxygen concentrations will decrease proportionally to the distance travelled across the floodplain (during overland flow), while, turbidity, carbon dioxide and dissolved organic carbon concentrations will increase (Zuijdgeest et al. 2016).

Agricultural sites are less likely to contain enough organic matter to initiate an event, though they may still become hypoxic under the right conditions. Dry plant litter loading, and the proportion of 'readily degradable' components such as grasses and leaves are key variables in hypoxia risk (Mosley et al. 2021). Mineral nitrogen compounds are readily released from organic matter, however these compounds are relatively rapidly converted into oxidised nitrogen (nitrate and nitrite, NO_x) compounds and subsequently degassed to the atmosphere (i.e. via denitrification pathway) or leached downstream. Nutrient release from litters may also increase dissolved P loading (Zhang et al. 2021) that can promote formation of algal blooms.

5.7 Transport of surface/subsurface materials to new places

Inundation of land with river waters in the MDB will transport (mobilise) surface/subsurface materials and waters containing PTEs to new places (Mosley et al. 2014 b). The term “mobilisation” is a concept that has been frequently used to estimate the risk of contamination from the soil to the surrounding environment by PTEs (Mosley et al. 2014 b).

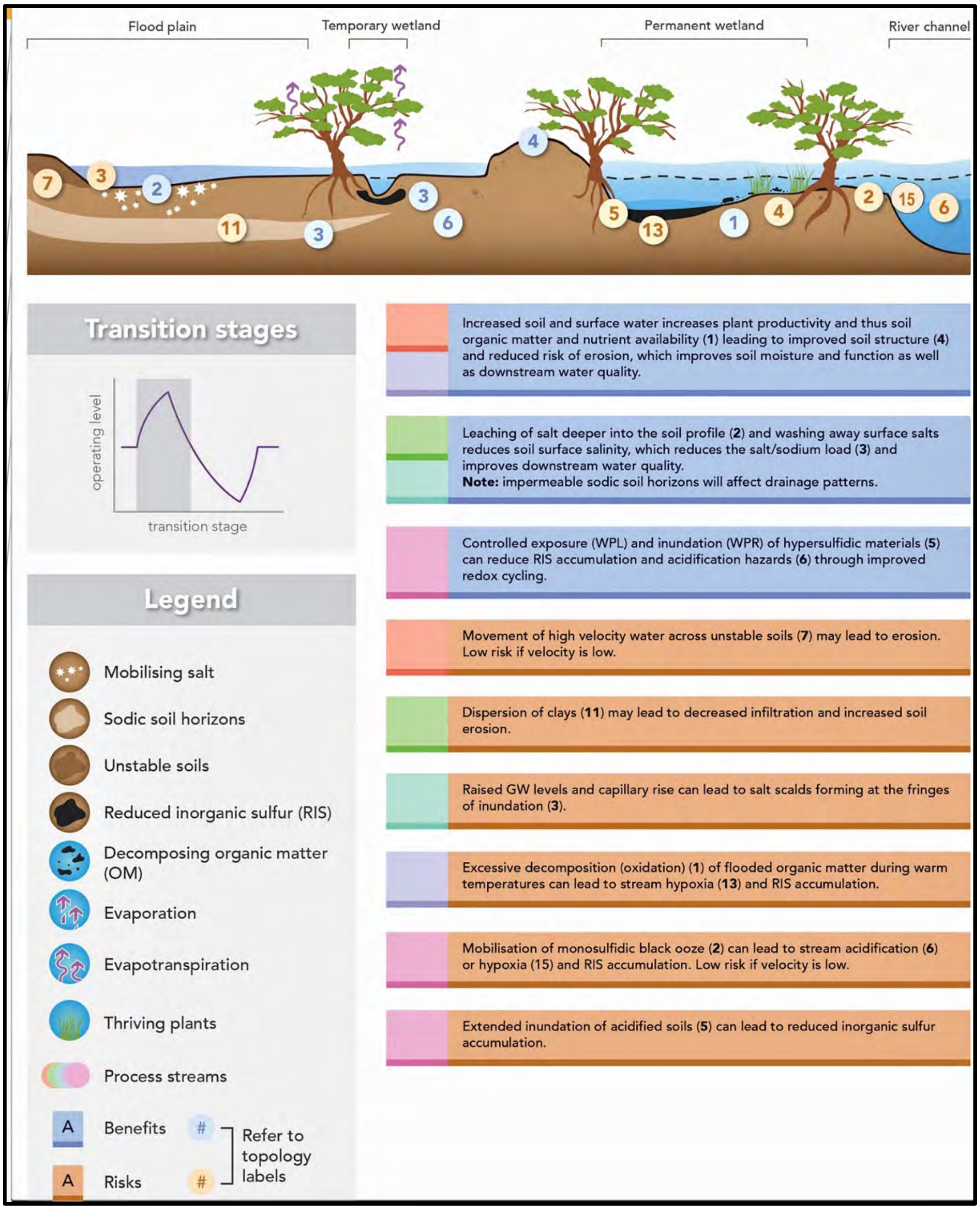
5.8 Subsequent plant growth will affect soil structure and nutrient conditions

Subsequent plant growth after weir pool raising will generate additional organic matter at the site (Thomas et al. 2019a). Similarly, below-ground biomass (roots) may also improve soil structure and subsequent infiltration capacity. Plant growth can also increase site roughness, increasing the amount of organic matter which may be trapped during future flood events. Additional nutrient capture in wetlands is likely to increase site productivity as microbial decomposition of organic matter increases the available nutrients for plants and other organisms (Stirling et al. 2020). Inundation of isolated wetlands and floodplains allows the transfer of allochthonous organic matter, nutrients and sediments between land and stream systems and improves ecosystem function.

5.9 Summary of soil-landscape threats from rewetting caused by prolonged high rainfall

The following six predicted threats/risks to future (50-year) MDB soil-landscapes as anticipated under the hydroclimate scenario caused by prolonged progressive stages of wetting (reflooding) from extreme rainfall events as shown in a generalized soil-landscape transect (Figure 9):

1. Movement of high velocity water across unstable soils can lead to erosion (decline in soil structure and texture as noted in Section 5.1).
2. Dispersion of clays can lead to decreased infiltration and increased soil erosion (as noted in Section 5.3; Figure 6).
3. Raised Ground Water (GW) levels and capillary rise can lead to salt salt scalds forming at the fringes of inundation (as noted in Section Section 5.6.1; Figure 7 (e)).
4. Excessive decomposition via oxidation of flooded organic matter during warm temperatures can lead to stream hypoxia and RIS accumulation (as noted in Section 5.6, Figure 7 (e)).
5. Mobilisation of monosulfidic materials (Monosulfidic Black Ooze: MBO) can lead to stream acidification or hypoxia and RIS accumulation (as noted in Section 5.6.2, Figure 7 (c; e)).
6. Extended inundation of acidified soils can lead to reduced inorganic sulfur accumulation patricularly in the presence of low molecular weight organic matter or labile carbon (as noted in Section 5.6.1; Figure 7 (e)).



Increased soil and surface water increases plant productivity and thus soil organic matter and nutrient availability (**1**) leading to improved soil structure (**4**) and reduced risk of erosion, which improves soil moisture and function as well as downstream water quality.

Leaching of salt deeper into the soil profile (**2**) and washing away surface salts reduces soil surface salinity, which reduces the salt/sodium load (**3**) and improves downstream water quality.
Note: impermeable sodic soil horizons will affect drainage patterns.

Controlled exposure (WPL) and inundation (WPR) of hypersulfidic materials (**5**) can reduce RIS accumulation and acidification hazards (**6**) through improved redox cycling.

Movement of high velocity water across unstable soils (**7**) may lead to erosion. Low risk if velocity is low.

Dispersion of clays (**11**) may lead to decreased infiltration and increased soil erosion.

Raised GW levels and capillary rise can lead to salt scalds forming at the fringes of inundation (**3**).

Excessive decomposition (oxidation) (**1**) of flooded organic matter during warm temperatures can lead to stream hypoxia (**13**) and RIS accumulation.

Mobilisation of monosulfidic black ooze (**2**) can lead to stream acidification (**6**) or hypoxia (15) and RIS accumulation. Low risk if velocity is low.

Extended inundation of acidified soils (**5**) can lead to reduced inorganic sulfur accumulation.

Figure 9. Generalized soil-landscape transects describing the distribution of the main soil types during the progressive stages of rewetting caused by reflooding from extreme above annual rainfall events (modified from DEW 2021). Where: WPR = Weir Pool Raising, WRL = Weir Pool Lowering; GW = Ground Water; RIS = Reduced Inorganic Sulfer (modified from DEW 2021).

6. Adaptive soil-landscape management under climate change

River regulation for more than 80 years in the MDB combined with frequent extreme soil drying and wetting caused largly by climate change (e.g. Millennium Drought across the MDB), has resulted in many soil-landscape degradation issues such as: soil erosion by water & wind, acidification, salinization, clay dispersion/sodicity, waterlogging, soil compaction, production of noxious gases, monosulfide accumulation & disturbance and bushfire impact.

Current scientific knowledge can support a range of possible conservation measures and nature-based solutions to rehabilitate MDB soil-landscape degradation in 50 years as outlined in Table 2.

Table 2. Adaptive soil-landscape management strategy recommendations

Drying Scenario	Wetting Scenario
Slow lowering of the weir pool and the extension of colonising plants to increase plant productivity and thus soil organic matter content, which will improve soil structure, stabilise banks and reduce soil erosion.	Increased topsoil and subsoil supply of water, which will increase plant productivity and thus soil organic matter and nutients leading to improved soil structure, reduced risk of erosion and improved stream water quality,
Careful exposures of hypersulfidic material with RIS to oxygen (air), which will allow oxidation to occur and reduce the quantity of accummulated RIS (i.e. hypersulfidic material) and thus acidification (i.e. formation of sulfuric material)[1].	Leaching of salts deeper in the soil profile and washing away suface salts reduces soil surface salinity, which reduces salt loads and improves downstream water quality.
Controlled drying, which will cause salts to leach out of soils leading to reduced salt loads in the longer-term 50-year hydroclimate changes leading to soil-landscape degradation.	Controlled exposure (via Weir Pool Raising: WPR) and inundation (via Weir Pool Lowering: WRL) of hypersulfidic material, which will reduce the accummulation of reduced inorganic sulfur (RIS) through improved redox cycling by managing reflooding to: (i) prevent further pyrite oxidation, (ii) neutralise acidity by introducing surface water alkalinity, (iii) establish reducing conditions to promote alkalinity generating geochemical reactions and the reformation of pyrite.
Use environmental and irrigation water where possible to prevent deep cracking and salinisation of clay soils and maintain plant cover.	Control inundation and flow rates were possible to prevent development of hypoxic blackwater events and scouring of sediment and monosulfidic black oozes (MBOs)

[1] Reduced sulfur species tend not to build up to harmful levels in wetlands that have frequent (annual) wetting and drying cycles (Fitzpatrick et al. 2009, Mosley et al. 2014a, 2019) due to: (i) regular 'burning off' of RIS materials in drying phases with limited time for build up in wetting phases, (ii) the periodic dilution and removal of sulfate, nutrient, salt loads to the river, (iii) seasonal flooding reworking and scouring fine (clay and MBO) surface sediments and organic matter, and (iv) flooding providing a supply of soluble ANC and decreasing stratification and anoxic conditions.

A summary of the positive and negative outcomes caused by drying and wetting scenarios are shown in an interactive flow diagram (Figure 10) together with the four key levers available for managing soil degradation processes and associated threats to surface and groundwater quality, whilst promoting other beneficial soil processes that contribute to a healthy functioning wetland.

However, some soil-landscape changes in the MDB are cyclic and recover from extreme acidification due to drying during the transition back to rewetting phases (i.e. because of the abundance of labile carbon as shown in Figure 7 (e)), while others result in permanent or irreversible changes to soil acidification (Mosley et al. 2017b) and hydrological properties (i.e. excavated and permanently drained landscape with deficient labile carbon as shown in Figure 7 (d)).

7. Conclusions

Soil-landscape degradation adaptation to climate change is challenging because of the cross-cutting issues connected to many disciplines as shown in the flow diagram (Figure 10). The flow diagram also shows the many interrelating positive and negative outcomes associated with soil drying and rewetting scenarios. To better understand the negative and positive soil-landscape degradation threats posed by climate change managers and policymakers should consult the flow diagram showing the soil processes related to drying and rewetting scenarios. Moreover, as shown in the interrelating flow diagram, it is no longer sufficient to manage only water quantity and quality issues in the MDB; soil-landscape management is also essential.

To achieve the goal of best "sustainable soil-landscape management" for the MDB in 50 years, we need an integrated approach to implement a **seasonal wetting and drying regime** to the river and adjacent wetland regulation, which will substantially reduce the many risks related to the **prolonged drying** and **subsequent rewetting**, which can potentially lead to the redistribution and accumulation of acidity and oxidation products (hazards) within a soil profile and the floodplain.

Climate change threats from prolonged drying and wetting increases the soil erosion rate in the dominant soil types, especially sodosols in the MDB. The higher soil erosion rate and the decline in soil structure lessens the soil organic carbon content in these soil types and acts as a carbon source to the atmosphere. In the MDB, these developments are acting as cyclic processes, which further enhances the global warming and eventually leads to enhanced climate change.

The risk of acidification in soils and water is partially determined by the substrate's proximity to the surface and its inherent acid neutralising capacity (ANC), which is determined by the content of alkaline minerals, organic matter, and clay particles in the soil environment.

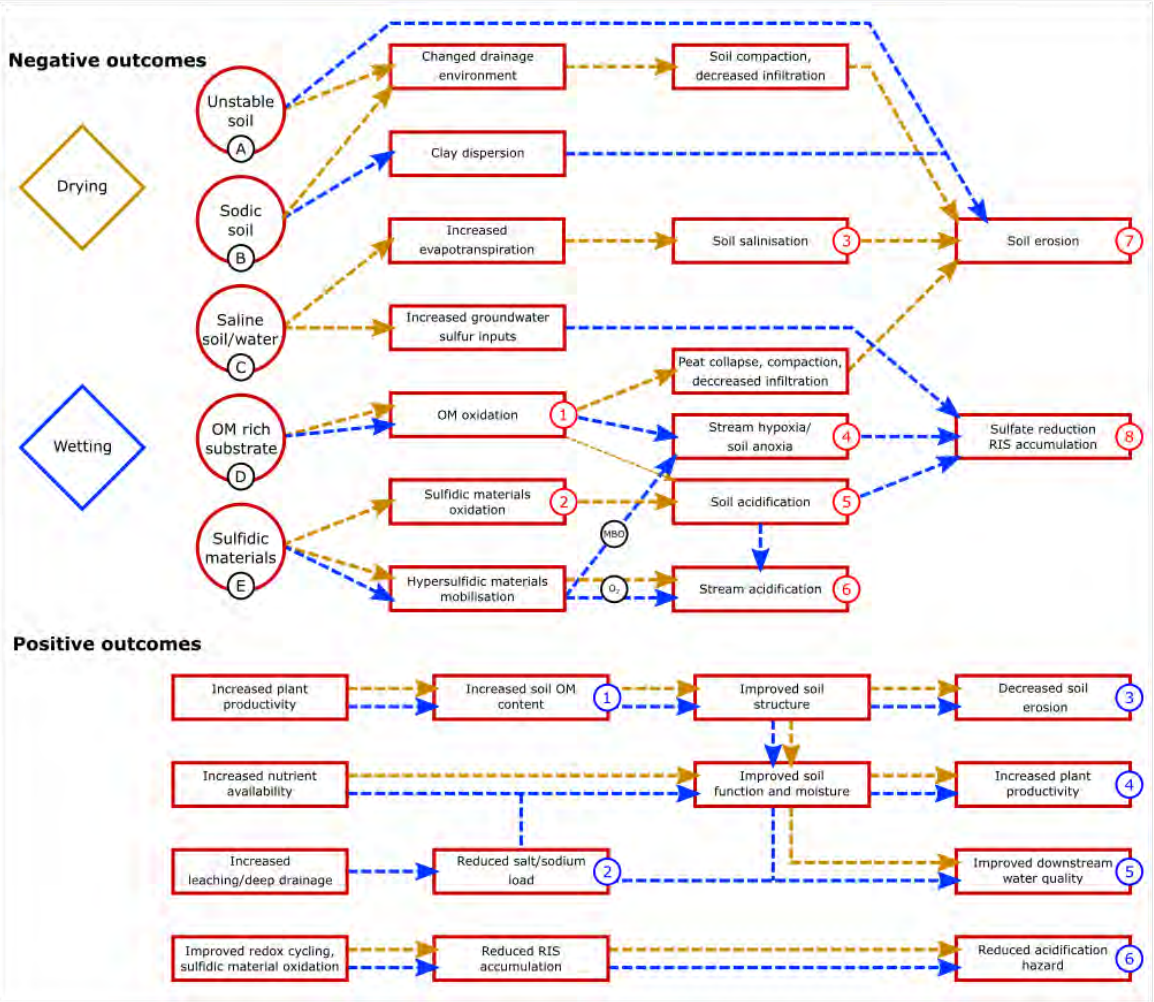


Figure 10. Flow diagram showing the soil processes relating to drying (brown arrows) and rewetting (blue arrows) scenarios, as demarcated and described in Figures 8 and 9 (modified from DEW 2021).

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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

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Above: Ramsar Wetlands, South Australia. John Brinkworth, iStock.

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.

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.

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).

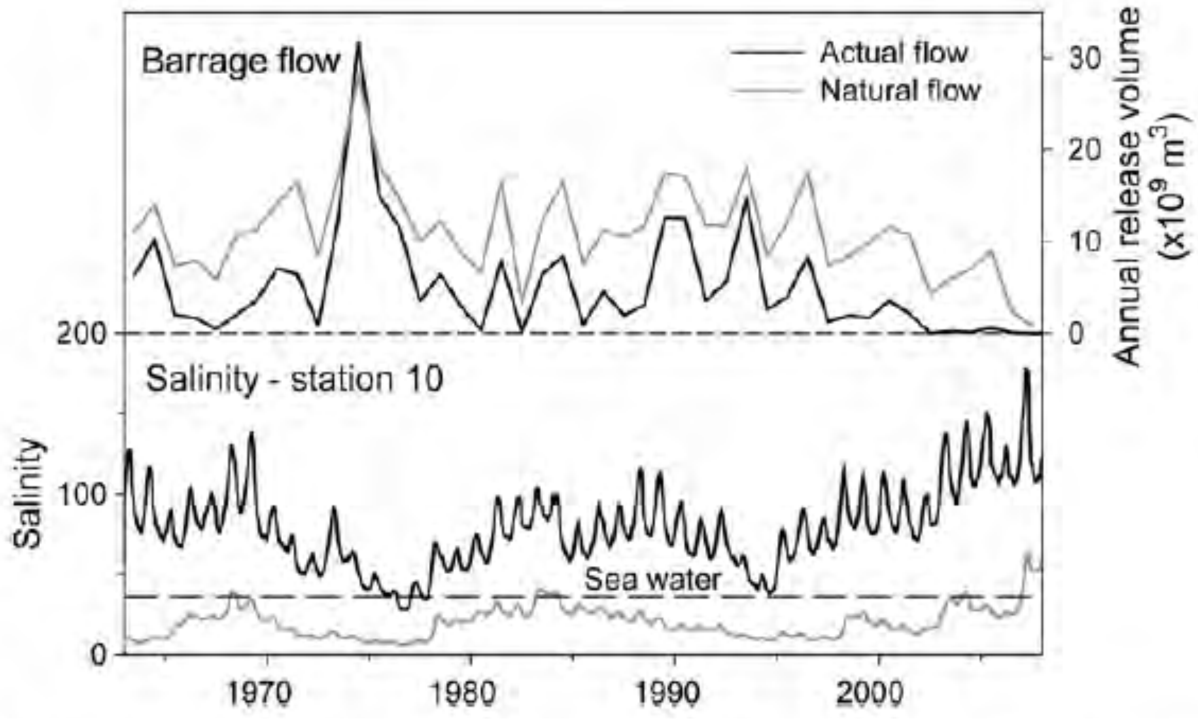

Figure 2. Annual release volumes for actual and natural barrage flows (top) and modelled salinity in the South Lagoon of the Coorong for actual and natural barrage flows (bottom), showing seawater concentrations (36 ppt, dashed line). Source: Webster (2010).

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).

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 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).

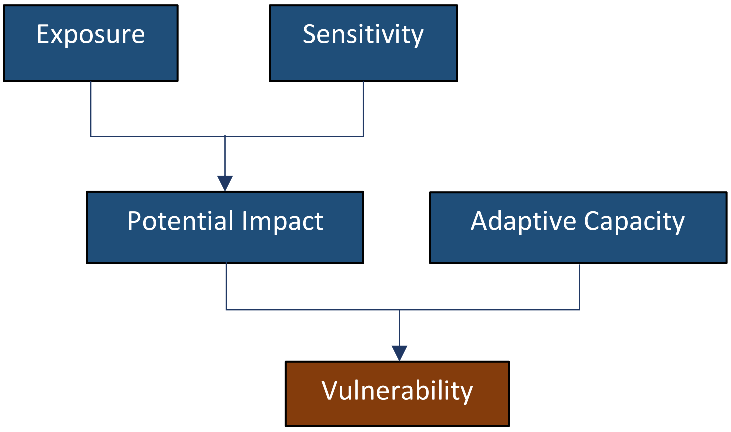

Figure 3. Qualitative climate change vulnerability assessment model. Source: Allen Consulting (2005).

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.

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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MURRAY-DARLING BASIN ESSAY

Essay #6 in a series of nine by Australia's leading water experts

The past, present and future of the Coorong, Lower Lakes and Murray Mouth

Luke Mosley, Brenton Zampatti and Matt Gibbs

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Above: Aerial views of Coorong National Park on the South Australian coast. traceloiuse, iStock.

EXECUTIVE SUMMARY

The Ramsar-listed Coorong estuary, Lower Lakes, and Murray Mouth (CLLMM) region has experienced substantial ecological decline over the last century due to reduced inflows caused by river regulation and water extraction, and unfavourable hydroclimate effects and natural calamities like the Millennium Drought.

Mosley et al. conduct a critical assessment of the causes of decline in ecological health of the CLLMM region and advise on the hydrological restoration, ongoing learning, and evolution of strategies that maximise the benefits from environmental water, coupled with infrastructure improvements. They also observe that the implementation of the Basin Plan has not resulted in expected increased flow of environmental water in the River Murray, particularly at the end of system and this may, at least in part, be a consequence of climate change.

Mosley et al. propose a more automated barrage operating system, thus enabling the operation of hundreds of gates in the barrages to manage finer-scale manipulations in response to flow, tide and prevailing wind will create a 'softer', more transparent and dynamic estuarine interface. Careful adaptive management to mitigate risks of seawater intrusion that may harm the ecological, cultural and socio-economic values of the Lower Lakes will be required.

The past, present and future of the Coorong, Lower Lakes and Murray Mouth

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Abstract

The Coorong estuary, Lower Lakes and Murray Mouth (CLLMM) region comprises a Ramsar-listed ecosystem that supports important ecological, cultural and socio-economic values. Owing to its location at the end of the of the Murray-Darling river system, it is particularly vulnerable to hydrological alteration. Over the last century, reduced inflows due to river regulation and water extraction have led to substantial ecological decline, exacerbated more recently by the Millennium Drought (1997–2010). The CLLMM is at a critical juncture. The ongoing impacts of river regulation, combined with projections of climate change, are likely to lead to continued hydrological, ecological, social and cultural decline, unless increased volumes of environmental water are made available, alongside improved ability to deliver this water to the region. Hydrological restoration, ongoing learning and evolution of strategies to maximise benefits from environmental water, coupled with infrastructure improvements, will be key to ensuring that the ecological health of the CLLMM can improve and potentially again support the values for which the region is recognised.

Introduction

The Coorong, Lower Lakes, and Murray Mouth (CLLMM) region in southern Australia lies at the terminus of the Murray-Darling river system. The region is the home and lands (Yarluwar-Ruwe) of the Ngarrindjeri, the indigenous people of this region (Ngarrindjeri Nation and Hemming 2018) and is recognised locally, nationally and internationally for a range of ecological, cultural and economic values. From an ecological perspective, the region is of national and international conservation significance, with the Coorong being ranked in the top six waterbird sites in Australia (Paton, 2010). In 1985, it was listed as a Wetland of International Importance under the Ramsar Convention. The area is also socio-economically important, including several regional towns (Goolwa, Milang, Meningie and Narrung) and industries such as farming, tourism and fisheries.

Historical and contemporary water resource development in the Murray-Darling Basin (MDB or Basin), alongside climate change, present a host of challenges to the ecological health of the region. Simultaneously, however, improving ecological knowledge, along with an understanding of the potential ramifications of climate change, presents adaptation opportunities for the CLLMM. This essay outlines a contemporary picture of aquatic ecosystems in the CLLMM, including historical and current states, the pressures and drivers of change, and an outlook on opportunities to preserve, protect and enhance the region's ecological character and values.

Geomorphology, hydrology, water quality

Before considering current and future challenges and opportunities in the CLLMM, we first briefly outline the diverse bio-physical setting of the system. The River Murray enters Lake Alexandrina, one of two lakes, along with Lake Albert, collectively termed the 'Lower Lakes' (Fig. 1). Lake Alexandrina is a large (~65 300 ha) and relatively shallow lake with a mean depth of 2.9 m and a maximum depth of 4.8 m (Gibbs et al. 2018). Lake Albert is a smaller (~17 270 ha) and shallower (mean depth of 1.4 m) lake linked to Lake Alexandrina by a narrow channel ('The Narrung Narrows'), but with no other outlet (i.e. a terminal lake). The combined volume of the Lower Lakes at a nominal full supply level of +0.75 m AHD is ~1900 GL.

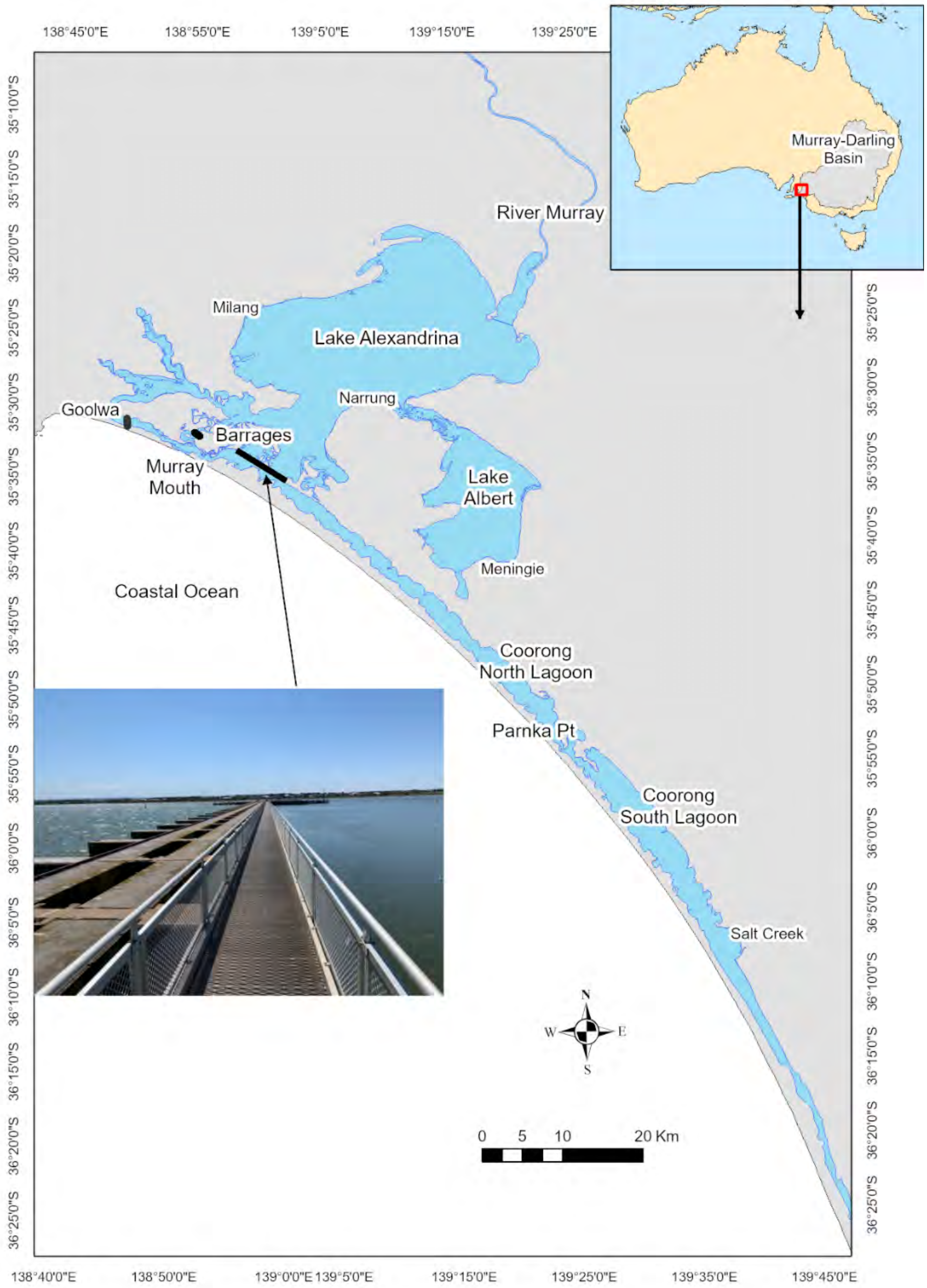

Figure 1. Map of the Coorong Lower Lakes and Murray Mouth system and inset photo of a barrage

At the downstream end of Lake Alexandrina, a series of regulating structures known as 'the barrages' separate the freshwater Lower Lakes from the estuarine lagoons of the Coorong. The barrages were constructed over 1935–1940, to mitigate the upstream incursion of saline water, which had become more pronounced due to water resource development in the MDB, and to maintain the Lower Lakes as a body of freshwater with relatively stable water levels (Sims and Muller 2004). The five barrages have a combined length of approximately 7 km and comprise >500 individual gates that are mostly manually operated, although there are some automated gates and fishways present (Bice et al. 2017). The barrage gates are opened when suitable conditions are present, i.e. sufficient River Murray inflows to the Lower Lakes to enable freshwater outflow without lowering of lake water levels beyond normal operating ranges and to prevent incursion of saline water. Water physicochemistry in the Lower Lakes is critically dependent on River Murray inflow, with the worst water quality on record - highest salinity, algae and nutrient levels, and acidification in marginal areas - occurring in the Millennium Drought when inflows were extremely low (Mosley et al. 2012; 2014; Aldridge et al. 2018).

Once freshwater has been released through the barrages, it enters an estuarine mixing zone near the Murray Mouth, the Murray-Darling Basin's sole outlet to the ocean. Under contemporary conditions, the Murray Mouth is relatively narrow, typically 100–200 m, and has a dynamic morphology. Large outflows from the barrages deepen the Murray Mouth channel via scouring of sand (Mosley et al. 2016). In contrast, during low flows, the Mouth may completely close, as occurred in 1981 and 2003 (Gibbs et al. 2018). Since 2002, the Mouth has predominantly been kept open, mostly by near continuous dredging. Despite the Mouth being maintained 'open' by dredging, during periods of low River Murray flows, the barrages themselves may remain completely closed for long periods of time, this included 1200 days during the Millennium Drought (Zampatti et al. 2010).

The Coorong is a shallow and narrow estuarine-lagoon system (Fig. 1), which extends ~110 km to the southeast away from the Murray Mouth, separated from the sea by a sand dune barrier. It is an atypical estuary type, termed an 'inverse estuary', as salinity increases with increasing distance from the river mouth. The Coorong is typically 1.5–2.5 km wide, but its geomorphology narrows to ~0.1 km about halfway along at a narrow constriction near Parnka Point (Figure 1). The Coorong waterbody north and south of the Parnka Point region is known as the 'North Lagoon' and 'South Lagoon,' respectively. The average water depths in the Coorong are 1.2–1.4 m, with a seasonally variable volume ranging between approximately 70.1 GL and 174.7 GL at water levels of -0.3m and 0.8 m AHD, respectively (Gibbs et al. 2018). The South Lagoon also receives seasonal inputs of fresh to brackish water from Salt Creek (see Fig 1.) which connects to a network of drains from the South-East region of South Australia.

Water quality in the Coorong is determined by a balance between evaporative concentration and flushing (Priestley et al. 2022, Mosley et al. 2023). An excess of evaporation over precipitation tends to accumulate salt, nutrients and organic matter within the Coorong, but currents driven by winds and by sea level variation penetrating into the lagoon through the Mouth give rise to longitudinal mixing that transports salt and other constituents back towards the sea (Webster 2010). The Coorong is exposed to regular coastal winds that cause mixing which, coupled with the lagoon's shallow nature, results in little salinity stratification, except near the Murray Mouth during significant barrage releases (Geddes and Butler 1984).

A key driver of Coorong hydrodynamics is oceanic water-level fluctuations that lead to water exchange with the North Lagoon through the Murray Mouth. Sea levels in the adjacent coastal ocean (Encounter Bay) are mainly semi-diurnal, between 0.4 and 1.2 m during neap and spring tides, respectively, and have high wave energy (Webster 2010). The effects of tidal cycles, however, are attenuated inside the Murray Mouth and Coorong due to the restricted geomorphology. Typically, in the absence of high barrage flows creating a deep channel, the diurnal tidal ratio inside the Murray Mouth is only 0.2–0.3 m in amplitude, which declines with distance away from the Mouth (Mosley et al. 2016, Gibbs et al. 2018).

Barrage flows also play a critical role in the dynamics of water level and water quality in the Coorong by, (a) allowing sea level variations to penetrate and facilitate long-lagoon mixing of water, salt and other constituents, (b) freshening the waters of the northern half of the North Lagoon that means water of lower salt content than sea water is drawn along the Coorong to replace the evaporative loss, (c) causing a springtime rise in water level along the length of the Coorong that significantly augments and extends that due to seasonal sea level variation, and (d) helping maintain relatively high water levels in the constricted Parnka Point region allowing for enhanced wind-driven exchange between the two lagoons (Webster 2010).

The CLLMM only maintains vestiges of its former hydro-ecological character compared to the natural system prior to regulation and water diversions within the MDB. Historically, the system would have been more dynamic, with higher river inflows and a more extensive and connected estuarine zone, including in the Holocene (Tibby et al. 2022). The barrages now maintain a predominantly freshwater lake system and create a fixed and ‘harder interface’ with the estuarine mixing zone restricted to downstream of the barrages and substantially compromised connectivity between the freshwater, estuarine and marine environments. Currently, connectivity between the Lower Lakes and Coorong tends to be very limited under low flows (e.g. only fishways open), increasing as flows increase, due to more barrage gates being opened. Connectivity, however, remains much less than natural, with negative implications for populations of aquatic biota and ecosystem function.

As a consequence of hydrological change, water quality in the Lower Lakes and Coorong lagoons has also been altered significantly from historical conditions. Before the barrages were built and River Murray inflows were reduced, there was likely a larger tidal prism (defined as the volume of water contained in an estuary or embayment between the low and high tide levels). Reductions in this prism have likely had water quality implications by increasing residence time of nutrients and other constituents (Luketina 1988). Reductions in flushing of the Coorong due to reduced River Murray inflows have also resulted in much higher salinities (Webster et al. 2010) and nutrient levels in the water and sediment (Mosley et al. 2022). Nevertheless, infrequent high flows still may have a major influence on connectivity and freshening of the system. For example, with the large River Murray floods in 2022-2023, all barrage gates were opened, leading to substantial scouring of the Murray Mouth, and reductions in Coorong South Lagoon salinities to <60 psu (Department for Environment and Water, unpublished data), which is much lower than the previous two decades (Mosley et al. 2023).

Aquatic ecosystem

Estuaries represent a unique ecotone and dynamic interface between freshwater and marine ecosystems and are considered among the world's most productive aquatic ecosystems (Hoellein et al. 2013). Globally, however, anthropogenic impacts such as river regulation and urbanisation threaten the ecological integrity of estuarine ecosystems (Gillanders and Kingsford 2002; Kennish 2002). The CLLMM region provides a stark example of a once dynamic and productive estuarine ecosystem transformed by diminished freshwater input and interrupted connectivity.

The hydrodynamics of the CLLMM are driven by tidal ingress through the Murray Mouth, freshwater flows from the River Murray and the southeast region of the Coorong, localised groundwater inputs and evaporation. The interaction of tide, freshwater flow and local hydrologic processes influence salinity throughout the system, and in turn structures biological communities. In its natural state, the unique structure of the CLLMM, including predominately freshwater lakes and a connected series of estuarine coastal lagoons, gave rise to distinct, yet spatially and temporally dynamic, biological communities. Data on the pre-European ecological character of the system are scarce but historical accounts and paleo-ecological data provide some insight. For First Nations peoples, the place where fresh and saltwater mix has profound spiritual relevance and has sustained cultural and resource needs for 10,000s years (Ngarrindjeri Nation and Hemming 2018).

Paleolimnological data and early European accounts indicate that the Lower Lakes were predominantly fresh, whilst the lagoons of the Coorong were brackish-marine (Fluin et al. 2007; Tibby et al. 2022). The interface between these environments, however, was spatially and temporally dynamic and, under periods of low freshwater input, regions of the lakes could tend brackish (Tibby et al. 2022) and the lagoons marine-hypersaline (Webster et al. 2010). Biological communities reflected this structuring of aquatic habitats and the dynamism in these. Furthermore, connectivity among these diverse habitats was not physically impeded, thus enabling the flux of biota and nutrients. Connectivity between marine and freshwaters led to the evolution of a diadromous fish assemblage of at least six species which undertake obligate migrations between riverine and estuarine-marine waters to complete their life cycle (Bice et al. 2018). The prevalence of this life history strategy indicates perennial connectivity between freshwater and marine environments (Mallen-Cooper and Zampatti 2018).

Human-induced reductions in freshwater inflows, commencing in the late 1800s, and the construction of the Murray barrages, have led to profound changes in the ecological character of the region. The barrages now present a hydrological and physical barrier between the downstream Coorong Estuary and lagoons, and the upstream freshwater lakes, and substantially reduce the area of the historical estuary (Harvey 1996). In their contemporary (post-regulation) state, the Coorong Estuary and Lagoons grade from brackish in the north to hypersaline in the south. As such there is a delineation of freshwater and estuarine-marine flora and fauna between the Lower lakes and Coorong, and the evolution of more salt tolerant aquatic biota in Coorong lagoons, particularly the South Lagoon. Nevertheless, even in their modified states, the freshwater Lower Lakes and Coorong Estuary and Lagoons are recognised nationally and internationally for their conservation significance (O'Connor et al. 2015).

A period of marked ecological change in the CLLMM occurred during the Millennium Drought in south-eastern Australia (Paton et al. 2009a, Kingsford et al. 2011). During this period, the barrages were closed and the River Murray ceased to flow to the sea for 1,437 consecutive days (Zampatti et al. 2010). At the same time, the water level of the Lower Lakes decreased to 1 m below sea-level (Gibbs et al. 2018). Ecological impacts were profound and included significant alterations to assemblages of flora and fauna, diminished estuarine productivity, consecutive years of failed recruitment of diadromous and estuarine species and the loss of obligate freshwater species (e.g. Yarra pygmy perch) (Brookes et al. 2015; Dittmann et al. 2015; Wedderburn et al. 2014; Zampatti et al. 2010). Migratory bird populations, which are a key component of the site's Ramsar list, were also significantly impacted (Paton 2009b). Recovery from these impacts appears to have been gradual over the past decade, although a key question is how is 'recovery' defined in a highly altered system, and is this even a viable concept in a dynamic system?

River flow for much of the past few decades has largely been insufficient to maintain an open Murray Mouth and this region is now mechanically dredged to provide connectivity between the CLLMM and the sea (Gibbs et al. 2018). Connectivity is a reoccurring theme in aboriginal and European culture, and in scientific understanding of ecological function. For commercial fishers, connectivity throughout the historical estuary was considered paramount to the productivity of key commercial fisheries species such a mulloway (Wood 2007). Subsequent declines in commercial fisheries are likely a result of a combination of factors including construction of the barrages, fragmentation of the estuary, diminished freshwater flows and the fishery itself. Full hydrological and ecological connectivity now only occurs during infrequent large floods (e.g. 2010-2011, 2022-2023 River Murray floods) when most barrage gates are opened and dredging is ceased at the Murray Mouth.

Pressures and drivers of change

An ongoing pressure on the CLLMM region relates to its vulnerability of being at the end of the Murray-Darling river system. Since water resource development commenced in the MDB in the late 1800s, end-of-system flows have declined markedly. With implementation of the *Water Act 2007* and associated *Murray Darling Basin Plan 2012,* water is being recovered for the environment. For example, Figure 2 shows the distribution of modelled barrage flows (over 1895–2009) for three modelled scenarios (see MDBA, 2012):

1. 'Baseline' representing conditions in 2009 prior to the Basin Plan.
2. 'Basin Plan' representing the improvements due to environmental water recovery from the Basin Plan when agreed in 2012 (BP2800 scenario).
3. 'Without development' which represents a natural flow regime through removing resource development in the model (e.g. storages and diversions).

The shift toward reduced annual barrage flow volume is evident as the scenario changes from near natural (without development) to a Basin Plan with water recovered for the environment, to baseline conditions, with the proportion of years with barrage flow exceeding 10,000 GL yr^{-1} changing from 53% of years under without development to 19% and 11% for the Basin Plan and Baseline scenarios, respectively. Without resource development, the modelled natural flow out of the Lower Lakes was 12,377 ± 585 GL yr^{-1} (annual mean ± standard error). Following water resource development and prior to Basin Plan implementation, there was on average 5,088 ± 585 GL yr^{-1} flow over the barrages, 41% of the natural flow. With Basin Plan implementation as modelled in 2012, the flow over the barrages is predicted to increase to 7,156 ± 597 GL yr^{-1} (58% of natural). The relative impact of water diversion, however, is much greater under low flow conditions, in contrast to the averages presented here.

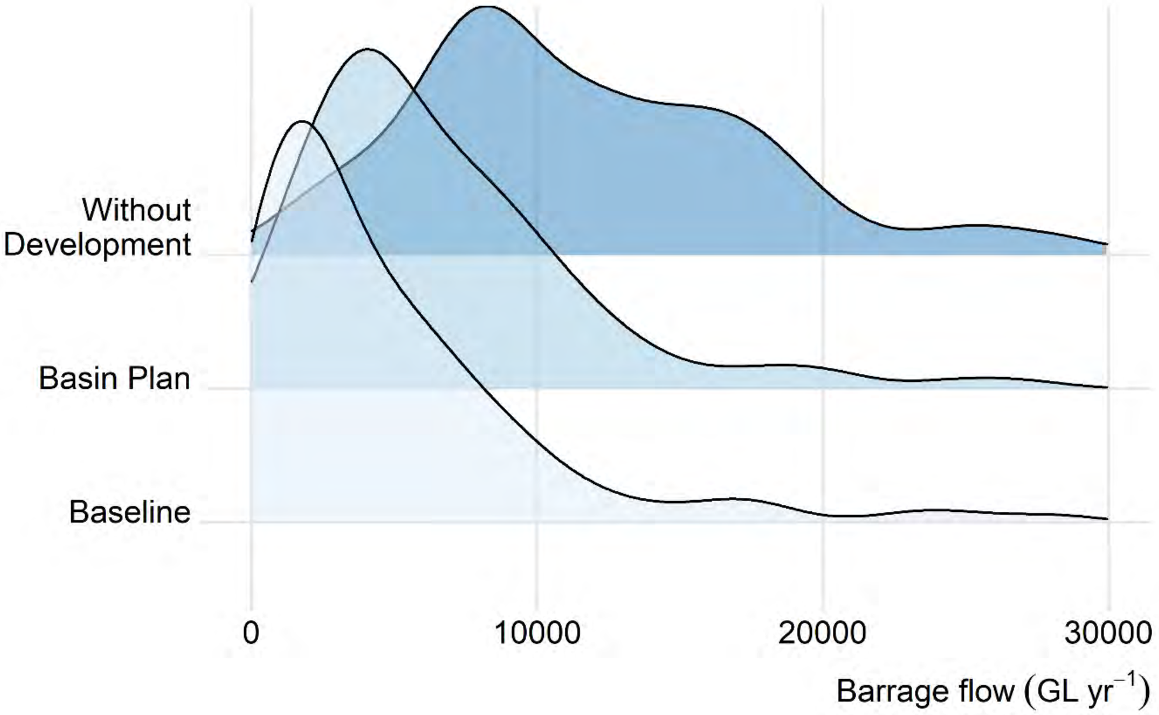

Figure 2. Distribution of modelled annual volume of barrage flow under three different scenarios, 'Baseline' representing pre–Basin Plan conditions, a Basin Plan water recovery (2,800 GL) scenario and 'without development' representing of natural conditions. Data is based on measured and modelled data from 1895-2009 provided by the Murray-Darling Basin Authority, as outlined in MDBA (2012).

Further reductions in flow are predicted due to climate change, yet this has not been considered in the Basin Plan modelling depicted in Figure 2. The 2008 CSIRO Sustainable Yields Project (prior to Basin Plan water recovery) found average surface water availability would fall by 11% and end-of-systems outflows by 24% under median 2030 climate predictions (CSIRO 2008). This study also suggested that 'At the MDB scale therefore, the largest share of the hydrological impact of climate change under current water sharing arrangements would occur at the end of the Murray River – that is, inflows to the Lower Lakes and the Coorong'. More recently, Whetton and Chiew (2020), identified that hydrological modelling studies, informed by future projections from global climate models, show a median projected decrease in mean annual runoff of 14% in the southern MDB (10–90 percentile range of -38% to +8%) by 2046–75 under the medium warming scenario. Of note, the median projected decline in runoff is similar to the volume of water returned to the environment under the Basin Plan. Furthermore, risks from more extreme scenarios also need to be recognised. For example, the MDBA (2020) Basin Plan evaluation reported that in the preceding two decades, Basin river inflows had fallen by 37% compared to the historical record. As such, whilst median projections can serve as a guide, alternative scenarios also warrant consideration.

Climate change will also promote sea level rise (SLR), another key pressure on the CLLMM that will affect this region more than any other area of the MDB. Figure 3a shows the observed SLR at the site since 1985 (based on Victor Harbor tide data), a linear projection of this rise out to 2100, and how SLR is predicted to affect the CLLMM region (Lawrence et al. 2022). The horizontal dashed lines indicate when spillways on the island between barrages are engaged. Seawater can flow over the spillways and into the lakes, at 0.83 m AHD, and the barrages structures themselves are broadly overtopped at approximately 1.1 m AHD. While the monthly average sea level is not projected to exceed these thresholds in all but the most extreme projections for 2090, the highest tides (defined as a water level exceeded for 6 or more hours) have exceeded these limits in the past and is projected to occur much more frequently into the future. The ability of the current barrages to maintain operations during the above sea level rise scenarios is doubtful. If the barrages are to retain their current function, these 80-year-old structures likely need to be redesigned and replaced in the face of sea level rise - we return to this opportunity below.

With significant sea level rise, some additional infrastructure may need to be built across the Hindmarsh and Mundoo Island land surfaces (Thom et al. 2020). This is also evident from inundation predictions, not considering the presence of the barrages, for a 0.6 m sea level rise scenario for the Hindmarsh Island region near the Murray Mouth (Fig. 3b), where large areas of low-lying land could be inundated. If required, there are likely to be engineering options to mitigate tidal ingress, (e. g. bunds that connect with the barrages). Nevertheless, with increased sea levels on the Coorong side of the barrages, opportunities to release freshwater from upstream of the barrages will be reduced, further limiting connectivity across these structures. Notwithstanding, the ability of coastal ecosystems and landscapes to adapt to keep pace with SLR also should not be disregarded, as there is global evidence emerging of coastal wetlands being able to keep pace with SLR where sediment and organic supply rates are sufficient (Schuerch et al. 2018).

Overall, there is uncertainty in the CLLMM region regarding the net outcome between climate change-driven reductions in inflows and increases in sea level, and water efficiency and buyback projects that are returning water to the environment. There is evidence that Basin Plan implementation has not resulted in the expected increased flow in the River Murray, particularly at the end of system (Grafton and Wheeler 2018, Colloff and Pittock 2022) and this may, at least in part, be a consequence of climate change. Hence, there is potential that the CLLMM could be worse off in the future under a changing climate compared with the late 20th and early 21st century, despite calculated water recovery under the Basin Plan. Furthermore, extreme events such as the Millennium Drought, which were modelled to be substantially mitigated through Basin Plan environmental water recovery, may again become part of the future for the region.

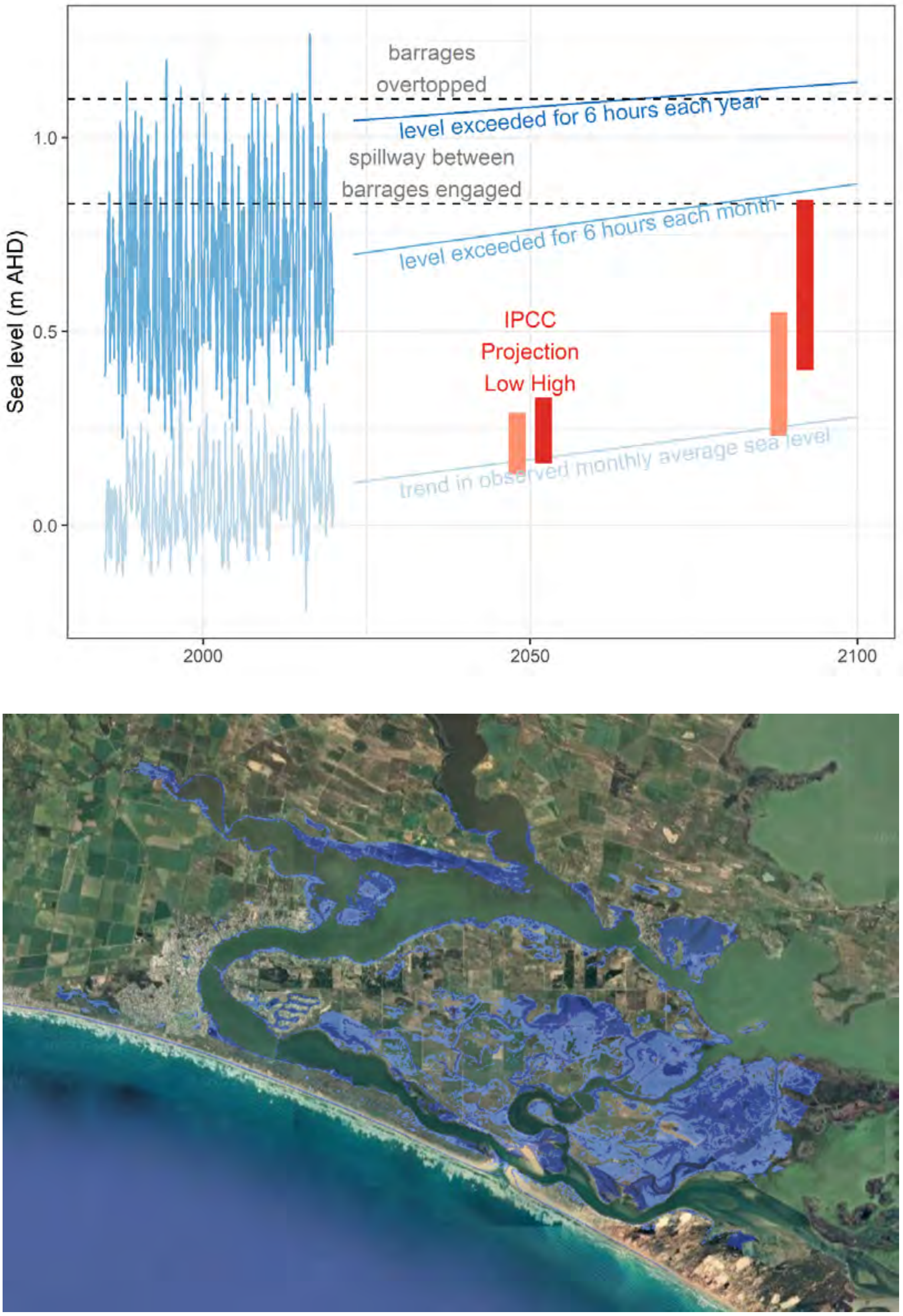

Figure 3. (a) sea level rise historic and projections with barrages overtopping. Monthly average recorded sea level at Victor Harbor (light blue) and the maximum level each month exceeded for 6 hours (blue) over the period 1963-2020. The sea level rise trend linearly extrapolated to 2100 shown as straight lines, as well as the maximum level exceeded for 6 hours each year (dark blue). AR6 IPCC projections for low (RCP 2.6) and high (RCP 8.5) emissions shown in red, along with levels where the barrages are overtopped, at the lowest point at the spillway between barrages (0.83 m AHD) and broad overtopping of the barrage structures (assumed to be 1.1 m AHD), and (b) Predicted inundation (blue areas) of Hindmarsh Island under a 0.6m sea level rise scenario (product from Coastal Risk Australia 2100 https://coastalrisk.com.au/viewer).

Opportunities and a long-term vision

In this section we explore opportunities and a future (~50 year) vision for how the values of the CLLMM region can be sustained in the face of changes that are expected to stem from climate change. Other visions have also previously been proposed for this region (e.g. Paton et al. 2009, Thom et al. 2019).

As outlined earlier, the CLLMM system, prior to river regulation, would have naturally been more dynamic, with higher river inflows and a more extensive and connected estuarine zone (Tibby et al. 2022). Our future vision is to, where possible, recreate aspects of this while managing risks that might arise. A summary of opportunities and risks is depicted in Figure 4.

Opportunities

Review of the Basin Plan and water recovery targets.

Development of minimum flow thresholds.

New, more flexible barrage infrastructure.

Improved integration of First Nations knowledge and values.

Consideration of climate change impacts and adaptation strategies.

Improved interconnected habitat.

Risks

Climate change and water resource development impacts:

- Reduced freshwater inflows
- Sea level rise
- Increased heatwaves
- Salinisation & eutrophication
- Ecosystem decline

Figure 4. Summary of Opportunities and Risks of achieving long term vision in CLLMM

The importance of the successful implementation of the Basin Plan for the future of the CLLMM region cannot be over-stated. Recovery and delivery of water for the environment will enable a range of benefits for the CLLMM and wider MDB. Nevertheless, in the face of climate change and predicted further reductions in run-off and river flow, the water recovery targets under the Basin Plan will likely need to be revised over time. This will be critical to maintain and rehabilitate values of the CLLMM under non-stationary climate and hydrological conditions. As documented by Colloff and Pittock (2022), however, there may be considerable discrepancies between planned water recovery, water rights acquired and ultimately, environmental water delivered, so there are residual risks with this approach. Given this, there may be merit in establishing end-of-system flow targets for the CLLMM that could be used to guide upstream water allocation, as proposed by Alexandra (2022).

It is also important to ensure future visions for the CLLMM, including Basin Plan objectives and actions, integrate Ngarrindjeri (First Nations) vision and values for the region (Ngarrindjeri Nation 2007, Ngarrindjeri Nation and Hemming 2018). Integral to this is the concept of connectivity. For example, a previous proposal to further fragment and engineer the system by constructing a twin lakes system in Lake Alexandrina was considered by the Ngarrindjeri to 'further destroy the creation of our lands and waters' (Ngarrindjeri Nation and Hemming 2018).

Proposals have been made to remove the barrages to return the Lower Lakes to a so-called 'natural state'. This does not align with the multiple lines of evidence for predominantly freshwater conditions in the Lower Lakes prior to water resource development in the MDB, and that opening the barrages under contemporary flow conditions would create major salinity risks in the Lower Lakes (Chiew et al. 2020, Tibby et al. 2020, 2022; Bourman et al. 2022). The reason for this is that the higher pre-water resource development inflows (Figure 2) were of sufficient magnitude to flush salt from the system. Mosley et al. (2021) concluded 'The current management of the barrages and water levels enables this Ramsar-listed wetland to maintain vestiges of its historical ecological character and services'. Removing the barrages would likely result in rapid and widespread loss of freshwater ecosystems and socio-economic values due to salinisation (Kingsford et al. 2019). Nevertheless, if climate change results in future 'extreme dry' scenarios, a key question concerns what salinity conditions could be maintained in the Lower Lakes?

Rather than barrage removal, it is likely that new and higher barrages may need to be considered to ensure the functionality of the barrages is maintained in the face of climate change and sea-level rise. Adaptation to climate change may also include novel solutions or other considerations such as landward retreat zones, which may be preferable if coastal marsh development can keep pace with sea level rise (Schuerch et al. 2018). Otherwise, bunds between the barrages may be needed to protect farmland and infrastructure from tidal inundation.

Rebuilding or upgrading the barrages would also present an opportunity for extensive automation of the barrage gates, thus enabling flexibility in operation that could facilitate finer-scale manipulations in response to flow, tide and prevailing wind to create a 'softer', more transparent and dynamic estuarine interface. This could:

- Provide opportunities to leave barrages open when there is a neutral or positive head difference between upstream and downstream of the barrages (i.e. higher on lakes side).
- Increase ecological connectivity, particularly important for diadromous and estuarine fish species.
- Expand the availability of estuarine habitat near the Murray Mouth, particularly under low-moderate flows.
- Increased the tidal prism to improve flushing and water quality.
- Improve the two-way flux of nutrients and carbon to better facilitate the transfer of trophic subsidies among freshwater, estuarine and marine environments.
- Provide a greater range of opportunities to push freshwater into the Coorong Lagoons while maintaining freshwater conditions in the Lower Lakes.

Implementing the above will require careful adaptive management to mitigate risks of seawater intrusion that may harm the ecological, cultural and socio-economic values of the Lower Lakes. Even when conditions may seem suitable, e. g. high river flows, there are risks of leaving the barrages open. So called temporary 'reverse flow' events have been observed, where seawater flows back into the lakes under suitable high wind and tide conditions. With relatively inflexible barrage infrastructure, as is the present case, it may take time to open/close the barrage gates to prevent these events, leading to caution in contemporary barrage operations. Nevertheless, with automated barrage infrastructure, rapid operation, based on feedback from wind, water level and salinity sensors, could enable acceptable management windows for gate opening and closure to be developed. Other climate change adaptation measures have also been previously considered for the Lower Lakes (e.g. Gross et al. 2012).

New infrastructure is also being scoped for the Coorong, that includes pumping options to enhance flushing of the South lagoon (DEW 2021). While these options may have the potential to reduce the long water retention times and extreme salinities experienced in the South Lagoon, from a whole of site perspective, there is a need to consider the scale of influence of these options. Ultimately the CLLMM historically functioned as a hydrologically and physically connected ecosystem and regionally specific infrastructure interventions may have minimal benefit for broader ecosystem function in CLLMM.

Hydrological and ecological connectivity with the coastal ocean is also gaining increasing recognition. Coastal productivity and food resources for seabirds have been linked to River Murray outflows (Auricht et al. 2018, Colombelli-Negrel et al. 2022). Again, a whole-of-system perspective of the CLLMM should include connectivity across the freshwater-estuarine-marine interface and the benefits of river flows to marine ecosystems. Considering the range of predicted future climate scenarios, it is unlikely that managed flow over the barrages will be sufficient to continually maintain an open Murray Mouth. As part of this, mechanical dredging of the river mouth may facilitate an estuarine-marine interface, but it is the flow of water from the river, through the estuary and into the ocean, that is necessary for ecosystem function and essential to rehabilitating the values of the region.

Conclusions

Water resource development in the MDB, and fragmentation of the CLLMM ecosystem, have led to ecological decline and compromised the values for which the CLLMM is recognised. Climate change is predicted to exacerbate these existing impacts and introduce new threats such as increases in sea level. As such, the CLLMM is now at a critical juncture. The ongoing impacts of river regulation, combined with projections of climate change, are likely to lead to continued hydrological, ecological, social and cultural decline, unless increased volumes of environmental water are made available. To this end, to potentially mitigate the impacts of climate change further reducing end-of-system flows, considerably more water for the environment may be required than that targeted in the Basin Plan. Together with hydrological restoration, ongoing learning and evolution of strategies to maximise benefits from environmental water, coupled with infrastructure improvements to improve connectivity, will be key to ensuring that the ecological health of the system can be protected and improved.

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MURRAY-DARLING BASIN ESSAY

Essay #7 in a series of nine by Australia's leading water experts

Restoring sustainability to Murray-Darling Basin freshwater fish and aquatic ecosystems

John Koehn

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Above: Menindee Lakes, New South Wales. JohnCarnemolla, iStock.

EXECUTIVE SUMMARY

Koehn describes the riverine ecosystems of the Basin and their health. They are generally in poor condition due to impacts from a range of threats, and many of these valuable ecological assets continue to decline. While much attention has been given to economic development and management in the MDB, investment in ecological management has lagged. The greatly diminished state of native fish populations (losses of > 90% in the past 150 years) together with massive fish kills in the Darling River and explosions in alien carp populations all provide clear wakeup calls to the ecological emergency occurring in MDB aquatic ecosystems. Comprehensive attention must be given to all biota, aquatic ecosystems, and the ecological services they provide. Reductions in the original amounts of environmental water recovered, pauses in Basin Plan implementation and neglecting to account for the consequences of climate change have postponed any major environmental improvements and threaten Basin Plan objectives.

In 50 years, Basin aquatic ecosystems and their biota can be sufficiently restored such that they are sustainable, resilient environments to provide for the socio-ecological and economic needs of future generations in the face of the challenges of climate change.

Restoring sustainability to Murray-Darling Basin freshwater fish and aquatic ecosystems

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Abstract

Aquatic ecosystems of the Murray-Darling Basin (MDB or Basin) are generally in poor condition due to impacts from a range of threats, and many of these valuable ecological assets continue to decline. While much attention has been given to economic development and management in the MDB, investment in ecological management has lagged. This essay focuses on the native freshwater fish as an example of MDB aquatic biota in crisis. The greatly diminished state of native fish populations (losses of > 90% in the past 150 years) together with massive fish kills in the Darling River and explosions in alien carp populations all provide clear wakeup calls to the emergency occurring in MDB aquatic ecosystems. This situation requires urgent and decisive actions to avoid further declines, degradation, likely extinctions and an intergenerational ecological catastrophe, where avoidance passes the ecological costs on to the next generations. As well as fish, comprehensive attention must be given to all biota, aquatic ecosystems, and the ecological services they provide. This essay provides only a few pertinent examples for non-fish biota. The efforts undertaken for freshwater fish can, however, provide direction to improved holistic management. Considerable investment in socio-**ecological** management is sorely needed.

Through full implementation of Basin Plan and other recovery initiatives there is an opportunity to rebuild the resilience of ecological assets so they can recover from disturbance. However, under the regime of current management, this is doubtful. Indeed, under existing progress, the objectives of the Basin Plan (improved ecological health condition and no extinctions) will not be met. Reductions in the amounts of environmental water recovered, pauses in Basin Plan implementation and neglecting to account for the consequences of climate change have postponed any major environmental improvements. To build ecological resilience, there is a need to restore populations, habitats and ecosystems. To achieve this requires improved management of water for the environment including full implementation of stalled environmental water reforms, further potential changes to water policy, and a comprehensive program of additional measures to address the range of other threats impacting native fishes. Restoring ecological assets can be achieved by working together, across jurisdictions, communities and stakeholders. The challenge is to have the long-term vision, political will, commitment, and adequate resourcing to implement these necessary actions. As the decline of MDB native fish populations has occurred over more than a century, a long-term strategy is needed for recovery.

A 50-year vision for Murray-Darling Basin aquatic ecosystems and their biota is that they be sufficiently restored so they can be sustainable, resilient environments to provide for the socio-ecological and economic needs of future generations in the face of the challenges of climate change.

Introduction

The Murray-Darling Basin (MDB or Basin) covers >1 million square kilometres (14% of Australia's land area), includes Australia's two longest, most iconic rivers (the Murray and Darling; Eastburn and Mackay1990; Breckwoldt et al. 2004) that each flow over 3,000 km across a range of habitats. Management involves water, natural resource and conservation agencies from six jurisdictions. Being about three times the area of the Great Barrier Reef, the MDB environments support unique biotic communities. For example, about a quarter of its native fish species are endemic to the MDB, not occurring anywhere else (Lintermans 2023). The Basin contains over 30,000 natural wetlands including sixteen listed under the Ramsar Convention (Zhang et al. 2024), along with their associated biota of plants, invertebrates, fish, waterbirds and other vertebrates. Despite having been greatly modified from their natural state (see below), these habitats and environments, even in their altered state, retain significant cultural, scientific, environmental/conservation, ecological, social/recreational, and commercial/economic values. These assets are recognised under the Basin Plan (MDBA 2011) and are owned and valued by all Australians, both regional and urban communities.

Much of the written history of the MDB reflects on the development of irrigation infrastructure and water management, which has resulted in considerable agricultural prosperity. Less has been recorded of the natural environments, the abundance of fish wildlife, their cultural (Ellis et al. 2022) and other values such as early commercial and current recreational fisheries (Rowland 2005). These are important perspectives. Water is the lifeblood of most regional towns, agriculture and industries. However, the prosperity and well-being of these communities is also dependent on the sustainable maintenance of MDB environments and their ecosystem services, especially rivers, wetlands, and their biota. While much attention has been given to economic development over time and management, less attention has been given to ecological management. Considerable investment in socio-ecological and ecosystem-based management (people and their ecological environments) (Woods et al. 2022) is sorely needed.

The MDB is often referred to as 'Australia's food bowl', contributing about 40% of the country's agricultural production (Koehn 2015; Bowland 2023). It accounts for more than 60% of the total water used for irrigated agriculture in Australia, with considerable associated irrigation infrastructure such as dams, weirs, channels, pipes and pumps that extract water from aquatic habitats. The MDB economy is currently worth around $230 billion per year, with agriculture contributing over $20 billion per year in gross value (since 2010), about 30% of which is from irrigated agriculture (Bowland 2023). While agriculture dominates land use and management (Hart et al. 2021a, b), mining, tourism and recreation also make valuable contributions to the economic and workforce diversity (Bowland 2023). Many of these industries, especially tourism (31,000 businesses in 2016; Hart et al. 2021a, b) rely on the natural environment and are particularly important for regional towns. Recreational angling is an important Australian pastime, and important to tourism, especially in regional areas (Henry and Lyle 2003). There is competition between water used for agriculture and to sustain these aquatic environments (Koehn 2015; Wheeler 2024) and demand for water in the MDB is increasing because of population and economic growth (Williams 2017). This demand is likely to be exacerbated by climate change (CSIRO 2008).

This essay uses fish as a basis for illustrating the condition and management of MDB riverine (and floodplain) aquatic ecosystems. Fish can be viewed as sentinel species for many issues impacting the requirements of the many other aquatic organisms present. It is recognised, however, that greater attention needs to be given to other biota, and that the rivers and floodplain ecosystems in particular, need to be addressed holistically. Mosley et al. (2024) provide an example of this for the Lower Lakes and Coorong, including estuarine fishes. Fish, however, are considered key assets of the MDB under the Basin Plan, are highly dependent on water, are mostly near the top of the food chain (and hence are reasonable overall ecological indicators), are highly valued by all stakeholders and communities, and have a high ecological knowledge base, with key threats and remedial options already considered in existing integrated restoration plans. The plans developed for freshwater fish may provide an example way forward for improved management of other ecological components. Within that context, the objectives of this essay are to:

1. Examine the key issues impacting freshwater fish and aquatic ecosystems.
2. In addition to fish, provide some similar examples for other key aquatic biota.
3. Indicate how populations and habitats have been affected by changes to flows and other threats.
4. Look at impediments and options for improved management.
5. Provide a 50- year vision with a way forward as to how it can be achieved.

Major changes to aquatic habitats, water and flows

To date, irrigation development has generally dominated management of the MDB, to the extent that it is one of the most regulated river basins in the world (Grill et al. 2019). Over-allocation of water, flow regulation and environmental damage have all been identified as issues that urgently need to be addressed (Walker 2006; Kingsford 2000; Lester et al. 2011; Walker 2019). Riverine aquatic habitats have been greatly impacted in many ways (also see Table 1):

- MDB now has 240 dams storing 29,893 GL of water (Kingsford et al. 2017).
- Only 40–50% of its main stem rivers remaining free-flowing (Liermann et al. 2012), and many of those having their hydrology altered to some degree by regulation or extraction.
- End-of-system flows are now zero for 40% of the time, compared with 1% of the time under natural flow conditions (CSIRO 2008).
- Extensive river reaches have been converted from lotic to lentic environments by weirs and reduced flows (Maheshwari et al. 1995; Walker 2006).
- Low water levels and critical no flow periods have increased significantly in previously naturally perennially flowing rivers (e.g. Darling River; Mallen-Cooper and Zampatti 2020).
- There are more than 5,000 barriers (Lintermans 2023) that cause disruption to river connectivity (Baumgartner et al. 2014).
- There has been a significant loss of off-stream lakes and wetlands that may provide waterbird and fish nursery habitats. While the quantum (e.g. area) is not readily available, only 11 of a potential 567 golden perch (*Macquaria ambigua*) larval nursery sites have been considered to be still operating in western NSW (Sharpe 2011).
- The effects of anthropogenic flow alterations were exacerbated during the ‘Millennium Drought’ (Murphy and Timbal 2008; van Dijk et al. 2013), as they will also be under projections for climate change (see below).

Predicted changes due to climate change

Climate change is projected to have a range of impacts on MDB aquatic habitats and their biota (Pittock et al. 2010; Pittock, and Finlayson 2011; Balcombe et al. 2011; Pratchett et al, 2011):

- The MDB will be hotter and drier under climate change (Grose et al. 2020, Chiew et al. 2023; Zhang et al. 2024), having already warmed by 1°C since 1910 and the warming will continue (Whetton and Chiew 2021). Changes to temperatures will impact fish metabolism and spawning, and may result in changes to their distributions (Bond et al. 2011).
- Water availability is decreasing (Prosser et al. 2021) and likely to reduce across the entire Basin with a greater reduction in the south of the Basin (CSIRO 2008).
- Average annual runoff is projected to decrease 9% by 2030 and 23% by 2070 (CSIRO 2008). There is high variability, however, with projected changes in mean annual runoff ranging from -40% to +10% in the southern MDB and -45% to +30% in the northern MDB (CSIRO 2008). The direction of change in summer rainfall is less certain with the magnitude of extreme high rainfalls expected to increase (Timbal et al. 2015).
- There will be large increases in frequency in the length and severity of multi-year droughts and hence low flow and zero flow periods (Zhang et al. 2020). Together with a decrease in freshes of up to 55% (Zhang et al. 2020) there is likely to be an increase associated events such as major cyanobacterial blooms, low dissolved oxygen concentrations and blackwater (Verhoeven et al. 2024).
- Severe drought conditions (Vertessy et al. 2019), together with increased fires and post-bushfire run-off will also cause increased fish kills (Legge et al. 2020).

Climate change has not been adequately addressed in the Basin Plan (Pittock et al. 2015; Prosser et al. 2021; Zhang et al. 2024) with future climate-induced flow reductions negating some of the benefits of projected environmental water allocations. The impacts of climate change reduction in MDB flows cannot be allowed to be borne by the environment as the median projected decline in annual runoff is similar to the volume of water returned to the environment under the Basin Plan (around 3,000 GL) (Whetton and Chiew 2021). For example, Kingsford et al. (2017) modelled the effects of returning water to riverine environments could improve waterbird abundances by 18% but projected climate change effects could reduce these benefits to only a 1% or 4% improvement, with annual recovery of environmental flows of 2,800 GL or 3,200 GL respectively. This is being further exacerbated by the fact that environmental water is now already being used for emergency events such as fish kills, rather than to promote population and general ecosystem recovery. Within the context of already reduced and much-delayed recovery of water for environmental purposes, the impact of climate change will be even greater and needs better consideration, especially as water management will become even more difficult (Neave et al. 2015).

While it is predicted that primary production in the MDB in 50 years' time will be substantially impacted by a changing climate (Boland et al. 2024), it is fair to say that aquatic ecosystems have already been impacted by far greater changes to flow regimes imposed by flow regulation and extraction. While climate change will impact water resources in the MDB, this impact will be less than that already caused by water extraction (Grafton et al. 2013). These further changes will greatly affect fish species and overall ecosystem services, with impacts differing among species (Chessman 2013).

Major changes to aquatic biota and ecosystems

Globally, freshwater biota and their ecosystems are under threat and in need of conservation and restoration (Malmqvist and Rundle 2002; Dudgeon et al. 2006; Flitcroft et al. 2019). The MDB is no exception and is now considered one of the most at-risk river systems in the world (Wong et al. 2007). There is no doubt that development of the MDB has caused great damage to natural aquatic ecosystems (Walker 2006; Kingsford 2000; Baumgartner et al. 2019; Koehn et al. 2020a), through impacts from a range of threats (see also Table 1). This is evidenced by monitoring that indicates that most MDB rivers and catchments are now in poor ecological condition (e.g. Davies et al. 2008, 2010).

Key documented changes for native freshwater fish include:

- Native fish populations have declined by >90 % over the past 150 years (MDBC 2004; Koehn and Lintermans 2012).
- Almost half the native species are now of conservation concern, being listed as rare or threatened under state or national legislation (Lintermans 2023).
- Many smaller fish species, especially wetland specialists, are at greatest risk (Lintermans et al. 2020) and Yarra pygmy perch (*Nannoperca obscura*) appear now to be extinct in the MDB.
- Several fish communities of the MDB have been listed as threatened under both State (Victorian and New South Wales) and Commonwealth legislation.
- There have been rapid declines in key, popular recreational and commercial 'flagship' species such as silver perch (*Bidyanus bidyanus*), freshwater catfish (*Tandanus tandanus*) and trout cod (*Maccullochella macquariensis*) (Cadwallader and Gooley 1984; Reid et al. 1997; Clunie and Koehn 2001a, b) with observed declines in recreational angling success.
- Almost all commercial fisheries have collapsed and are long closed (Rowland 1989, 2005).
- There is the likely loss of Murray cod and silver perch from the Paroo River (Sarac et al. 2011).
- Important traditional cultural practices of First Nations People have been weakened (Humphries and Winemiller 2009; Ellis et al. 2022).
- Fish kills are increasing in magnitude and becoming more frequent (see below) including from post-fire run-off (Lyon and O'Connor 2008; Legge et al. 2020).
- Cold water released from dams impacts spawning, recruitment and growth in over 3,000 km of MDB rivers (Lugg and Copeland 2014).
- Alien species (12) now comprise a quarter of MDB fishes with carp dominating fish biomass in many river reaches (Harris and Gehrke 1997; Stuart et al 2021).
- There has been damage to and loss of habitats for wetland species (Closs et al. 2006; Sharpe 2011).

In addition to riverine fish, there have been major impacts on other biota – here are some select examples for wetlands. Flow alterations have greatly reduced flows into wetlands reducing their number and area (Sharpe 2011), impacting vegetation and waterbird habitats (Kingsford and Thomas 1995; Kingsford et al. 2011) and changing their ecological character (Pittock et al. 2010). This has caused major ecosystem-wide impacts, including successional changes in aquatic vegetation; reduced vegetation health; declining numbers of waterbirds and nesting; declining native fish and invertebrate populations (Kingsford 2000) and changed organic-matter dynamics and physicochemistry (Watkins et al. 2010). Significant long-term declines in total waterbird abundances are associated with reductions in cumulative annual flow (Kingsford et al. 2017).

The major threats to MDB fishes have long been identified (e.g. Cadwallader 1978) and urgent and effective remediation of them has been recognised as essential for the recovery of fishes (Baumgartner et al. 2019; Koehn et al. 2020a; Table 1). Given the poor and declining status of native fish populations in the MDB, it must be concluded that the MDB is not currently being managed in an ecologically sustainable manner. While there are a range of threats, it is evident that the footprint of irrigation and its infrastructure (in terms of area and extraction overall) on the aquatic biota of the MDB is very large (see shaded rows in Table 1). There is a need to recognise this current critical state and the urgent need for restorative policy, management and community actions; we can no longer just manage for the *status quo.* We need to build resilient populations able to withstand and recover from the unsustainable collective impacts and consequences of human-induced disturbances as well as the existential impact of climate change (currently not addressed by the Basin Plan).

Table 1. A summary of key impacts on native freshwater fishes by various threat mechanisms, along with potential solutions (from key references such as MDBC 2004; Baumgartner et al. 2019; Koehn et al. 2020a, b; MDBA 2020 and references therein). Shaded rows indicate association with water extraction or infrastructure.

Threat mechanism (cause)	Detail of the threat	Impact on fish populations	Potential improvements
Water storage and delivery for consumption	Major reduced inflows through the river system	Loss of habitats and flow components vital to population growth (e.g. movement, spawning and recruitment cues)	Use environmental water and design irrigation water delivery to meet optimal flow components required by aquatic biotas Protect refuge habitats
	Altered flow regimes: Reduced winter flows; reduced overbank flows, very low base-flows	Loss of habitats, and flow components vital to population growth	See above; increase critical flow components in line with natural seasonal frequencies, Protect refuge habitats
	Altered flow regimes: Increased summer flows (seasonal flow reversal)	Loss of seasonal flow components vital to population growth	See above: increase critical flow components in line with natural seasonal frequencies
	More uniform flows	Reduced biological cues (e.g. spawning, movements)	Increase delivery variability in line with biological needs, including overbank flows
	Lack of flushing flows	Poor water quality; Fish kills; Reduced biological cues	Decrease no flow periods; better real time remote water quality monitoring for key parameters, informed, adaptive water management planning and actions
	Release of cold water from deep outlets	Prevention of spawning and recruitment, reduced growth	Install mechanisms such as curtains or variable level outlets

Water extraction	Reduced overall flows	Loss of habitats and spawning/recruitment cues and needs	Adequate environmental water allocations, altered water delivery, all extraction remotely monitored in real time
	Pumps	Loss of fish through extraction	Install pump screens
	Irrigation channels	Loss of fish through diversion	Install screens
Weirs and structures (barriers)	Reduced river connectivity	Inability to move, complete life-cycle requirements, recolonise or escape poor water quality	Install effective fishways for longitudinal upstream and downstream fish movements
		Accumulations below barriers- increased susceptibility to disease, predation, poor water quality and capture	See above- with adequate flow cues for movements
		Reduced connection to floodplain habitats	Install effective lateral fish passage
		Mortality of larval and juvenile fish passing weirs	Replace undershot weirs
		Conversion of flowing to still-water habitats, increased carp abundances	Remove unnecessary infrastructure or alter operations
	Floodplain regulators	High risk to native fish; increased carp abundances	Recognise risks to native fish and use sparingly
Habitat removal and destruction	De-snagging; originally for river boats, later for ‘improved’ water delivery	Woody habitats, aquatic vegetation, reduced population capacity	Habitat reinstatement and protection; protection of riparian vegetation; more natural flow regimes

	High irrigation flows	Aquatic vegetation loss	
	Riparian zones	Erosion and cattle grazing.	Vegetation reinstatement and protection e.g. from stock grazing
	Wetland drainage	Wetland loss	Habitat reinstatement and protection; connection and re-connection flows
Angling	Angler harvest	Reduced adult spawning stock, reduced populations	Harvest and stock management
	Hatchery stocking	May increase populations of some predators	See above
Alien fishes	Especially: Salmonid species, carp, redfin (*Perca fluviatilis*) Gambusia (*Gambusia holbrooki*), oriental weatherloach (*Misgurnus anguillicaudatus*	Increased predation and competition	Implement an effective alien species management Strategy

Two key events that have engaged (and enraged) the public and highlighted the critical status of MDB aquatic ecosystems are worthy of further comment.

Fish Kills

Fish kills are predictable (with adequate attention and monitoring) and very visible events, with high levels of public scrutiny and media attention. Significant, large-scale events in the lower Darling River In 2018-19 (estimated 2-4 Million fish killed) (Australian Academy of Science 2019; Vertessey et al. 2019) and 2023 (estimated 20-30 Million fish killed) (Office of the NSW Chief Scientist & Engineer (2023), created anger, despair and dismay within local communities and the broader Australian population. The losses included important cultural, threatened and popular, iconic and angling species that cannot be quickly regenerated. Such losses cannot be sustained, especially for long-lived species such as Murray cod (Thiem et al. 2017). These events and the publicity surrounding them (including international coverage) caused serious questions to be asked regarding the competence of the protection of fishes and of MDB water management. Numerous other fish kills have occurred but received less attention, especially during drought conditions and subsequent bushfires (e.g. Legge et al. 2020). Given the predicted increasing frequency and severity of fish kills under climate change, there is an imperative for greater dedication to this area of resource management (Koehn 2022).

Carp

There are estimated to be between 199.2 M ('average' hydrological scenario) and 357.5 M ('wet' hydrological scenario) carp across Australia, most being in the MDB (Stuart et al. 2021). Populations fluctuate with flows and there have been increases in carp recruits following the 2022-23 flooding (Stuart et al. 2023). Being a highly visible alien species, in very large numbers, this has also caused public concern. Managing carp is difficult (Koehn et al. 2000), even with potential widespread actions such as the proposed carp herpes virus (KHV) (Stuart et al. 2023). Consistent with most invasive species they take advantage of ecosystems in poor condition. Carp are often also favoured by current water management regimes; including still weir pools, use of floodplain regulators and the delivery of high-level annual irrigation flows that inundate low lying floodplains such as Barmah- Milawa (Koehn 2004; Koehn et al. 2016).

Declines of over 90% in natural populations, frequent and massive fish kills and explosions in carp populations must be seen as giant wake-up calls to the poor resilience of MDB ecosystems as a result of a century of inadequate management. There is a need to philosophically change our approach to more seriously address these and other ecological issues.

Challenges

A key challenge is to work together to ensure the sustainability and resilience of MDB ecosystems on which communities and industries rely. This includes redressing impacts and balancing the quantity of water extracted and used for irrigation with that which can be used to protect and restore ecosystems. We must work together to meet all interests and community values – e.g. for irrigation, to restore environmental assets and water to First Nations to preserve their cultures (Jackson and Moggridge 2019). There is also the need to recognise the damage that has been done by a range of factors and accept that there is the need to facilitate recovery so that ecosystems have the resilience to recover from future hits- including from climate change related events. Most impacts on aquatic ecosystems are well-known with potential solutions identified. Actions, however, require the undertaking of a wide range of identified non-water measures (e.g. provision of fish passage; MDBC 2004; Koehn and Lintermans 2012; Baumgartner et al. 2019) that need to be integrated with the water reforms in the Basin Plan (MDBA 2011).

There is the need for proper recognition of non-agricultural values and assets, and this will require extensive and timely changes in both attitudes, approaches and commitments. Water in the MDB is highly managed- because it is valuable. We need to apply similar levels of management and valuation to ecosystems, their biota and the services they provide as these are also important assets within this highly managed river system. MDB ecosystems are ‘common property resources’ belonging to, and valued by all Australians, both those within the MDB and also those outside it, including the capital cities. The public reaction by capital city population to the plight of farmers during the Millennium drought was one of great sympathy. The reaction of the same citizens to recent fish kills has been one of horror- ‘what are we doing wrong out there?’

One of the most significant and impactful droughts recorded in the MDB (the ‘Millenium’ drought) provided a major wake-up call that resulted the development of extensive water policy reforms. The Basin Plan, however, has been controversial with considerable community outrage and significant public discourse (Pittock et al. 2015, Prosser et al. 2021; Zhang et al. 2024). There is opposition to any reductions of water available to agriculture, and equally, criticism of the lack of water projected to be returned to the environment (Chen et al. 2020), the limited amount of water actually returned to date and where is has been applied (Kirsch et al. 2021; Colloff and Pittock 2022). There have been several reductions to returns of environmental water following legislation of the Basin Plan, changes to the accounting and ‘water savings’ mechanisms utilised (e.g. Sustainable Diversion Limit Adjustment Mechanism projects (SDLAM), which along with other Federal and State government actions have been criticised (Walker 2019).

Some of the difficulties in Basin Plan implementation over the past two decades have been outlined in Wheeler (2024). Advice on Basin Plan implementation provided by the Murray-Darling Basin Authority on July 25, 2023, however, provides dismal reading. “Full implementation of the Basin Plan not possible by 2024 deadline. There will be a shortfall of water for the environment as set in the Basin Plan.”

- Very little progress has been made in achieving the 450 GL/y efficiency target, and this water will not be recovered by 30 June 2024 as required under current settings.
- Only 5 of 20 water resource plans in New South Wales (NSW) have been accredited. These plans are more than 4 years behind schedule, and NSW still has 7 plans to submit for assessment by the MDBA.
- Critical measures for improving outcomes in the northern Basin will not be delivered on time. Only 2 of 6 are on track for delivery by 30 June 2024. The remaining 4 measures are expected to take longer, delaying the achievement of environmental outcomes.
- With 16 key SDLAM projects unlikely to be operable by 30 June 2024, the Authority estimates a shortfall in water recovery of between 190 and 315 GL.

(https://www.mdba.gov.au/news-and-events/newsroom/authority-advice-basin-plan-implementation#msdynttrid=6pgxvlfAP0fGPIJtmrREzpWRSOJjnXYnVd1DOnxXyS0, accessed on 8 March 2024)

There is little doubt that the negative changes to the original water reforms and the considerable delays in implementation of measures to redress the water imbalance between agriculture and the environment have delayed any major improvements to aquatic environments, and probably led to further declines (e.g. contributed to the increased scale and frequency of fish kills). Maintaining the current incremental approach to water policy and management reform will not address all the current impacts or those from climate change. Hence it is likely that further degradation will occur and further changes to water policy and management may be required (Boland et al. 2024; Verhoeven et al. 2024; Wheeler 2024).

The ecological effectiveness of SDLAM measures has been highly criticised (Colloff and Pittock 2019). SDLAM in effect, decreased the need to recover 605 GL for the southern MDB of water entitlements within the Basin Plan through 'an equivalent reduction in surface-water diversions' (mostly installing regulators or building levee banks or improving on and off-farm water infrastructure) (Wheeler 2024). In relation to native fish, they have been assessed as being of minimal benefit, generally causing great risks, but being of great benefit to increasing carp populations. They cause risks to native fishes and benefit carp (Mallen-Cooper et al. 2008, 2010; Koehn et al. 2016).

Opportunities

Many voices continue to show concern about the state of aquatic habitats and biota in the MDB (e.g. Australian Academy of Science 2019; Walker 2019) and researchers, stakeholders, communities, and natural resource agencies must coordinate their activities and act decisively to improve the dire state these ecosystems are in.

The actions required to restore MDB native fish populations can be categorised into: (1) Flow management; (2) Water infrastructure; (3) Other restoration (actions to be implemented in parallel with appropriate flow management); and (4) Support and engagement (Koehn et al. 2020a). This requires: (a) coordinated policy settings under which actions can be implemented; (b) sound supporting science; (c) prioritised actions; (d) commitment and investment; and (e) stakeholder and community support (MDBA 2020).

The good news is that there are two existing policy frameworks that can help achieve this. The Basin Plan (MDBA 2011), which has the objective of improving flows through increased delivery of water for the environment (Hart 2016a, b; Stewardson and Guarino 2018), is funded and needs full implementation. While the Basin Plan (MDBA 2011) provides a much-needed framework for water reform, including the recovery of water for the environment to support native fishes, there are many additional non-water-related threats that impact recovery. Hence the Basin Plan must be complemented with additional measures to address threats. The value of addressing additional threats through parallel restorative actions has been recognised (Koehn and Lintermans 2012; Baumgartner et al. 2019) and these have been included in the Native Fish Strategy (2003-2013) (MDBC 2004) which is currently not adequately funded or fully implemented (Koehn et al. 2014), nor its the subsequent the Native Fish Recovery Strategy (NFRS) (MDBA 2020).

These documents provide a whole-of-fish-community approach that address priority threats and aims to rehabilitate native fish populations to 60% of levels prior to European settlement (current populations are estimated to < 10%). The NFRS had a 50-year time frame and coordinated actions across jurisdictions, communities and stakeholders in an effective partnership model where central coordination, coupled with focused jurisdictional actions, can deliver benefits to all governments. This model can readily incorporate other State and regional plans (e.g. ACT Government 2018).

A key purpose of such restorative programs is to restore the ecological requirements of the biota that have been impacted by human-induced ecosystem alterations (Cooke et al. 2012; Baumgartner et al. 2019). Both the Basin Plan and the NFRS restoration programs recognise the requirement for policy setting and decision-making to have a strong foundation and to be guided by contemporary knowledge of the species' ecological requirements (MDBC 2004; Swirepik et al. 2016). In more good news, the past 20 years have seen significant advances in the scientific understanding of native fish ecology, the impacts of human-related activities and potential solutions. This includes the science for environmental water, which aims to re-establish critical components of flow regimes that have been lost to benefit biota (Bunn and Arthington 2002; King et al. 2016). This rapidly developing sphere of water management (Arthington 2012) requires a range of data and knowledge, and while some gaps remain, there is adequate knowledge to undertake robust restoration-enabling policies and actions for most key MDB fish species (Stoffels et al. 2018; Koehn et al. 2019, 2020b).

We can also take heart and build on some of the successes that have already been made by restoration actions. For example, the Sea to Lake Hume fishway program has allowed the passage of many fish along the Murray River and has benefited population of migratory species such as silver perch (Baumgartner et al. 2014). The partial recovery of trout cod populations through a dedicated recovery plan has also been promising (Koehn et al. 2013). The use of environmental flows has been shown to increase spawning and recruitment of some fish species (e.g. King et al. 2009) and reinstalment of woody habitats has increased populations of Murray cod (Lyon et al. 2019). The design of hydrographs and effective water strategies to enhance population growth is rapidly developing (Yen et al. 2013; Stuart and Sharpe 2020). Recent modelling of the proposed implementation of higher flows under the Constraints Management Strategy (MDBA 2013) in the Murray River indicates likely improvements to golden perch populations (Todd et al. 2023). These successes show some progress and provide proof of the success of such remedial actions that now need to be funded and greatly up-scaled to be undertaken at the Basin-scale.

The way forward

The challenge now is to have the long-term vision, political will, commitment, and adequate resourcing to implement the necessary actions. Providing a legacy of healthy fish populations in the MDB, rather than continuing the significant declines and likely extinctions, is our moral obligation. The need for further institutional change water policy has been suggested (Wheeler 2024) and the integration of biotic assets on a more equal footing with water utilisation (e.g. restoration of threatened species) would be a step forward. The efforts of futures thinking and management that has been applied to industry and water resources (Horne 2022; Boland et al. 2024) should also be applied to aquatic biota, predicting the impacts and forecasting likely outcomes. Hard choices will need to be made regarding water policy in the future, as well as many trade-offs between competing demands, especially with regard to climate change (Wheeler 2024) with increased value given to environmental and cultural values and uses of water (Moggridge et al. 2019; Ellis et al. 2022).

The word *Sustainability* is used in many essays in this collection, but this is currently not a reality for our aquatic ecological assets. *Status quo* management is no longer an option as it will only result in further degradation, extinctions and an intergenerational ecological catastrophe where avoidance of the situation passes the ecological costs on to the next generations (Bommier and Zuber 2008). The existing losses to MDB aquatic ecosystems outlined in this essay highlight the urgent need for both change and action. The current incremental, partisan political and self-interest, transactional management approach must evolve to equitably consider all interests with an approach toward ecosystem restoration and reducing risk of ecological collapse. This must focus on major issues such as the over allocation of water and other recognised threats and the objectives of the Basin Plan, with a holistic view that focusses on habitats, ecosystems and the services they provide to communities.

Two existing key policy frameworks in the Basin Plan and Native Fish Recovery Strategy provide a solid basis from which recovery can begin. The science and knowledge of MDB fishes is considerable and growing, and while additional information will help maximise outcomes, knowledge is not a constraint to species and ecosystem restoration. From an aquatic ecosystem point of view there is the need for long-term continuity in restoration and a whole of the MDB approach – not site by site. As the decline of MDB native fish populations has occurred over more than a century, a long-term strategy is needed for recovery (Koehn and Lintermans 2012). We need to commit and stay the course. What is now required is the political vision and commitment to support investment to drive this recovery.

Working across interest groups (rather than just opposing each other) can initiate some easy ecological wins. For example, while irrigation and ecological water needs may be different, they are not always incompatible. For example, designing consumptive water delivery to provide for the needs of fish species needing population restoration (e.g. Stuart et al. 2019). Screening of pumps (Baumgartner et al. 2009) or irrigation outlets (Boys et al. 2013) can not only save fishes from injury or death but also save maintenance costs for irrigators. We need agencies to help facilitate such mechanisms that can be mutually beneficial. The removal of redundant weirs, replacement of weirs (Baumgartner et al. 2006) or altered weir pool management (Bice et al. 2017; Mallen-Cooper and Zampatti 2018) may also have ecological benefits at minimal costs.

The 50-year vision for agriculture in the MDB proposed by (Boland et al. 2024) is for a highly profitable industry producing more from less through sustainable practices. Objectives of the Basin plan include Improvements to the health of rivers and no extinction of species. This includes not just fish but other aquatic biota, water birds and vegetation, which are also listed as key ecological assets under the Basin Plan. Existing management is unlikely to meet these objectives and cannot currently be considered to be ecologically sustainable given the assessment of the state of MBD fish populations and riverine health (Davies et al. 2008, 2010).

A 50-year vision for Murray-Darling Basin aquatic ecosystems and their biota is that they be sufficiently restored so they can be sustainable, resilient environments to provide for the socio-ecological and economic needs of future generations in the face of the challenges of climate change.

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Australian Academy of Technological Sciences & Engineering

MURRAY-DARLING BASIN ESSAY

Essay #8 in a series of nine by Australia's leading water experts

Challenges and adaptation opportunities for the Murray-Darling Basin in response to climate change: Industry development & adjustment

Anne-Maree Boland with Claire Flanagan-Smith, Carl Larsen, Rebecca Schwarzman and Tim Cummins

Above: Centre-oivot irrigator, near Mulwala New South Wales, JohnCarnemolla, iStock.

EXECUTIVE SUMMARY

Boland et al. address the emerging challenges and opportunities for the agricultural industry in the MDB considering four plausible futures in 50 years: base case, drying and contracting agriculture, adaptive and market-driven agriculture, water abundance and agriculture powerhouse. The cases are evaluated through critical variables like water, climate, commodity mix, production systems, and market conditions.

The authors conclude that the preferred future is one where industry works with society and the environment, relying on advances in technology and sustainable management practices, and embedding principles of a circular economy (eliminate waste and pollution, circulate products and materials, and regenerate nature). Hence, they identify critical adaptation factors for a future ready agriculture as water resource sharing, producing more from less, securing domestic supply, thriving in export capabilities, using innovative and advanced technologies, capitalising on a skilled workforce, and responding to the Basin's societal and cultural values.

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Challenges and adaptation opportunities for the Murray-Darling Basin in response to climate change:

Industry development & adjustment

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Summary

Primary production in the Murray-Darling Basin (MDB or Basin) in 50 years' time will be substantially impacted by a changing climate. This essay explores the emerging challenges and opportunities for industry considering:

- The likely factors (drivers and barriers) influencing the future of the MDB
- A series of plausible futures for a 50-year time frame
- Opportunities (options) to protect or enhance the values of the Basin.

The MDB supports an economy currently worth around $230 billion per year including agriculture, tourism and recreation, and mining. Agricultural production has contributed over $20 billion per year in gross value since 2010 with irrigated agriculture responsible for a significant portion of this value (around 30%) from 3% of the land area (MDBA 2020b). The prosperity of irrigated agriculture relies on the sustainable management of water resources and provision of a reliable supply for consumption.

A 50-year future for the agriculture industry in the MDB must concede a significant decline in water availability (due to climate change and continued policy reforms), more frequent and severe extreme weather events and increasing temperatures impacting feasibility of certain production systems. Sharing of water under a changing climate will continue to challenge industry with meeting environmental needs essential to ensuring a healthy and thriving river system resilient to more extreme and frequent shocks.

Our 50-year vision for agriculture in the MDB is for a highly profitable industry producing more from less through sustainable practices and technology advances. This preferred future is one where market-driven agriculture adapts (Future 3) to the impacts of climate change and water scarcity. This future is desirable as it will ensure the sustainability of the Basin values, maintain production levels and protect the environment, while producing high-quality, safe, healthy, and environmentally friendly food that meets consumer expectations and supports a circular economy.

To reach this preferred future, the industry will need to adopt innovative technology and sustainable management practices supported by a favourable policy environment. Interventions will include a mix of implementation of technology and management practices and changes to policy settings. At the core of this response is the protection of the environmental and social values of the MDB – while supporting and encouraging an industry known globally for its innovation, efficiency and market responsiveness. Industry has demonstrated an ability to adapt to changing conditions and we are confident this capacity will continue resulting in a thriving agriculture sector.

1. Introduction

Primary production in the Murray-Darling Basin (MDB or Basin) in 50 years' time will be substantially impacted by a changing climate. Exploring the emerging challenges and opportunities for primary production under these conditions will ensure that policy settings, technology and management practices can support industry to successfully adapt – maintaining productivity and retaining its 'social license'.

To consider the potential challenges and opportunities of climate change on primary production in the MDB we have explored:

- Current industry supported by the MDB
- The likely factors (drivers and barriers) influencing the future of the MDB
- A series of plausible futures for a 50-year time frame incorporating climate change projections and uncertainty
- Opportunities (options) to protect or enhance the values of the Basin through transformative technology, management and policy.

Our vision for a 50-year future is one that acknowledges the considerable impact of climate change and variability on the agriculture industry in the MDB with a significant decline in water availability (due to climate change and continued policy reforms to ensure sufficient water for the environment), more frequent and severe extreme weather events and increasing temperatures effecting feasibility of certain production systems. However, we are confident that industry is well equipped to undertake adaptive and transformative change to meet the demands of this future.

Adoption of technology and sustainable management practices and policy settings that support industry will ensure that the needs of society and environment are optimised. Agriculture will be market driven, sustained by smart people and sustainable production systems and focused on valuing precious resources.

Key concepts in this paper: futures thinking and complex systems

This essay is underpinned by a number of key concepts including futures thinking and acknowledgement that we are dealing with a highly complex system.

The capacity of MDB industry to thrive is influenced by a multifaceted set of factors including availability of natural resources, access to infrastructure and services, skills and education of regional workforces, industry diversity and financial resources accessible to businesses and individuals (Productivity Commission 2017). These factors are interdependent with many unpredictable relationships, interactions and feedback loops between the people, organisations, environments, infrastructure, policies and laws at play. These connections at times appear to be competing and/or contradictory.

> *"We can't impose our will on a system. We can listen to what the system tells us and discover how its properties and our values can work together to bring forth something much better than could ever be produced by our will alone."* (Meadows 2018)

In such a complex system like the MDB, many futures are possible, some are plausible and even fewer are the future we want to see realised (Hancock et al. 1994). In this essay, we describe several possible futures and select a preferred future we believe the MDB system should navigate towards.

To describe the 50-year future for the MDB we have used the CSIRO Global megatrends (Naughtin et al. 2022) as a framework to explore potential impacts of climate change. We have also utilised the current state of the MDB as described in detail in the publication by Hart et al. (2021) including challenges over the next 30 years, particularly due to climate change and possible policy and management responses.

2. Murray-Darling Basin industry

The MDB as the largest river system in Australia, provides essential resources (biophysical and social) to support communities and a thriving economy based largely on primary production and tourism. Water resources are a key ingredient of the prosperity of the MDB contributing to irrigated agriculture production. The MDB consists of the Northern and Southern Basins (Figure 1).

The MDB Economy

The MDB supports a large economy currently worth around $230 billion in Gross Regional Product per year (Aither 2022). Many water sensitive industries contribute to the economic value of the region including agriculture, tourism and recreation, and mining.

Agriculture is the major economic contributor to the MDB with more than $20 billion per year in gross value since 2010 (MDBA 2020b). Agriculture dominates land use in the MDB, with over 82 million ha or 80% of the total land area used primarily for agriculture (Hart et al. 2021, ABS 2022a). Grazing is the principal agricultural land use at around 80%, with the remaining area used for cropping and horticulture (ABS 2022a). In 2020-21 the gross value of production of agriculture in the MDB was around $30 billion per annum or more than 40% of the total value of agricultural production in Australia.

Tourism, including water- and environment-related tourism, is also a significant industry contributing more than $7 billion in gross value added in 2017-18 and 2018-19 (Aither 2022). Over 31,000 tourism businesses operated in the MDB in 2016 (Hart et al. 2021).

While water sensitive industries are important economically in the MDB, the range of sectors providing employment is diverse. The largest employers in 2016 were construction including mining and transport (14%), retail and wholesale trade (12%) and health and social assistance (13%) (Hart et al. 2021).

The future demands on water and water sharing arrangements are likely to shift as water sensitive industries develop. Improved infrastructure will assist the growth of agriculture and export reliant industries such as mining. Energy transformation and decarbonisation and increased interest in tourism may also encourage growth in regional areas. The relative composition of water sensitive industries is uncertain, however policy will need to support equitable and sustainable sharing of water.

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Figure 1. Map of the Murray-Darling Basin. The northern Basin is delineated in pink and the southern Basin in green.

Irrigated agriculture contributes to the national economy

The irrigated agriculture industry in the MDB contributes significantly to Australia's economy and the local communities. Irrigated agriculture is responsible for around 30% of the gross value of agriculture production (MDBA 2020b) despite representing only 3% of the land used for agriculture (Hart et al, 2021).

In the southern MDB there are large areas of irrigated pastures, cereals, and rice as well as high value horticulture crops including permanent plantings such as fruit and nut trees and grapevines. In contrast, cotton and grain are the major crops in the northern MDB (MDBA 2020).

The development of irrigation infrastructure in southern MDB in the 1950s-1980s prompted the replacement of low-intensity agriculture, mostly grazing, with high-intensity and higher value crops (horticulture and pasture for dairy and grain cropping) (Hart et al. 2021). Irrigation communities expanded with industry development, government support and access to low-cost water supplies.

The number of businesses irrigating in the MDB is around 8,300 (ABS 2022b). This number has continued to decline over the past 30 years, consistent with trends in agriculture across Australia as smaller farm businesses consolidate into larger commercial holdings.

Irrigated agriculture in the MDB remains important in terms of its contribution to the Australian economy at a national scale and to local communities, offering employment and supporting local economic activity including associated businesses and services. In 2020-21, the MDB contributed $8.4 billion of the gross value of irrigated agriculture making up around 45% of the national irrigated agriculture value (ABS 2022c).

The gross value of irrigated agricultural production has remained above $7 billion for the past decade despite fluctuating water availability. Agricultural output has increased from a smaller land area, with fewer businesses compared with the past 40 years. Greater disparity also now exists between the economic output of larger and smaller agricultural enterprises with more than 80% of value generated by just 30% of the largest farms in the MDB (Hart et al. 2021).

Managing water for agriculture use

The prosperity of the irrigated agriculture industry relies on the sustainable management of water resources and provision of a reliable supply for consumption. The management of water resources in the MDB has become increasingly important with over consumption leading to a stressed system. Water sharing agreements within a sustainable consumptive volume has become the primary focus.

Management of the MDB has involved four State governments, the Australian Capital Territory (ACT) and the Commonwealth (Federal) governments working together for over 100 years on issues of water resource development, water sharing between states, river management, and key aspects of catchment and land management.

Recent challenges have included:

- Over allocation of the consumptive pool resulting from high rates of water extracted for irrigation
- Environmental impacts arising from decline in water availability and poor water quality
- Social and economic impacts with changing land systems and communities
- Declining flows exacerbated by a warming and drying climate.

Implementation of policy to address these challenges and working towards the sharing of water within a sustainable consumptive pool has been the focus of recent times. The irrigated agriculture industry has adapted to increasing production with less available water.

Basin communities and their links to agriculture

Around 2.4 million people live in the MDB with just under 60% of the population residing in cities or regional centres of more than 10,000 people, including Canberra (around 500,000) Toowoomba (around 134,000), Bendigo and Albury-Wodonga (each 100,000). At least 2% of the population reside in very remote areas (ABS 2022d).

Over 40 Aboriginal Nations are represented in the MDB by an Aboriginal and Torres Strait Islander population of more than 120,000 people. Water is central to the cultural, social and spiritual identity of Australia's First Nations people, as well as to their livelihoods. 'Cultural flows' are water entitlements owned and managed by First Nations to improve the spiritual, cultural, environmental, social and economic health and well-being of Traditional Owners and Country. Water is an important part of self-determination.

Some parts of the MDB are home to culturally and linguistically diverse populations and around 10% of the total population speak a language other than English at home (including Indigenous languages) (ABS 2022d). These culturally and linguistically diverse communities have intergenerational links to agriculture as both business owners and labourers throughout the MDB.

Direct employment in agriculture or agricultural services accounts for up to 8% of those employed in the MDB. This includes farmers and farm managers, labourers, skilled workers, machinery operators, and scientists (ABS 2022d).

The demand for employment for tourism, mining and service industries will continue to grow providing competition for agriculture industries. Agriculture will require more skilled labour as farming systems continue to become more sophisticated.

3. Influencing factors at play in the MDB

The MDB system is influenced by a complex suite of factors. To consider the future impact of climate change on industries in the MDB, we must understand the impact that water (resources, infrastructure and policy reforms), climate, and global trends have had on the development of the MDB and its likely future.

WATER

The availability and use of water in the MDB is a critical factor influencing agricultural development. Over time, water infrastructure and policy reforms, together with environmental factors such as climate change, have changed access to water resources, who uses the water, and the way it is managed to balance competing demands. Challenges and adaptation opportunities for the MDB have been influenced by:

- Infrastructure development and policy reforms
- Consumptive pool of water resources, agricultural water use, and water quality issues.

Water limited agricultural growth until infrastructure was built

Variability in water availability has played a significant role in the development of surface water resources for agriculture in the MDB. In the early 1900's, shortly after the Federation drought, state governments entered into an agreement to share water resources along the Murray River. The agreement included joint investment in the development of major infrastructure (dams, weirs, and locks) to ensure that the river would remain navigable and to maintain access to water resources under low flow conditions. Between the 1950s and 1980s, the MDB experienced very wet conditions which were accompanied by a rapid expansion in government owned infrastructure (including dams, weirs and channels), this time primarily for irrigation along with flood mitigation.

Irrigation facilitated rapid expansion of agriculture

These developments set the stage for a rapid expansion in irrigated agriculture and resulted in flows of major river systems in the southern MDB, particularly the Murray, Murrumbidgee, and Goulburn, being highly regulated by large storages and diversions to irrigation districts. Irrigated agriculture was initiated later in the northern MDB, in the 1960's and 1970's (Hart et al. 2021), mainly driven by private investment in infrastructure development. Major irrigation areas now occur along the Murray River (NSW, Victoria and South Australia), Murrumbidgee and Goulburn Rivers. This includes irrigation districts centred around infrastructure typically built originally by governments, and now managed as private corporations or cooperatives while many river diverters access entitlements using private infrastructure directly from waterways. Small but important irrigation districts also include the Coleambally and Lachlan in the southern MDB and Namoi, and Gwydir irrigation areas in the northern MDB. There are also several very large properties with significant private water collection and storage infrastructure in the northern MDB.

In addition to surface water, groundwater resources support irrigated agriculture and stock and domestic use across the MDB. Private infrastructure (bores) is typically used to access groundwater and yields can be more or less sustainable depending on local hydrogeological conditions and rates of use.

Water reforms addressed over-allocation

With the development of infrastructure and irrigated agriculture, water consumption from the MDB rapidly increased leading to a system that was over-allocated. The past 30 years has seen a number of urgent reforms to the planning and management of water in the MDB to reduce the proportion of water that is allocated to consumptive uses – primarily agriculture. Significant reforms impacting on the current availability of water for irrigated agriculture have included the following (Table 1).

Table 1. Major reforms affecting the MDB and impacting on its consumptive pool and availability for irrigated agriculture

Reform	Description
Water Reform Framework (1994)	Council of Australian Governments (COAG) endorsed the Water Reform Framework which underpins many aspects of our system for managing water resources today. Reforms included: ▪ Separating water access rights from land title ▪ Allowing trading of water rights ▪ Water pricing for full cost recovery, and ▪ Provisions for water for the environment.
Murray-Darling Basin Cap (1995)	An upper limit of surface water diversions in the MDB. Responding to a decline in river health and establishing 'a line in the sand' to ensure conditions did not deteriorate.
Intergovernmental Agreement on the National Water Initiative (2004)	States agree to a National Water Initiative to re-energise the water reform agenda of 1994. The initiative clearly defined key aspects of the water management framework including "entitlement" (perpetual access to a share of consumptive pool) and "allocation" (volume or proportion of an entitlement made available each year). The agreement also recognised the need for overallocated water systems to be returned to sustainable levels of use through water planning and recovery of water for the environment.
Water Act (2007)	A significant phase of water reform prompted by the Millennium drought that had devastating impacts on communities, irrigators, and the environment. Desire to reset the balance between consumptive and environmental water in the MDB with the establishment of new Sustainable Diversion Limits (SDLs) for Basin catchments and the Basin overall.
Basin Plan (2012)	Legislated to ensure that water resources of the MDB are managed in an integrated and sustainable way to achieve 'a healthy working Murray–Darling Basin that supports strong and vibrant communities, resilient industries, including food and fibre production, and a healthy environment' (the Vision). Key elements to implement the Basin Plan were (i) purchase of water entitlements and (ii) subsidies for irrigation efficiency. In addition, the Basin Plan aims to establish long-term average SDLs that reflect an environmentally sustainable level of water use and introduce water trading rules to facilitate water reaching its highest value use. SDLs came into effect from 2019 for each of the 29 surface water areas and 80 groundwater areas. The Basin Plan includes a SDL accounting framework and to provide flexibility, it includes a mechanism to adjust SDLs.

Current availability of surface water resources

With the implementation of the Basin Plan, there has been significant change to the consumptive surface water allocation across the MDB. The current situation with regards to water that is available for agricultural irrigation, the volume of water that has been recovered through purchases and irrigation efficiency programs and the current environmental water entitlements is described in Table 2. Since the commencement of the Murray Darling Basin Plan, the consumptive pool has declined by 2,137 GL per year.

Adaptive management enables governments and communities to adjust their approach with regular 10 yearly reviews of the Basin Plan required to consider emerging climate change patterns, new information, tools and techniques. These reviews could result in changing water limits or other water management arrangements with the first review in 2026.

Table 2. Consumptive pool of surface water resources in the Murray-Darling Basin and recovery of environmental entitlements

Item	Value	Description
Consumptive pool prior to Basin Plan	13,957 GL per year (MBDA 2022a)[2]	Total Baseline Diversion Limit (BDL) – or the amount (long-term average estimate) of water being extracted annually at the time of Basin Plan development under the Murray-Darling Basin Cap
Current consumptive pool	11,820 GL per year (MBDA 2022b)[3]	Total Sustainable Diversion Limit (SDL) – or the amount (long-term average estimate) of water resources available for annual extraction as of 2022.
Surface water recovery – purchases	1,231 GL per year (DECCW 2022a)	Total volume of water recovered towards 'bridging the gap' between BDLs and SDL through the purchase of consumptive entitlements
Surface water recovery – irrigation efficiency	693 per year (DECCW 2022a)	Total volume of water recovered towards 'bridging the gap' between BDLs and SDL through irrigation efficiency subsidies (both on and off-farm). Note there is some disagreement about the figure due to uncertainties as to whether the return flows from these infrastructure projects are increasing or decreasing flows to groundwater and rivers.
Environmental water entitlements	2,877 GL per year (DECCW 2022a)	Commonwealth Environmental Water Holdings in 2021–2022

Which agriculture industries use the water?

The MDB accounts for more than 60% of the total water used for irrigated agriculture in Australia, including more than 70% of water used from irrigation district infrastructure such as channels and pipes and more than 70% of water extracted from rivers, creeks, and wetlands in Australia.

The amount of MDB water resources used for irrigation, and the proportion of water resources used by different crop types varies greatly according to seasonal and market conditions. The water used for irrigation in 2020-21 in the MDB is summarised in Table 3 as total volumes and a percentage of water use for irrigated agriculture in Australia.

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[2] Note: Estimate as of July 2022. BDLs reflect estimates due to difficulties measuring diversions. Adjustments continue to be made in each sub-catchment as more information becomes available, for example through the development of water resource plans.

[3] Note: Estimate as of July 2022. SDL estimates are updated annually to accommodate revised BDL figures and progress on recovery and the SDL adjustment mechanism.

Table 3. Water used for irrigation in 2020-21 (ABS, 2022a)

Item	MDB 2020-21	% of total use/applied
Total water used for irrigation	5,082 GL	
Water use by source		
Irrigation districts (channels or pipes)	2,481 GL	49%
On-farm dams or tanks	268 GL	5%
Rivers, creeks, lakes	1,582 GL	31%
Groundwater	703 GL	14%
Recycled or re-use	39 GL	1%
Town or reticulated mains	9 GL	0.2%
Water applied[4] by commodity		
Pastures	1,103 GL	23%
Vegetables	88 GL	2%
Fruit trees	800 GL	17%
Grapevines	418 GL	9%
Nurseries	12 GL	0.2%
Rice	530 GL	11%
Cereals	585 GL	12%
Cotton	1,223 GL	25%
Other	86 GL	2%

Water availability, trade and reliability varies across the Basin

Water availability and the reliability of that water being supplied varies across the MDB. The southern MDB is a highly connected system with a mature trading market and an allocation system, that allows water products with different levels of reliability to be 'moved' across the Basin and used according to availability. For example, high reliability water in the southern MDB supports significant areas of perennial horticulture which require certainty around water supply each year. Lower reliability water is often used more opportunistically in the southern MDB to grow annual crops such as rice and cereals when water is available. This pattern of use is interrupted in dry years when lower reliability water becomes largely unavailable, leading to large transfers of remaining water allocations to higher value perennial horticulture, as was observed during the Millennium drought.

The northern MDB is less connected with the movement of water between basins constrained. There is a less mature trading market and the security of water is significantly lower with greater fluctuations in the yearly allocation of water. Given this reduced water security, the production of crops is more opportunistic on an annual basis - this suits the production of annual crops such as cotton, rice and cereals.

To manage the uncertainty of irrigation water supply businesses have implemented risk management strategies including maintaining a portfolio of held and leased entitlements across

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[4] Note: Discrepancies exist between total water used (i.e. diverted) and applied. Total water applied in 2020-21 was reported as 4,844 GL.

jurisdictions, trading water through the water allocation market and having access to both surface and groundwater allocations.

These strategies allow irrigators to manage production through variable seasons.

Water quality varies across the Basin

Water quality varies across the MDB and is impacted by external environmental conditions. Fluctuations in water flows (i.e. floods and droughts) has major impacts on parameters such as:

- Salinity
- Acid sulfate soils
- Blackwater events
- Thermal stratification
- Blue-green algae

The primary water quality issue for irrigated agriculture is salinity with excessive concentrations causing a reduction of production and potentially damaging plant health.

CLIMATE

Agricultural production in the MDB has long been influenced by both natural geographic climatic variations and human induced climate change, leading to industry adaptation and innovation. The important factors are:

- Climatic variations across the MDB and how they impact commodities grown and their production systems
- Impact of human induced climate change on agriculture.

Geographic climate variations influence commodity mix

The historical and current climate of different locations across the MDB has governed the agricultural commodity mix. This has been driven by rainfall, temperature and runoff determining water availability for irrigation in combination with other agronomic suitability factors such as soil types and topography.

As a result, more perennial horticulture, such as citrus, table and wine grapes, nuts, stone and pome fruit as well as pasture for dairy is grown in the southern MDB, compared to a higher proportion of cropping, cotton and cereals, and livestock in the northern MDB. The predominance of crops regionally is demonstrated analysing the current climate and commodity mix in selected key locations across the MDB (Table 4). Temperature is particularly important for some horticultural crops, with citrus requiring adequate heat units or growing degree days, or pome fruit needing sufficient chill units to promote optimal budburst and flowering.

Extreme historic climate drivers such as droughts and floods have heavily influenced the expansion and subsequent contraction of specific agriculture industries across the MDB, in combination with other critical factors such as commodity prices, market access and pest and disease pressure. Most notable was the recent Millennium Drought, causing significant agricultural, social and economic disruption and adjustment. There were differing impacts in the southern MDB which has higher and more regular rainfall, than the northern MDB, with more opportunistic cropping.

Table 4. Current climate (1991-2020) and commodity mix of key MDB locations (BoM 2022)

Key location	Current climate (ave.)	Commodity mix
Southern MDB		
Mildura, Victoria	Rainfall (annual): 264 mm Temperature (annual): 24.8°C Evapotranspiration (annual): 1,642 mm	Dominated by irrigated perennial horticulture including citrus, table grapes, dried fruit and nuts (almonds), with some annual horticulture (vegetables). Large areas of dryland cropping (wheat, barley and oats) with some sheep.
Shepparton, Victoria	Rainfall (annual): 465 mm Temperature (annual): 22.0°C Evapotranspiration (annual): 1,434 mm	Large areas of irrigated pasture for dairy, perennial horticulture (stone and pome fruit) and fodder cropping (maize, lucerne).
Griffith, New South Wales	Rainfall (annual): 395 mm Temperature (annual): 24.2°C Evapotranspiration (annual): 1,613 mm	Dominated by livestock, cereal crop and other broadacre crops, wine grapes, citrus, vegetables and nuts.
Northern MDB		
Bourke, New South Wales	Rainfall (annual): 336 mm Temperature (annual): 28.0°C Evapotranspiration (annual): 1,893 mm	Includes cotton, citrus and other fruit, livestock (cattle) and irrigated wheat,
Moree, New South Wales	Rainfall (annual): 577 mm Temperature (annual): 27.4°C Evapotranspiration (annual): 1,828 mm	Dominated by cotton and cereal crops with livestock (sheep and cattle), oil seeds, olives and nuts (pecans).
St George, Queensland	Rainfall (annual): 476 mm Temperature (annual): 28.2°C Evapotranspiration (annual): 1,893 mm	Includes cotton, wheat, livestock (sheep and cattle), and some grapes.

Production systems have adapted as technology advancements are made

Agriculture has and continues to adapt to changes in climate across the MDB due to its reliance on biophysical climatic factors and the natural resource base for production. Irrigated agriculture is particularly exposed and sensitive to reduced water availability in the MDB system.

The Millennium Drought provides a number of insights into how irrigated agriculture adapted to the lowest inflows on record, which differed across industries, and how these industries may respond in the future (Kirby et al. 2014). Overall, there was an increase in water use efficiency with more agricultural output produced per unit of water between 1996-2009. While there was a decline in water for diversion of 67%, this was only accompanied by a reduction in adjusted gross value of irrigated production across the MDB of 20%. On-farm irrigation efficiency measures were also coupled with significant water delivery infrastructure investment through modernisation.

In the southern MDB, the dairy industry was able to adjust production systems by ceasing or reducing on-farm pasture irrigation, purchasing more feed (hay and grain), and/or using ‘cut and carry' systems whereby fresh grass is cut daily and fed to housed cows. This was combined with selling water on the market. Higher value horticulture in the southern MDB maintained productivity by purchasing water from lower value annual crops and pastures, which had more flexibility in their production systems. Inter-basin trading occurred from Murrumbidgee primarily a rice growing region, to the South Australian and Victorian Murray which are primarily horticultural and viticultural irrigation regions.

In the northern MDB, lower irrigation requirement crops such as irrigated cereals increased, while higher irrigation requirement crops like cotton significantly decreased. Large price rises in cereals and meat also contributed to buffering the extent of the worst effects of the drought.

Productivity gains within sectors, substitution of inputs, and water trading among sectors and regions will continue for perennial and annual cropping, with this adaptation potentially offsetting the impacts of a reduction in water availability (Kirby et al. 2012).

There has also been transformative change within some sectors as a result of recent and predicted future climate changes. Examples include wine grape businesses in the southern MDB establishing vineyards in Tasmania and changing varieties produced in the MDB. This has been driven by continuing earlier and more rapid ripening and more compact vintages over the past 20 years.

The structural adjustment and adaptations made by agriculture in response to climate change will continue to have implications for the MDB environment and communities that are part of the complex system.

Human induced climate changes and their impact on agriculture

Based on the historical climate and industry adaptation, it is important to consider the predicted changes in climate over the next 50 years and the impact this will likely have on agriculture. Climate change will cause an increase in average temperature, reduced average rainfall and water availability for irrigation, as well as increase in frequency and severity of extreme events (e.g. heat waves, drought, rainfall intensity and flood).

The MDB has warmed by around 1°C since 1910 and will continue to warm (by 0.6–1.5°C by 2030 relative to 1995 and by 0.9–2.5°C by 2050 without mitigation), with more hot days and fewer cold days (Hart et al. 2021). Rainfall is projected to decrease, particularly in the southern MDB in winter and spring, with more time in drought and decreased soil moisture (BoM 2020). The median estimated decrease in mean annual runoff is 14% in the southern MDB (10–90 percentile range of -38% to +8%) by 2046–75 under the medium warming scenario. In the northern MDB the median projection is a decline in mean annual runoff of 10% (10–90 percentile range of -38% to +21%). Importantly, the median estimated decline in runoff is similar to the volume of water sought to be returned to the environment under the Basin Plan (Hart et al. 2021).

There are significant uncertainties as to the impacts of climate change on run-off and water availability in the MDB. However, there is an expectation that there will be significantly less water available for consumption in the southern MDB and likely a smaller reduction in the northern MDB. The water allocation system will need to adjust to a highly variable climate.

The relationship between plants, soils, climates, microclimates, and the human inputs necessary to generate economic outputs will continue to evolve in the MDB, accelerated by climate change. Potential future climate of key locations across the Basin region may generally increase the suitability of annual cropping and pastures in the southern Basin, with continued increase in intensity of production systems particularly for higher value perennial horticulture crops. These production systems will continue to use infrastructure (e.g. shade, hail netting) and other technological developments (e.g. protected cropping systems with precise monitoring and management of water, nutrients and temperature) and varietal advancements to adapt to reduced water availability.

For example, factors that will influence type, extent and location of horticulture in the southern MDB include:

- Optimum temperatures and sunlight during the growing season: Optimum temperature range for growth for specific cultivars – for example the optimum range for citrus is between 13^0 and 36^0C.
- Less rainfall during the harvest period: Minimal rainfall during harvest is preferred to ensure harvest continuance and reduced profitability from pest and disease damage.
- Better trafficability after rain and other soil suitability issues: Well drained soils reduce waterlogging to achieve commercial yields and enable operational access to the orchard following high rainfall.
- Water availability, trade and reliability: A portfolio of held and leased entitlements will ensure that risk can be managed. Secure water and ability to trade is essential for perennial horticulture.

In the northern MDB, there will continue to be opportunistic irrigated cropping like cotton in response to more variable water availability and higher average temperatures, with an increase in suitability for livestock (sheep and cattle) and cereal and oilseed crops. Perennial horticulture will be less suitable due to the higher risk of variable water availability and more frequent extreme weather events. The climate analogues show a general shift north to north-west from their current location, with the future climate of Mildura, Victoria similar to current day Leonora, Western Australia and the future climate of Moree, New South Wales similar to current day Blackall, Queensland in the year 2090 (Table 5).

Table 5. Future climate (2056-2085) and commodity mix of key MDB locations (BoM 2022)[5]

Key location	Future climate (ave.)	Similar to current day (CSIRO 2020)	Commodity mix
Southern MDB			
Mildura, Victoria	Rainfall (annual): 267 mm (→) Temperature (annual): 27.4°C (↑) Evapotranspiration (annual): 1,794 mm (↑)	Leonora, Western Australia	Potential increase in dryland cropping (wheat, barley, oats) and livestock (sheep), with continuation of perennial horticulture citrus and table grapes. Reduced suitability of some nuts (almonds) and vegetables.
Shepparton, Victoria	Rainfall (annual): 461 mm (→) Temperature (annual): 24.8°C (↑) Evapotranspiration (annual): 1,576 mm (↑)	Cobar, New South Wales	Potential increase in fodder and dryland cropping (wheat, barley, oats) and livestock (sheep), with warmer climate wine grapes. Reduced suitability of stone and pome fruit.
Griffith, New South Wales	Rainfall (annual): 419 mm (↑) Temperature (annual): 27.0°C (↑) Evapotranspiration (annual): 1,717 mm (↑)	Bourke, New South Wales	Potential increase in livestock (cattle) and dryland wheat, with some citrus. Reduced suitability of vegetables and nuts.
Northern MDB			
Bourke, New South Wales	Rainfall (annual): 342 mm (→) Temperature (annual): 31.0°C (↑) Evapotranspiration (annual): 2,048 mm (↑)	Longreach, Queensland	Potential increase in dryland cereal crops and livestock (sheep and cattle). Reduced suitability of irrigated cotton and citrus.
Moree, New South Wales	Rainfall (annual): 578 mm (→) Temperature (annual): 30.3°C (↑) Evapotranspiration (annual): 1,947 mm (↑)	Blackall, Queensland	Potential increase in cereal crops with livestock (sheep and cattle), oil seeds, olives. Reduced suitability of irrigated cotton and some nuts (pecans).
St George, Queensland	Rainfall (annual): 489 mm (↑) Temperature (annual): 31.3°C (↑) Evapotranspiration (annual): 2,030 mm (↑)	Winton, Queensland	Potential increase in wheat and livestock (sheep and cattle). Reduced suitability of irrigated cotton and grapes.

Legend: → = remains relatively similar to current climate; ↑ = increase (negative impact on agriculture); ↑ = increase (positive impact on agriculture); ↓ = decrease (negative impact on agriculture)

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[5] Note: Under a High Emissions – Scenario RCP8.5

The changing climate will continue to present numerous challenges, testing the resilience of the agriculture industry and its ability to persist, adapt and/or transform. Structural transition will be facilitated by the water market and trade, with reduced water availability for irrigation from the consumptive pool increasing prices and shifting water to higher value uses. This is a key adaptive capacity mechanism that allows agriculture to manage the implications from climate variability and change. For example, a three percent reduction in average rainfall has been modelled to result in a 17% increase in temporary market prices in the southern MDB (Gupta & Hughes 2018). Added to this is a potential challenge of increased salinity and reduced water quality due to declining in-flows with the remaining water potentially less fit-for-purpose.

Industries and businesses will need to continue to evaluate the use, quality, security and price of water relative to other input costs and commodity prices, as this will ultimately govern the profitability and sustainability of irrigated agriculture in the MDB (MDBA 2020).

Dryland agriculture will also be impacted by climate change through, for example, reduced pasture productivity rates, reduced forage quality, livestock heat stress, and increased risk of soil degradation (MDBA 2020).

REGIONAL TRENDS

Significant changes have occurred in regional Australia over the past decade expedited by the impacts of the coronavirus pandemic. We are likely to see these regional shifts continue in the next 50 years with regional centres having a big role to play in the future of living in Australia.

The ability to work remotely has encouraged the growth of regional centres. Flexible working arrangements and the desire to balance work and lifestyle has seen many move from coastal cities to the regions. This shift is likely to continue with the expectation that strong regional economic growth centres with world-class liveability, seamlessly connected physically, digitally and economically to cities and other regional centres will emerge (Lazarow et al. 2021). Critical to this regional growth will be the development of small and medium-sized enterprises (SMEs) and high value-added advanced manufacturing capacity, accompanied by modern and agile agricultural systems.

Improved infrastructure including housing, digital connectivity and transport (e.g. the Inland Rail) will support the growth of regional centres in the MDB and ensure the provision of skilled workforce. Increased water security will also ensure prosperity for irrigated agriculture.

GLOBAL TRENDS

What megatrends will impact agriculture in the MDB?

The key influences on the global economy and society (or megatrends) have been considered by CSIRO (Naughtin et al. 2022). Megatrends are trajectories of change that typically unfold over years or decades and have the potential for substantial and transformative impact. Seven megatrends were described in the CSIRO 2022 update highlighting the significant changes that have occurred since the first release (Hajkowicz et al. 2012) exposing new risks and opportunities.

The relevance of these megatrends for agriculture in the MDB and how they may influence future development have been considered in Table 6.

Agriculture adaptation in the face of these trends

The agriculture sector has experienced significant change over the past 30-50 years including:

- Agricultural output continuing to increase (e.g. a target of $100 billion in farm gate output by 2030 due largely to unprecedented demand (NFF, 2030)
- Farm numbers and land used in agricultural production falling with an increase in average farm size
- A major disparity between farming enterprises with the largest 20% of farms producing 80% of the output
- Growth of larger inland population centres and the decline of smaller outlying towns.

In a thriving and growing economy, we expect the trends of larger farms, growth of larger cities and increasing agricultural production in the MDB to continue. The description of megatrends shaping our world reinforces the exciting opportunities for agile and well-resourced agricultural industries. In particular, a more sophisticated and nuanced agriculture industry will be well positioned to respond to these emerging issues in 50 years.

Table 6. Relevance of CSIRO megatrends for the agriculture industry in the MDB

Megatrend	Relevance for the Murray-darling basin
Adapting to a changing climate	• Decreasing run-off will lead to declining water quantity, quality and availability • Extreme and unprecedented weather events increasing in their frequency and scale will impact production in both short-term (e.g. frosts, hail storms) and long-term (e.g. droughts) • Climate variability may require economic policy intervention in the form of subsidies and grants to protect industry and communities • Changing climate will require organisations and communities to adapt and identify new ways of operating • Communities will need to prepare to live in a hotter world with higher evapotranspiration
Leaner, cleaner and greener	• Resource constraints will drive cutting-edge innovations that aim to do more with less, achieve carbon neutrality, reduce biodiversity loss and address the global waste challenge • Changing consumer expectations will increase demand for food produced sustainably - clean, green and resource efficiency • Escalating pressures will be placed on finite food, water, mineral and energy resources • Global population growth and more people transitioning from lower to higher income brackets will increase global demand for high value food
The escalating health imperative	• Healthcare expenditure will continue to increase • Opportunities provided by preventative and precision health in supporting better health outcomes will increase interest • Changing diet including a focus on healthy options and differing protein sources will increase demand for high value food
Geopolitical shifts	• Emerging geopolitical shifts relating to science, technology, trade, supply chains and defence strategy will influence position in global markets

	• Ensuring self-sufficiency and secure supply chains will ensure diversity in domestic food production and establishment of robust export markets • Fluctuating global trends will cause increasing impacts on Australian communities
Diving into digital	• Adoption of digital and data technologies will provide opportunities for organisations and businesses • New technologies for primary industries and water resource managers will increase efficiencies and productivity • Increased ease in global communications and responsiveness will contribute to improved production systems
Increasingly autonomous	• Scientific breakthroughs in artificial intelligence (AI) and global investments in technology-driven research and development (R&D) will improve efficiencies • AI and related science, research and technology capabilities will boost agricultural productivity • Increased automation will result in decreased reliance on workforce in primary industries
Unlocking the human dimension	• Heightened influence of human perspectives and experiences on future community, business, technology and policy decisions will increase collective decision-making • Consumers demand for increased transparency from organisations, governments and scientists to maintain their trust will result in more sustainable production systems • Changing consumer expectations will result in ethical and trusted food production systems

4. Industry development 50 years from now….

FUTURES THINKING

To plan and manage our future water resources in the MDB, we must understand what the future might look like under a changing climate (Horne 2022). We know there is considerable uncertainty and that the future may unfold in a multitude of ways. While the changes that will lead to the future are largely out of our control, it is possible to improve our response to change by considering the types of changes that may occur. This approach allows us to build our resilience to change – our capacity to persist, adapt or transform as needed.

One lens to explore the future is through what is known as the “cone of futures” (Figure 2) whereby a range of futures are described:

- Possible futures are the full range of futures that changes could lead to
- Plausible and probable futures are the futures that we think are likely
- Preferable futures are the futures that we wish to steer towards.

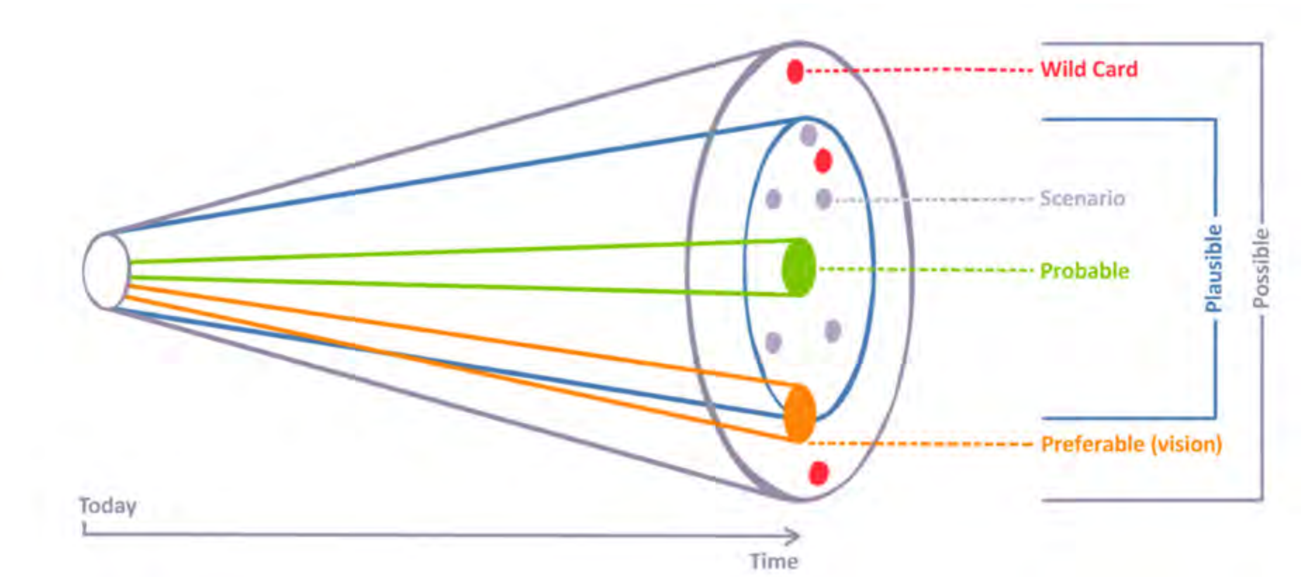

Figure 2: The cone of possibilities: possible, plausible and preferable futures

A series of plausible futures for a 50-year time frame have been developed to:

- Encourage different ways of thinking about the future
- Inspire the development of problem-solving skills and
- Focus on solutions.

PLAUSIBLE FUTURES

Four Plausible Futures for industry in 50 years in the MDB are described below and in Table 7 with the critical variables of:

i. **Water** – availability (including conveyance considerations) and quality
ii. **Climate** – averages and extremes
iii. **Commodity mix** – annual and perennial crops
iv. **Production systems** – intensive versus extensive
v. **Markets** – consumer preferences and export/domestic.

Future 1: Base Case

The Base Case considers a consumptive pool which is relatively stable with over-entitlements having been successfully dealt with through the MDB Plan. The impacts of declining water availability due to a changing climate (at an intermediate level (RCP4.5)) is to some extent built into the allocations. For agriculture, whilst the consumptive pool has been reduced the allocations are more sustainable being delivered most years. Water quality continues to improve due to better management of flows. Under this future the industry adapts to a changing climate through the breeding of new varieties and movement of production to different areas. While the agriculture industry can adapt to averages it is ill-equipped to respond to extreme events. The commodity mix remains relatively consistent with horticulture in the southern MDB and cropping and mixed enterprises increasing in the northern MDB. There is limited adoption of new technology and management practices with a focus on incremental change and stagnation in productivity and value of output per ML of water. Production systems are similar to the current practices and industry responds to market signals both domestically and internationally.

Future 2: Drying and contracting agriculture

Future 2 provides a scenario where the consumptive pool is 30% less than the current due to a changing climate (at a high level (RCP8.5). Impact of reduced rainfall and run-off and increased evapotranspiration are experienced in both southern and northern production regions and also resulting in negative effects of salinity. The drying conditions will also result in severe and more frequent droughts causing a significant reduction in perennial horticulture and an increase in dryland and mixed annual enterprises in the northern MDB. Adaptation to conditions of reduced water resources and increasing salinity will see the adoption of technology and management practices to moderate levels. This will mean that production levels in the MDB will decline but not proportionate to the reduced volumes of water with marginal improvement in the value of output produced per ML of water. Production systems will adapt incrementally. There will be a focus on the domestic market and exports will decline.

Future 3: Adaptive and market driven agriculture

Future 3 explores an option in which the consumptive pool declines by 10–30% (in line with intermediate current climate models (RCP4.5)) with a consistent decrease in the southern MDB and a more variable change in the northern MDB. Unlike the Base Case, this scenario results in a greater reduction in water allocations to agriculture with SDLs declining to benefit the environment. However, this reduction in water availability is accompanied by a pro-active response from the agriculture industry increasing its resilience with a focus on improved practices and technology. Transformative change will ensure that production systems can meet the challenges of producing more with less and pre-empt the impacts of climate change.

Horticulture will expand in the southern MDB with a smaller footprint and greater reliance on intensive systems. Annual cropping will expand in the northern MDB but will be opportunistic depending on weather conditions and water allocations with the use of precision agriculture. There will be an increase in the value of product per ML of water. Regional centres will provide a highly skilled workforce. Under these conditions industry will demonstrate a high degree of resilience and adaptability by being on the front foot. Industry will be responsive to market drivers striving for efficient and profitable production for the domestic market and production efficiency to increase export competitiveness. Production will focus on clean, green and healthy products demonstrating environmental credentials including efficient use of resources.

Future 3 is the scenario that we consider most preferable. A reduction in the consumptive pool is most likely under the intermediate climate change models. The ongoing protection of environmental values of the MDB is paramount resulting in 10-30% decline in water available for agriculture. However, we believe that the agriculture industry can respond to this challenge through technology, management and policy modifications.

Future 4: Water abundance and agriculture powerhouse

Future 4 reflects a scenario where the consumptive pool increases periodically particularly in the northern MDB. This scenario predicts a changing climate (RCP2.6) that results in increased run off in the northern basin MDB and fluctuating allocations. Under this future, industry would be well positioned to adapt to increasing water allocations on an annual basis. Horticulture production would continue to use the more secure water in the southern MDB whilst growth in annual production would be experienced in the northern MDB – this would be highly opportunistic based on seasonal conditions. It is likely that production would increase in the northern MDB although the unstable nature of this will challenge the provision of a skilled work force in the region. An increase in total production volumes will be accompanied by a greater focus on self-sufficiency and also high value export markets. There will be a marginal improvement in the value of output produced per ML of water.

Table 7. Plausible futures for agriculture industry in 50 years

Variable	Future 1: Base case	Future 2: Drying and contracting agriculture	Future 3: Adaptive and market driven agriculture	Future 4: Water abundance and agriculture powerhouse
(i) Water				
Availability – consumptive pool	**Allocation:** Continues as is Consumptive pool relatively stable	**Allocation**: > 30% decline on average Consumptive pool shrinks rapidly due to climate and policy decisions	**Allocation:** 10-30% decline on average Consumptive pool declines – consistently in southern MDB and more variable in northern MDB	**Allocation:** Increases periodically Consumptive pool increases periodically particularly in northern MDB
Water quality	Water quality (salinity) improves	Salinity levels restrict production at certain times	Water quality (salinity) is variable with technology supporting improved river management	Water quality (salinity) improves due to an abundance of water
(ii) Climate				
Averages	Continued decline in annual rainfall, particularly in southern MDB in winter and spring, with increased temperatures and evapotranspiration (RCP4.5)	Significant reduction in annual rainfall and run-off, combined with increased temperature driving evapotranspiration and higher plant water requirements (RCP8.5)	Decline in annual rainfall, particularly in southern MDB in winter and spring, while increased temperature and evapotranspiration are less pronounced (RCP4.5)	Decline in annual rainfall, with periodic heavy falls and increased run-off and storage in the northern MDB, while increased temperature and evapotranspiration are less pronounced (RCP2.6)
Extremes	Industry adapts to averages, but not resilient to extremes	Millennium drought conditions occurring one in every 4-5 years	Industry resilient to extremes through the implementation of practices and technology	Industry responds to regular increases in the availability of water in northern MDB

(iii) Commodity mix				
Agriculture commodities	Commodity mix remains relatively similar with horticulture (almonds, winegrapes, citrus, dried fruit, table grapes) and dairy in southern MDB and dryland cropping (cotton and grain) and mixed enterprises in northern MDB	Decrease in area of horticulture and minimal pasture irrigation in southern MDB. Large increase in dryland cropping and mixed annual industry in northern MDB	Significant expansion of horticulture in southern MDB with an increase in intensive production systems. Minimal pasture irrigation in southern MDB with intensive livestock production relying on cut and carry. Growth in annual cropping which is opportunistic in northern MDB	Maintenance of horticulture as predominant commodity for highly secure water in the southern MDB with maintenance of the current footprint. Growth in irrigated annual cropping in the northern MDB which is highly opportunistic
(iv) Production systems				
Production system advances	Similar production systems to current Limited innovation and incremental adoption of technology and practices Stagnating output and value from irrigation water applied ($/ML)	Moderate level of technology and automation advancement results in moderate increases in productivity in southern MDB and increases in dryland annual cropping in northern MDB Adoption of technology and management practices are through necessity and a required adaptation response to reduced water resources and increasing salinity Moderate output and value from irrigation water applied ($/ML)	High level of technology and automation advancement Intensification of agriculture particularly in the horticulture sector with protected cropping in the southern MDB Implementation of precision agriculture in the northern MDB for annual crops allows industry to respond effectively and opportunistically to water supply increases Increased automation requires reduced reliance on labour Thriving inland regional centres provide the required skilled workforce to implement	Moderate level of technology and automation advancement Abundance of water results in production in southern MDB increasing and considerable expansion of irrigated annual production systems in northern MDB A highly flexible workforce is required challenging some production systems Moderate output and value from irrigation water applied ($/ML)

			sophisticated production systems Adoption of technology and management practices is transformational due to a focus on innovation and pre-empting impacts of climate change Industry demonstrates a high degree of resilience and adaptability by being on the front foot High output and value from irrigation water applied ($/ML)	
(v) Markets				
Market demand	Remains similar with domestic and export production varying across commodities	Increased importance of domestic market and greater focus on self-sufficiency Reduced exports as total production declines	Efficient and profitable production for the domestic market Strong commodity prices and labour efficiency increase export competitiveness Increased focus on clean, green and healthy products demonstrating environmental credentials including efficient use of resources Increased demand for plant-based products	Increased importance of domestic market and greater focus on self-sufficiency Total production increases (irrigation and dryland) Increase in high value export markets

WHAT NEEDS TO CHANGE?

A 50-year future for the agriculture industry in the MDB must concede a significant decline in water availability (due to climate change and continued policy reforms), more frequent and severe extreme weather events and increasing temperatures impacting feasibility of certain production systems. Sharing of water under a changing climate will continue to challenge industry with meeting environmental needs essential to ensuring a healthy and thriving river system resilient to more extreme and frequent shocks.

Industry will have a known consumptive pool for use – with a high level of certainty in the southern MDB and greater variability in the northern MDB. Industry will actively use the water market to ensure that perennial production is maintained during periods of low water allocation with more opportunistic annual production, particularly in the northern MDB.

Innovation is core to Australian agriculture and production systems will continue their reliance on adoption of the most current and efficient management practices and technology. Increased levels of automation replacing labour will also ensure more profitable farming systems. A skilled workforce drawn from regional centres is required for managing intensive and sophisticated production systems.

The demand for Australian produce will increase globally with a reputation for high quality, safe and environmentally friendly food focused on health benefits. We will continue to focus on domestic production with less reliance on imports. Being highly efficient and innovative, agriculture businesses in the MDB will respond to changing market demands in response to an increasing domestic population and consumer expectations.

Critical adaptation factors for agriculture in 50 years are described below and in Figure 3.

- **Water resource sharing** – ensuring the equitable sharing of water in the MDB for communities, environment, cultural and recreational purposes. Adapting to a more secure supply in the south and opportunistic production in the north and working with the environment.
- **Produce more from less** – aiming to reduce consumption and produce more with less resources. In some instances this will lead to more intensive production with a smaller footprint.
- **Secure domestic supply** – securing the production of essential agriculture commodities to alleviate geo-political challenges and supply-chain breakdowns.
- **Thriving export** – exporting high value products to an increasingly wealthy global consumer focused on health benefits and bulk commodities produced efficiently and profitably.
- **Innovation and advanced technology** – using technology and communications to improve efficiency and mitigate challenges presented by climate change/variability. This includes improved plant and animal genetics.
- **Skilled workforce** – capitalising on the highly skilled workforce in regional centres where they are attracted due to excellent services and community capital.
- **Responding to societal, cultural values** – appealing to consumer expectations associated with changing societal and cultural values. A desire for agriculture production to be ethical, safe and environmentally responsible meeting Sustainable Development Goals (SDGs) (United Nations 2015), environmental, social and governance (ESG) and Agricultural Sustainability (AFI 2022) and progressing the principles of circularity (Ellen Macarthur 2022).

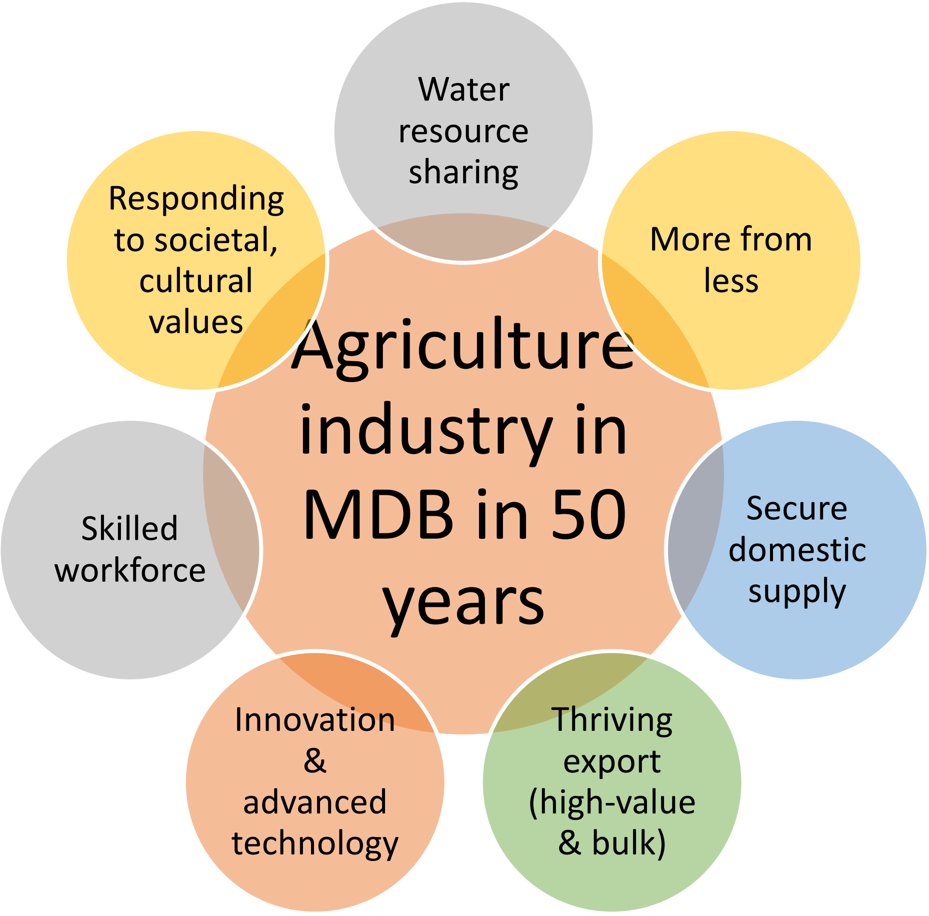

Figure 3. Adaptation factors in the face of global trends

A PREFERRED FUTURE FOR AGRICULTURE

Our 50-year vision for agriculture in the MDB is for a highly profitable industry producing more from less through sustainable practices and technology advances. This preferred future is one where market-driven agriculture adapts (Future 3) to the impacts of climate change and water scarcity. This future is desirable as it will ensure the sustainability of the Basin values, maintain production levels and protect the environment, while producing high-quality, safe, healthy, and environmentally friendly food that meets consumer expectations and supports a circular economy.

The preferred future requires the implementation of technology enabling water to be shared equitability, resources used efficiently and agriculture using a smaller footprint to produce the same amount. Highly automated and intensive production systems producing for the domestic and export markets will facilitate this change. Automation will have replaced reliance on a casual labour force. Sophisticated production systems will be managed by a skilled workforce, providing economic benefits to the region. Smart people will manage farming systems more suited to a drier and more variable climate (including floods and storms). Technology will assist in better decision-making to ensure the best use of finite resources. Food and fibre production will be safe, clean, green and ethical responding to the expectations of well-informed consumers and societal values.

Our vision emphasises a thriving industry in charge of its own destiny with light touch government involvement.

INTERVENTIONS TO ACHIEVE THIS FUTURE

To reach this preferred future, the industry will need to adopt innovative technology and sustainable management practices supported by a favourable policy environment.

Proposed changes will incorporate both a 'resilience' approach where we aim to protect industry from environmental trends and an 'adaptive' approach where industry changes with the environment (Hart et al., 2021). Opportunities to protect industry are summarised in Table 8 and include a mix of implementation of technology and management practices and changes to policy settings.

Table 8. Potential interventions to achieve our preferred future

	Technology	Management	Policy
1. Water resource sharing	▪ Infrastructure management to optimise beneficial use ▪ Live information to assist equitable, transparent and adaptive water sharing	▪ Active water market which ensures water reaches most appropriate use	▪ More water for the environment and cultural water through Sustainable Diversion Limits ▪ Continuation and enforcement of Murray-Darling Basin Plan ▪ Improvements to Plan based on monitoring and evaluation
2. Produce more from less	▪ Maximising resource efficiency through the precision agriculture and current technological advances ▪ Intensive production systems that are resource efficient and have a smaller footprint (e.g. protected cropping)	▪ Change to the crop types grown including more drought tolerant or water efficient varieties ▪ Spatial shift in where crops are grown with a reduction in area of permanent plantings and an increase in annual crops allowing for greater interannual flexibility in water use	▪ Incentives provided for efficiency in resource use and recovery ▪ Incentives provided for decarbonisation of production systems
3. Secure domestic supply	▪ Efficient production systems that provide secure domestic supply of essential food and fibre	▪ Efficient production systems that provide secure domestic supply of essential food and fibre	▪ Incentives to ensure the supply of domestic market of essential food and fibre
4. Thriving export (high-value and bulk)	▪ Efficient production systems supplying international markets – commodity and niche products	▪ Efficient production systems supplying international markets – commodity and niche products	▪ Support for development of international markets and trade ▪ Promotion of high value production – clean, green, and safe

5. Innovation and advanced technology	▪ Production systems reliant on advanced technology and automation	▪ Production systems reliant on good management decisions	▪ Incentives and support for research and development and an innovative industry
6. Skilled workforce	▪ Automation replacing casual labour force	▪ Educated and expert labour force focused on decision-making skills ▪ Thriving and resilient regional centres	▪ Investment in regional centres in MDB ▪ Investment in skills and training
7. Responding to societal, cultural values	▪ Technology to ensure production of clean, green and safe food	▪ Management decisions to ensure production of clean, green and safe food ▪ Production systems that respond to societal values and consumer expectations	▪ Industry investment in responding to market expectations and promoting sustainable practices (e.g ESG) ▪ Financial markets investing in ESG businesses

Interventions will require significant investment in research and development, to create and implement cutting-edge solutions that address the challenges posed by climate change and water scarcity. The government will need to play a role in promoting sustainable practices by creating policies and regulations that encourage the adoption of these technologies. Additionally, the industry will need to collaborate with researchers, farmers, and other stakeholders to share knowledge and implement best practices.

Water sharing rules will need to be well-defined to promote water efficiency. Market signals and incentives will drive industry towards sustainability and ESG principles. Sustainable production systems will also be supported financial institutions providing ‘green financing’.

There may be incentives to supply the domestic market when needed to ensure continuity of supply. Support and promotion of exports and our associated credence values (safe, clean, green and ethical) will be provided. Investment in regional centres and skills and training will ensure ongoing provision of a skilled workforce. This will include the requirement for management that is familiar with technology and sophisticated production systems.

Production systems that minimise the risk of climate variability will be viewed favourably in an environment where insurance premiums have increased significantly. With increased intensity however comes increased concentration of resources and the potential for greater pollution. Improved understanding of resource recovery and enhanced logistics infrastructure in inland Australia will ensure these production systems move towards circularity.

6. A bright future – if we're up to it

Primary production in the MDB provides significant return for Australian GDP and is a major feature of the landscape. It is clear that industry will need to change through adaptation and transformation in response to a suite of influencing factors that will shape the MDB in 50 years.

A high degree of uncertainty leads to many plausible futures – a few of which we have explored. We have concluded that our preferred future is one where industry works with society and the environment relying on advances in technology and sustainable management practices and embedding principles of a circular economy (eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature). Society will have higher expectations on how their food and fibre is produced and our industry will be uniquely placed to respond.

At the core of this response is the protection of the environmental and social values of the MDB – while supporting and encouraging an industry known globally for its innovation, efficiency and market responsiveness (high-quality, safe, healthy and environmentally friendly). Industry has demonstrated an ability to adapt to changing conditions and we are confident this capacity will continue resulting in a thriving agriculture sector.

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MURRAY-DARLING BASIN ESSAY
Essay #9 in a series of nine by Australia's leading water experts

Achieving a healthy, resilient and sustainable Murray-Darling Basin

Sarah Ann Wheeler

EXECUTIVE SUMMARY

Wheeler states that continued focus is essential to ensure water governance structures are strong. Though there are a few welcome efforts to improve MDB water governance, policy reforms and continued invigilation are essential for strong governance, and to ensure that monitoring, compliance and enforcement are followed by all states – otherwise there is a real danger of further reduced environmental sustainability.

Wheeler also states that there is considerable room for improvement in rural development and structural adjustment programs within the MDB, mainly the water recovery program. Based on Wheeler's review, there are three key water recovery and economic development policy lessons that need to be considered to mitigate the hydroclimate issues in the Basin: proper structural and economic development policies, avoiding policy instruments that have substantial unintended consequences, and using buybacks as the most effective and efficient form for water recovery among all the water recovery programs in the MDB.

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Above: Gouburn Weir near Nagambie, Victoria.
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Achieving a healthy, resilient, and sustainable Murray-Darling Basin

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Abstract

This article provides an overview of recent water policy in the Murray-Darling Basin (MDB or Basin) and discusses water recovery issues (and their economic impact) in further detail. A vision for a healthy, resilient, and sustainable Basin in fifty years is put forward, with three key water recovery and economic development policy lessons detailed, including:

1. Of all policy instruments for environmental (community) water recovery, (institutional/ regulatory change, Buyback, infrastructure modernisation), generally the most effective and efficient instrument is Buyback.
2. The need to avoid policy instruments that have substantial unintended consequences (e.g., irrigation infrastructure subsidies).
3. To achieve healthy, resilient and productive rural communities, proper structural economic development policies, and essential social service spending, are needed.

Introduction

The issues of future climate change impacts and increasing water scarcity (and variability) are some of the biggest global risks facing humanity (WEF, 2019). Indeed, predictions are that many agricultural regions face drier and more volatile climate futures (IPCC, 2019). Coupled with changing economic circumstances and variable markets, this means that rural societies face a highly uncertain future. Farms will need to improve productivity (i.e. produce more crops with less inputs) to remain profitable. The drive to increase farm productivity, along with the decline of quantity and potentially, quality of water resources, requires the production of more crops with less water – without compromising ecosystems (Perry et al., 2017).

Plans for future adaptation within rural communities include a suite of strategies which expand, but also those that contract, various agricultural activities (Seidl et al., 2021). Irrigated agriculture will be one of those activities that will probably be forced to contract, or at least adapt considerably. Individual farm and regional adaptation will require a diverse range of policy strategies – both demand and supply management focussed (Wheeler et al., 2013; 2014; Rey et al., 2019; Wheeler, 2023). Nowhere will this be more needed than in irrigated production within the MDB.

The Murray-Darling Basin (MDB)

The MDB is Australia's largest agricultural region – an area of major environmental, economic, social, cultural, and recreational significance. It has many key environmental assets, including internationally important Ramsar-listed wetlands. Agricultural production across the Basin is diverse: ranging from primarily broadacre farming and grazing livestock in the north, to dairy and horticulture in the south. The MDB generated 42% of Australia's $70.9 billion gross value of agricultural production in 2020-21 (ABS, 2022a), encompassed 64% of Australia's irrigated area, and was home to around 42% of all irrigating businesses (ABS, 2022b). The majority (around 60-65%) of Australia's agricultural production is exported overseas. One of the worst recorded droughts in the MDB's history occurred in the 2000s, and widespread fears about environmental collapses led to significant water policy reform (Quiggin et al. 2010).

The MDB provides a perfect case study as an example of a region that faces a multitude of extreme challenges - hampering its ability to achieve a healthy, resilient, and sustainable future. Some of these challenges include climate change, in the form of increasing temperatures, more extreme droughts, reduced water allocations and more variable rainfall increasing the risk of severe flooding (Chiew et al., 2011; Zhang et al., 2020); environmental problems and increased extinction (SoE, 2021); water licence over-allocation (Grafton and Wheeler, 2018); inequitable land and water property right distribution to First Nation groups (Jackson et al., 2019; O'Donnell et al., 2021); falling farm numbers and reduced agricultural terms of trade (Wheeler et al, 2020b; Wheeler & Zuo, 2017); reduced social, education and other economic services (Alston, 2004; Wittwer and Young, 2020); and increased mental health challenges (Wheeler et al., 2018; Yazd et al., 2020; Xu et al. 2023).

Many of these challenges have resulted in considerable water policy reform and innovations, with the Basin leading the world in implementing a range of reforms. In particular, the over-allocation of water licences and climate variability have prompted a series of water policy changes over recent decades (Quiggin, 2001; Crase et al., 2004; Lee and Ancev, 2009). These reforms include the development of formal water markets, establishing caps on water use, the *Water Act 2007* and the development of the MDB Plan (Wheeler, 2014; 2022). Indeed, water sharing has been an issue between States in the Basin for a very long time, with formal arrangements put in place since the early 1900s. Wheeler (2014) provides an overview of all the major water policy changes that have occurred in the Basin, beginning with the *1914 River Murray Waters Agreement* between NSW, Victoria, and South Australia. In the last couple of decades, other major funding programs and policies have been implemented (driven by the region's worst recorded drought – the Millennium drought), with the biggest reforms including the *Water Act 2007,* followed by the MDB Plan in 2012.

The Water Act and the MDB Plan

At the height of the Millennium Drought in the 2000s, the Australian Government implemented the *Water Act 2007*, which involved substantial legislative, regulatory and stakeholder water reform (Grafton and Wheeler, 2018). The reforms included the creation of the Murray-Darling Basin Authority (MDBA) to replace the former MDB Commission, and federal entities responsible for managing water entitlements on behalf of the Australian Government. Importantly, the *Water Act 2007* established the parameters for a future *MDB Plan* with key objectives: "3d(i) to ensure the return to environmentally sustainable levels of extraction for water resources that are over-allocated or overused"; and "3d(ii) to protect, restore and provide for the ecological values and ecosystem services of the MDB" (*Water Act 2007*, pp. 2-3).

Passed into law in 2012, the Basin Plan has since been the framework determining the relationship between consumptive and environmental use of MDB water resources (MDBA, 2020), and its aim was to specify long-term levels of sustainable water use – known as Sustainable Diversion Limits (SDLs). After a lengthy process and much controversy in the lead up to implementation, the Basin Plan stipulated the recovery of 2,750 GL from both a) willing sellers (the *Restoring the Balance* program, otherwise known as "buyback" of water entitlements); and b) subsidised irrigation infrastructure (the *Sustainable Rural Water Use and Infrastructure program*). To ensure the state government of South Australia did not proceed with legal objections to the Plan, and provide for smooth passage of the legislation, a further 450 GL of water for the environment was to be secured through 'supply infrastructure efficiencies' (Grafton and Wheeler, 2018), bringing total recovery to 3,200 GL.

Water Recovery and Reform Post the Plan

After the Plan was legislated, water policy reform in Australia stalled and, in many respects, went backwards (Wheeler, 2014) – largely as a result of concentrated lobbying and rural community backlash (Grafton and Williams, 2020). A change of Federal water minister in 2015 also resulted in many negative changes. For example, an amendment to the *Water Act 2007* in 2015 limited the voluntary purchase of water entitlements ('buyback') to a total of 1,500 GL. This halted the most effective instrument the country had in recovering water, leaving water recovery only possible through irrigation infrastructure upgrades (Grafton and Wheeler, 2018). Other policy changes included: the axing of the National Water Commission in 2015; the relocation of the water portfolio from the federal Department for the Environment to the Department for Agriculture; the abandonment of the Sustainable Rivers Audit in 2012; and states providing far less emphasis and attention to water monitoring, metering, enforcement, and compliance.

To top all these reversals off, in 2018 the parliament legislated the MDBA's proposed sustainable diversion limit (SDL) Adjustment Mechanism, which in effect decreased the need to recover 605 GL of water entitlements within the Plan through 'an equivalent reduction in surface-water diversions' through proposed water supply (e.g., installing regulators or building levee banks) and efficiency projects (e.g., improving on-farm and off-farm water infrastructure). The effectiveness of these supply measures has been highly criticised (Colloff and Pittock, 2019) and, to date, very few of these projects have been successful or even implemented. Physical water recovery in the northern Basin was also reduced from 390 to 320 GL. The SA MDB Royal Commission strongly criticised the MDBA for these amendments, along with federal and state government actions with regards to water policy post-legislation of the Plan (Walker, 2019).

Common Community Perceptions about the MDB Plan and Reality

A range of economic instruments and water demand management strategies are being introduced worldwide to deal with water scarcity problems (Wheeler et al., 2017; Wheeler, 2021; 2023). The impact of rural socio-economic development and population dynamics on agriculture, the environment and water resource use has become a challenging issue globally (de Sherbinin et al., 2007; Hibbard and Lurie, 2013) – largely due to dwindling rural populations (Winkler et al., 2012). Despite this, many rural communities have experienced significant economic transformations, resulting in greater rural economic diversity, less interdependence and greater income parity with urban regions, developing exurban areas and amenity-led rural growth (Irwin et al., 2010).

Over the past decade and a half, the most common concerns with the MDB Plan (and water recovery in general, which began in the 2000s) raised by rural communities are fears around reduced agricultural output and economic activity – leading to farm exit (e.g., Kiem, 2013, numerous submissions to parliament enquiries, etc). This consequently is believed to have an external impact on the surrounding community in general, resulting in a decrease of services, jobs, farm numbers and population sizes. Wheeler et al. (2023) provides further detail on this discussion and the validity of much of the modelling done.

However, the causal impact of reduced water allocations on production, farm and community outcomes is incredibly complex, because of the many factors in play. For example, community perceptions regarding the MDB Plan are intrinsically linked with an ongoing worsening agricultural and rural community situation. Following on from the challenges identified in the

Basin earlier, Figure 1 provides a longitudinal view of what many in rural communities view as a negative consequence – the loss of farmers in rural communities over time.

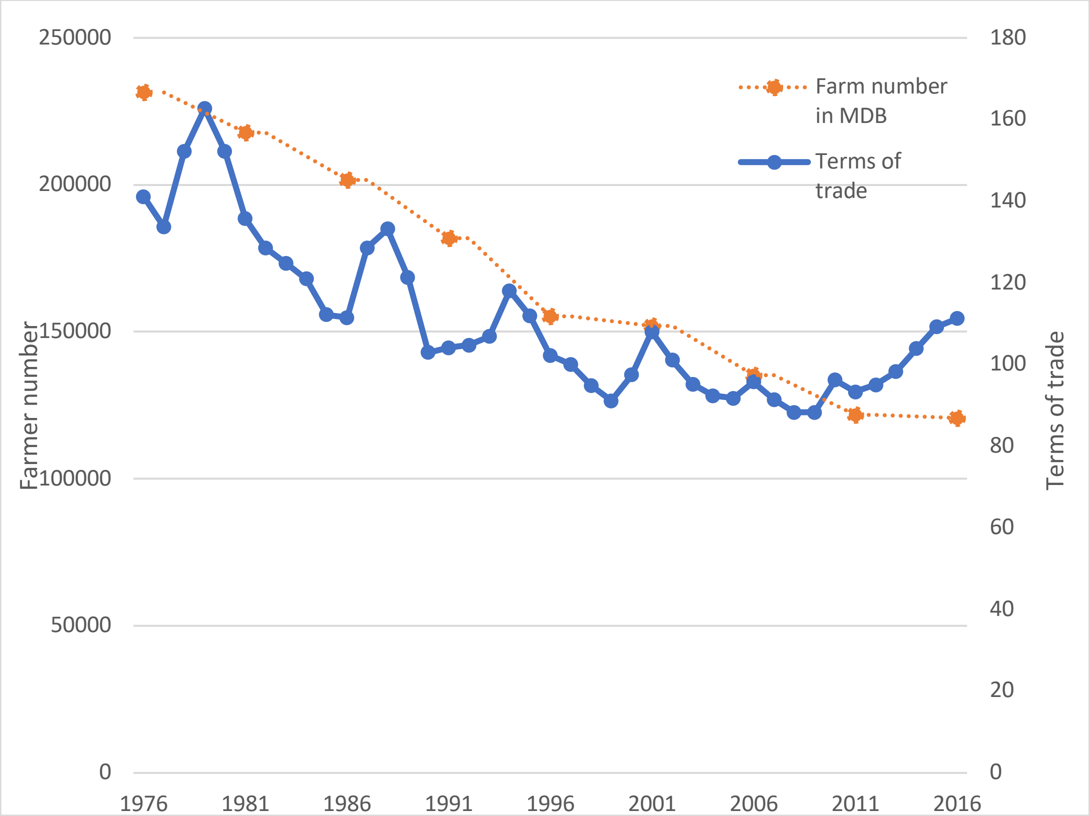

Figure 1. Farmer numbers in Murray-Darling Basin States
Updated from Wheeler et al. (2020b). Farmer numbers come from the ABS population census, specialised request and TableBuilder used for 2016 numbers. Australian farmers terms of trade from ABARES (undated).

There is debate over how much farm exit is desirable – on one hand it allows farmers to consolidate and become larger, more productive and efficient; and on the other hand, it may lead to a loss of people and consequently services in a region. Farm numbers have steadily decreased for decades, which has been coupled in general with a worsening farmers' terms of trade. Of note, it does seem that the improving terms of trade situation from 2008 onwards may be related to a slowing in the number of farmers leaving in Basin states.

When times are difficult, whether it be because of trade sanctions, drought, flood or disease – it is easy to have false attribution regarding water policy issues. Economists attribute farm number changes to labour market restructuring, technological change, terms of trade change, trade sanctions, economies of scale, changes in agricultural production, economic return and weather/drought/climate change pressures, and a withdrawal of public and private sector services (Wheeler et al., 2020b; Wittwer and Young, 2020).

What defines a healthy, resilient, and sustainable MDB?

Everyone will have differing criteria as to their own personal preferences about what makes a healthy, resilient, and sustainable MDB. The National Farmers Federation's future goal is that by 2030, agriculture will be a $100 billion industry (note: Australia was at $82 billion gross value of agricultural production (GVAP) in 2021-22). The five pillars on which this goal rests includes (National Farmers Federation, 2022):

1) *Customers and the Value Chain*: Deep engagement with customers and competitive connections to markets (measured by trust in industry, freight costs and tariff barriers to exports).
2) *Growing Sustainably*: Increased environmental stewardship, carbon neutral approach, smart water policy, reduce farmland and food loss (measured by food waste and farmland loss, water use efficiency, ecosystem services to be 5% of farm revenue).
3) *Innovation*: Public and private R&D, increased technology, and renewable adoption (measured by energy sources, adoption, and innovation efficiency).
4) *People and Communities*: Trained workforce, increased available workforce, gender equity, strong communities, decreased workplace injuries (measured by fatalities, increased wellbeing, gender parity measures, available trained and general workforce).
5) *Capital and Risk Management*: Increased farm planning; increased investment, increased use of innovative tools for risk management (measured by adoption, investment and farm equity levels).

Although all of these goals are worthy, many are private agricultural-only focussed goals. The $100 billion industry goal by 2030 is an example of this, whereby the target has become a proxy for other wider goals within the five pillars (given it's one of the easiest goals to measure and track). We do need to question whether the $100 billion is a goal that should be pursued – a turnover goal is not necessarily indicative of higher farming profitability or wellbeing, or of gains spread across all farmers.

Apart from the need to try to change the climate trajectory (e.g. address higher temperatures and more variable rainfall) in the Basin, this essay proposes the following criteria (in no particular order):

1. A healthy environment – greater surface water flows, groundwater reserves and sufficient water quality for environmental, cultural, community, agricultural, industry and domestic use.
2. Reduced level of farm exit from current trends (recognising that stopping farm exit or consolidation altogether is not desirable).
3. Reduced suicide and mental health problems in rural societies[6].
4. Reduced irrigated land footprint and a consolidated industry (albeit one that is more productive and profitable).
5. Minimal agricultural food waste or other distributional problems.
6. Increased ownership of water by First Nation groups.
7. Profitable farms – that can earn money from natural capital assets (soil, water, land, vegetation) as well as traditional agricultural outputs.
8. Transparent, data-driven and increased sustainable investment in economic and social services and structural adjustment programs that positively influence wellbeing within regions whilst mitigating pork-barrelling.

Given length restraints, it is not possible to provide detailed analyses of how to try to achieve all the objectives above. Hence, this essay will concentrate on water recovery policy in the Basin, and what is required to help meet these objectives in future.

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[6] For a recent analysis on the impact of drought and temperature on suicide in the MDB – see Xu et al. (2023).

Water Recovery Policy in the Basin

As a society going forward, there is a need for water to be ‘shared’ more effectively, with mitigation and adaptation encouraged wherever possible. It is important to understand where there is market failure and, given overallocation, we then need to work out the most effective way of returning water from consumptive to environmental/cultural/community use.

Given that climate change was not accounted for in the first Basin plan, and that there exist considerable arguments over whether a sustainable form of extraction has been achieved, coupled with the call for more cultural water (Alexandra, 2022; Grafton and Wheeler, 2018; O’Donnell et al., 2021), means that arguments over the need for more water recovery will continue.

Water can be recovered from consumptive uses through three primary methods - institutional; buyback; and irrigation infrastructure:

1. **Institutional changes (i.e., changing the rules of the game).** Includes resetting entitlements to a lower yield level, or changing rules over their use, hence changing existing property rights. Other changes could include having downstream flow targets needing to be met before extraction upstream, giving legal rights to rivers or having minimum river flow requirements (Alexandra, 2022; Young, 2019). If a strategy were chosen to cut allocations to entitlements across the board by the same percentage, two approaches (uncompensated vs compensated) could be chosen by states:
    - ***An uncompensated and permanent percentage cut to water allocations:*** Hence offering the environment a greater share to water resources. This scenario has happened in a number of places, for example, groundwater in the South-East of South Australia.
    - ***A compensated and permanent percentage cut to water allocations:*** This scenario happens regularly in other situations, such as compulsory land acquisition for transport infrastructure projects.
2. **Direct purchase of entitlements from willing sellers (‘Buyback’)**. This method protects existing property rights and includes:
    - ***A voluntary buyback of entitlements:*** This was the prime focus of the *Restoring the Balance program*, which is the program where most water has been recovered to date through voluntary offers of water by multiple sellers via an open tender process (Grafton and Wheeler, 2018).
    - ***A strategic buyback of entitlements:*** This involves strategic purchase of water entitlements via direct negotiation with the seller, a strategy that has only been occasionally used (DAWR, 2018). The 2017 purchase of Lower Darling entitlements from the Tandou property provide one such example.
    - ***Buying temporary water allocations:*** It is possible for the Commonwealth Environmental Water Holder (CEWH) to supplement environmental flows from permanent entitlements by buying water allocations in areas where needed. Using temporary trade – rather than permanent trade - has been shown to be preferred by many irrigators (e.g. Wheeler et al, 2013). However, to date trade has been used rarely (and CEWH are more likely to sell water allocations than buy them).
3. **Irrigation Infrastructure Subsidies/Modernisation**: This also protects existing property rights and includes on and off-farm programs:
    - ***On-farm subsidisation of irrigation infrastructure in return for water entitlements*:** This is the *Sustainable Rural Water Use Infrastructure Program*, where the most money to date has been spent, for the smallest amount of water recovered. On-farm projects include converting flood irrigation systems to drip irrigation systems or deepening on-farm storages to reduce evaporative losses. Some irrigation water recovery programs (e.g. in South Australia) allowed expenditure on other farm investments, beyond irrigation infrastructure.

- ***Off-farm subsidisation of supply projects to achieve environmental outcomes (or 'offsets'):*** Off-farm projects include lining delivery channels to reduce seepage or decommissioning underutilised parts of an irrigation network. The irrigation infrastructure operator provides a share of the saved water to the Australian Government, and the entitlements of irrigators are unchanged. Many have argued that very little environmental outcomes have been achieved to date, and significant issues surround existing projects (Colloff and Pittock, 2019; Williams and Grafton, 2020; Grafton and Wheeler, 2018). Non-irrigation infrastructure modernisation projects include environmental or other farm works that return water to the environment (such as the South Australian Riverine Recovery Project).

As we move towards the Basin Plan Review in 2026, it is important to consider all these policy options, and what must be implemented to achieve this essay's key overall objective: healthy environments and communities. The remainder of this essay makes three key water recovery and economic development policy points, namely:

1. Of all the policy instruments (institutional, buyback, modernisation), generally the most effective and efficient form for water recovery is **Buyback**.
2. The need to avoid policy instruments that have substantial unintended consequences (e.g., irrigation infrastructure subsidies).
3. To achieve healthy, resilient, and productive rural communities, proper structural and economic development policies are needed.

1. Of all the policy instruments, generally the most effective and efficient form for water recovery is Buyback

Of the three broad instruments outlined above, allowing for a voluntary buyback of water entitlements from willing irrigators represents the most effective and efficient method. A straight cut to water allocations across the Basin (uncompensated or compensated) technically is not as efficient, as it involves transfers from those who do not wish to participate. However, the efficiency of buyback can be challenged as compared to a straight water allocation cut across the board, if transaction cost issues are considered. For example, a straight regulatory cut could be implemented in one hit, causing significant upheaval for a number of years, but achieving the reallocation goal much sooner – as compared to a voluntary buyback situation where buying back over time can lead to rising opposition and successful attempts to block and change policy (all which happened when buyback was limited to a 1,500GL cap purchase in 2015 (Parliament of Australia, 2015)).

The *Restoring the Balance* buyback program has achieved notoriety in the MDB, with irrigators and rural communities regularly blaming the buyback of water entitlements for higher water prices, farm exit, and the subsequent decline of rural society – although these factors were found to be primarily caused by drought and worsening terms of trade for farmers (Wheeler et al., 2020b; Wittwer, 2011). Others find little relationship between water trade movements and regional economic indicators (Haensch et al., 2021). Wheeler (2022) provides a review of the water trade literature in the MDB, and summaries findings in the literature that water scarcity is the biggest driver of water prices (not water recovery programs).

Indeed, the economic scientific consensus is that water buybacks are the most effective, low-cost method of recovering environmental (community) water, resulting in the least impact on third parties (Productivity Commission, 2010; Dixon et al., 2011; Wheeler et al., 2012; 2013; 2014; 2023, Wheeler and Cheesman, 2013; Grafton and Wheeler, 2018).

Using data provided by the Department of Climate Change, Energy, the Environment and Water (DCCEEW) in late 2022, to date it has cost Australia just over $2,100 per megalitre (in long-term average annual yield equivalent (LTAAY)) to recover water through buybacks, and over $6,550 per LTAAY megalitre to recover through irrigation infrastructure subsidies. As of 30 June 2022, the total volume of water entitlements recovered to achieve environmental outcomes was 2,107.4 GL (MDBA, 2022). This represented 77% of the original 2,750 GL diversion target reduction in the Basin Plan. Around 64% of these water volumes were recovered through the *Restoring the Balance* buyback program, with the remainder achieved through infrastructure upgrades. Implicitly there is a cost differential of more than three times per megalitre for water recovered through infrastructure upgrades as compared to buyback.

This cost differential in water recovery methods will only worsen. The projects put forward by states are now quoting huge amounts – regularly figures over $20,000 per megalitre for water recovery are being asked (e.g. Ley, 2022). Allowing for return flows and other issues, the cost differential between the methods increases substantially (Williams and Grafton, 2020).

Strategic purchases of water have also been criticised due to their lack of transparency, potentially inflated values and negative environmental externalities (Seidl et al., 2020). Furthermore, a review has found that it is near impossible that the additional 450GL will be recovered in time (DAWE, 2021). On the 22nd February 2023 it was announced that open, competitive and transparent buybacks (up to 49 GL in total) over 7 targeted catchments in the Basin would open in March 2023. Commitments to feasible off-farm infrastructure and supply projects were still reinforced (Plibersek, 2023a). In August 2023, the Minister was formally recognising that water recovery targets of the MDB Plan would not be met, and that legislative change would be needed (both in amending timelines, and in allowing buybacks to be used for the recovery of the additional 450GL) (Plibersek, 2023b). Continual arguments by irrigator groups about how much it will cost to use buybacks to achieve water recovery targets often miss the point, especially in regards to a) the money that has currently been wasted on other supply and on-farm and off-farm projects for little (sometimes none) water recovery or offsets; and b) the alternative money that would need to be spent on other methods except buybacks to recovery the water.

2. The need to avoid policy instruments that have substantial unintended consequences (e.g., irrigation subsidies)

The intended, and unintended, consequences of water recovery policies need to be taken into consideration. As first summarised in Wheeler et al. (2020a), the main justifications put forward for subsidising irrigation infrastructure in order to recover environmental (community) water include: 1) *farm productivity*: increases farm productivity and income (Hughes et al., 2020; Perez-Blanco et al. 2020) and hence makes recovery more politically acceptable; and 2) *water quality*: upgrading irrigation infrastructure can reduce saline return flows into the rivers (Wang et al., 2018). On the other hand, the negative consequences of irrigation infrastructure subsidies include:

- *Cost – actual direct recovery and transaction costs*: as noted – subsidies cost at least three times more per dollar per megalitre recovered, compared with buyback (Grafton and Wheeler, 2018), partly because of the increased transaction costs of subsidy programs.
- *Governance*: irrigation infrastructure programs have been plagued with a lack of transparency, with some schemes subject to corruption charges (e.g., Victorian Ombudsman, 2011).
- *Return flows – additionality issue*: reduces seepage into groundwater and flows to streams and rivers and hence there is a percentage of environmental water that is 'double-counted' in the system – namely it was already available for the environment and does not represent additional total environmental water (Williams and Grafton, 2020).
- *Rebound effect on irrigated land area*: rising water values from upgraded irrigation infrastructure often increases the area of land under irrigation or the area of land growing

crops, potentially increasing water extractions (Wheeler et al., 2020; Perez- Perez-Blanco et al. 2020). For example, in Perez-Blanco et al's (2020) review, they found that water consumption increased in 83% of the studies, and also found a positive correlation between income and water consumption in 87% of the 134 case studies analysed. The higher income followed the increased benefits from increasing irrigation or changing crops. Note: these are private level farm benefits, but not necessarily community level benefits if irrigation and water consumption increase, especially in a closed or capped system.

- *Utilisation*: increased utilisation of water entitlements and allocations (Wheeler et al. 2014; Perez- Blanco et al. 2020). In the context of the MDB, this is a salient issue, given that surface and groundwater are often interconnected – yet accounted for and regulated quite separately (Wheeler et al., 2021).
- *Substitution*: groundwater substituted for surface-water (Wheeler et al., 2021).
- *Equity*: benefits are not evenly spread, with large corporate entities having a much higher probability of securing irrigation subsidies over family farms (Wheeler et al. 2020a). In addition, the amount paid per ML varied considerably in irrigation infrastructure programs, with some farmers paid very little.
- *Floodplain harvesting*: some programs (e.g., Healthy Headwaters program in Queensland) fund new dams (or fund dam walls to be raised), with the aim of not increasing capture but reducing evaporation in existing take. However, there is no monitoring to check if increased take occurs, with existing evidence suggests that increased water diversion has happened (Four Corners, 2019; Slattery et al., 2019).
- *Resilience*: changing the value of water – coupled with changes in output prices, this can encourage a shift towards higher value and more water intensive crops – as due to modernisation there is now more things that can be done. This therefore increases the incentive to convert from annual production to permanent crops, increases both electricity costs and demand for water during drought (Wheeler et al., 2018; Perez-Blanco et al. 2020)) and reduces community resilience. High electricity costs have been shown to be a key contributor to stress within rural communities (Wheeler et al., 2018). Perennial production reduces flexibility to adapt to climate change or drought, given plant assets need to be kept alive to avoid substantial capital loss.

It should be noted that there are at least 13 different irrigation infrastructure programs to recover water across states that were funded through the *Sustainable Rural Water Use Infrastructure Program.* They all contain differing criteria, objectives, budgets, and methods/activities allowed. At least one of these schemes – the SA River Murray Sustainability Program – allowed for other (non-irrigation infrastructure) farm activities to be subsidised instead. For example, irrigators could use the money to subsidise various farm productive activities (e.g., netting fruit/nut trees), and transfer some of their water entitlements as part of the program. There is the strong potential that such programs may have less unintended consequences on water extraction and water behaviour than other irrigation infrastructure programs (e.g. the Healthy Headwaters program noted above).

However, even in such programs as the example above, there are still rules about what farmers can spend the money on, and hence farmers cannot simply choose the option that suits them the most (e.g., they may prefer to claw back debt, or provide for farm succession, or invest in off-farm activities). Buying water directly back from farmers allows farmers total freedom in investing the money as they desire – hence – this implicitly maximises social welfare. Arguments regarding the impact of buyback on the rural community ignore real world evidence, and over rely on studies that have minimal internal and external validity (Wheeler et al., 2023).

As outlined by Wittwer and Young (2020), the problem with infrastructure upgrades is that they seek, with a single instrument, to address two policy objectives at once, namely water recovery and to maintain jobs and incomes within the Basin. However, it is much more efficient to use separate policies to address each objective, as discussed further next.

3. To achieve healthy, resilient and productive rural communities, proper structural adjustment and economic development policies are needed

As Wittwer (2019) outlines, when designing rural water policy, the following factors must be considered:

1) Irrigated farming in the MDB only represents around a third of all agricultural output – hence dryland agriculture provides a greater share of GDP.
2) Drought has a much larger impact on MDB farming output than water recovery or recovery through buyback itself – but it is common for buybacks to be blamed for drought and other impacts.
3) For every dollar 'lost' in irrigation output, there is an increase in dryland production value of about half a dollar – hence it is not a 'zero-sum' calculation.
4) Irrigation infrastructure subsidies have little multiplier or economic impact within the economy, if money was spent on social services (rather than, for example, drip irrigation) it would generate up to four times more jobs (Wittwer 2019; Wittwer and Young 2020).

Within the Basin, downstream processing of food and beverage products accounts for around 5.5% of the income base, with approximately 75% of the income base in industries other than agriculture and downstream processing. A healthy and resilient community and their quality of life depends on adequate access to services such as health, education, childcare, utilities, aged care, roads, internet connectivity and recreation. Reduced provision of essential services places people in rural communities at a disadvantage relative to other regions (Wittwer and Young, 2020).

Wittwer and Young (2020), in an updated version of the TERM-H2O CGE model, modelled investing $4 billion over five years in irrigation infrastructure upgrades in the MDB between 2020 and 2024 to procure around 500 GL of water for the environment. The results indicated a net present value (NPV) welfare loss of almost $1.8 billion, although jobs will increase as a result of this investment (compared to a no investment scenario). The investment in upgrades increases jobs in the Basin by around 1,000 relative to no investment for each of the five years of upgrades. Thereafter, Basin jobs increase by around 100 relative to no upgrades, based on estimated productivity gains arising from the upgrades. Hence, the irrigation infrastructure subsidies increased jobs.

However, the study also indicated the opportunity cost of this investment in infrastructure, relative to spending on other public services. For example, the marginal impacts of increased public spending of $4 billion over ten years on essential services in the Basin would create four times as many jobs as spending on infrastructure upgrades. Namely, jobs rise relative to the no investment scenario by between 1,800 and 2,100 over the decade of additional spending. The NPV of the welfare loss is $0.13 billion.

The key point is that putting money in rural activities such as subsidising irrigation infrastructure really only creates **short-term jobs**, versus investing in essential social services like roads, childcare, education, health, telecommunications etc, that creates more **long-term jobs**. In terms of enhancing farmer productivity, policies that encourage adaptation, reward farmers for provision of public goods and build farmer social and financial capital will also help. In addition, increased public policy agricultural research (and extension) that investigates (and facilitates) ways of coping with climate change is essential given declining research and extension dollars over time.

Recent work (Wheeler et al., 2023) established an internal and external ranking validity method to judge quality of water economic studies conducted in the MDB. Key findings suggested that studies that have been used as showing evidence of significant socio-economic harm from water recovery (e.g. consultancy studies using methodologies such as input-output analysis or basic assumptions/scenarios) – have very little reliability and are all ranked as low quality, **hence should not be relied upon for policy decisions**. The broad assumption that a 1% decrease in water allocations equals a 1% reduction in production, with assumptions linked to other socio-economic consequences is just plain wrong, and misleading.

Hence, prioritising irrigation subsidy programs over buybacks for water recovery can be viewed as a short-term strategy to address political risk and the preferences of powerful vested interests, rather than a policy to create healthy, resilient rural societies (Grafton and Williams, 2020). Indeed, buyback as a policy has a lot more support from irrigators than is recognised (Loch et al, 2014), as evidenced by the number of farmers in late 2022 that approached and tried to sell water to the Commonwealth. The March 2023 open tender will provide more indication on the current depth of willingness to sell water to the Commonwealth. Irrigation infrastructure subsidy programs may ultimately cause significant, long-term negative effects – especially within prolonged drought scenarios and a more volatile climatic future driven by climate change.

Structural adjustment policies in the Basin

The aim of structural adjustment policies is to improve growth in targeted areas by helping existing firms to expand their businesses, or by attracting new firms, often in the context of major cultural or social transitions. Evaluation of the success of such programs is often difficult, and questions are frequently raised regarding transparency, fair assessment, pork-barrelling, displacement of activities and hence social deadweight loss (Falck et al., 2019; Grafton and Williams, 2020).

To date, there has been four structural adjustment proxy programs implemented in the MDB since water recovery began. These include:

- ***The Strengthening Basin Communities Program*** (2009-2011 with $200 million allocated): aimed to mitigate the effects of water reallocation and help communities adjust to a future with less water, using funding to promote regional economic diversification. Contained a water planning and water saving component. Around 100 projects funded. Productivity Commission (2020) noted that $64m had been spent as of 2020.
- ***South Australia River Murray Sustainability Program*** (2013 onwards) with $25 million allocated): aimed to increase economic diversification and adjust to a water constrained environment (Productivity Commission 2018).
- ***Murray-Darling Basin Regional Economic Diversification Fund*** (2013 onwards to June 2019 ($73 million): this program is being administered by the Australian Department of Infrastructure, Regional Development and Cities to fund projects selected by Basin States, with aims to increase economic diversification and adjust to a water constrained environment, for the states of Qld, NSW and Victoria.
- ***Murray-Darling Basin Economic Development Program*** (2019–2023 with up to $73 million allocated): Assist eligible communities to develop their economies, increase job opportunities and enhance their resilience to manage economic challenges, administrated by DCCEEW (Sefton et al., 2020).

There has not been that much evaluation of the success of such programs, although the Australian National Audit Office (2014) found a lack of clarity regarding eligibility requirements, along with the need to appropriately document decisions relating to the assessment and selection of applications. A Senate Select Committee on the Multi-Jurisdictional Management and Execution of the MDB Plan (2020) report also criticised how money was allocated within the schemes and questioned the checks and balances around whether the money was used wisely. The Productivity Commission (2018) and Sefton et al. (2020) found little evidence that the transition assistance provided through these programs was well targeted or helped in transition through Basin water reforms. Upon evaluation of where the money had been spent, it was found there had been expenditure in areas outside the Basin.

It is clearly evident that there is considerable room for improvement in rural development and structural adjustment programs within the MDB. Indeed, in an era of climate change and falling water availability, further rationalisation of irrigation areas will need to be increasingly considered, with perhaps large amounts of area removed from the system. This will require an understanding of the best way to facilitate this – which will then mandate the need for proper structural adjustment and regional community packages – not band-aid or pork-barrelling programs.

So, what is required moving forward?

Much has been written about regarding next steps for water policy in the MDB. As summarised in Wheeler (2022), what is clear is that policy must focus on both meta-governance institutional as well as specific water recovery, policy reforms.

Institutional reform recommendations include items such as: paying greater attention to monitoring, detection and enforcement; understanding substitutability between ground and surface water resources; estimating historical and current water extraction (and consumption) information from satellite and thermal imaging; water pricing; water accounting; stronger water resource plans; rationalisation of existing irrigation regions; greater water banking investigation; a reinstated National Water Commission; a Water Market Information Platform; and the establishment of an independent Water Markets Agency. Walker (2019) provides further recommendations.

Continued focus is essential to ensure water governance structures are strong, and that monitoring, compliance and enforcement are followed by all states – otherwise there is a real danger of further reduced environmental sustainability. It must be noted that there are some welcome recent efforts to improve governance – such as the Parliament of Australia (2021) passing legislation to establish the Office of the Inspector-General (IG) of Water Compliance, aimed at strengthening compliance and enforcement powers in the MDB by creating new water theft and illegal water trading offences and penalties. The Natural Resources Access Regulator in NSW (formed in 2018) is also leading the way with combining both satellite imagery for potential detection of offences with on-the ground investigation. Scaling up these investigative activities into a Basin body (whether it be the IG or a reinstated National Water Commission) is an idea worth considering. Carmody and Chipperfield (2021) argue that factors such as how the IG chooses to exercise its discretion; resources allocated to the office; and its ability to remain independent will determine its future success in policing water extraction and policy in Australia. The rise of greater legal rights for rivers may also force a revision of how we allocate water in our river systems, and the insights of Young (2019) will be valuable to consider. Current ongoing work (Seidl and Wheeler, 2023) has also made a number of water compliance recommendations regarding: 1) improving compliance data and reporting; 2) increasing the probability of detection and prosecution; and 3) increasing penalties and reforming legislation.

Water recovery policy reform includes moving away from off-farm and on-farm subsidisation of irrigation infrastructure as a means to recover water (plus the removal of other inappropriate subsidies causing negative externalities). Alternative choices that may need to be on the table include mandatory cuts to water allocations across the board (compensated and uncompensated). Voluntary buyback will be preferred by many farmers as an alternative to such a policy. It is likely that the recent open buyback tender in March 2023 will see many farmers offering to sell water to the government. Reduction and/or consolidation of some irrigated areas and districts will also need to be considered, along with facilitating appropriate farm exit.

A decoupling of economic development and water recovery programs as one policy instrument is clearly required, which will involve much more investment in MDB regional essential services, as well as more targeted, open, and transparent economic regional adjustment and development funding.

Finally, but most importantly, policy reform will need to address two most pressing issues: 1) allowing for climate change in the Basin Plan; and 2) the need to reallocate water for cultural reasons. Hardwig et al. (2020) found water ownership by Aboriginal entities represented just 0.2% in the NSW segment of the MDB, while Jackson et al. (2019) revealed there is a strong public willingness to support reallocating more water to indigenous stakeholders. Along with dealing with climate change, this will be the next significant challenge facing water reallocation efforts in the MDB.

My vision of the Basin in fifty years' time

Hard choices will need to be made regarding water policy in the future, as well as many trade-offs between competing demands. Water will be required to be shared, creating 'new' water sources will be expensive – and limited primarily to recycled water management and desalination in urban settings – although we will probably see increased use of small-scale desalination units for groundwater in high value agricultural industries, and also more managed aquifer recharge schemes used for water storage purposes.

In rural settings, greater competing demands for water, along with increased value given to environmental and cultural uses of water, will mean that further sharing and adaptation to a hotter and more variable future will be essential. It is hoped that such hard choices will mean a more sustainable environment, as well as greater equity for all stakeholders and water users in the MDB. Environmental (namely community) water provides benefits to all Australians.

As a community, if we focus on using the most effective and efficient policy in recovering water (namely buyback of entitlements from willing sellers) and invest in the optimal way to improve rural community viability (though both valid structural adjustment programs and funding ongoing critical social services), this remains our best chance to succeed in obtaining a healthy, resilient, and sustainable MDB for all.

In fifty years' time, the Basin must adapt to a reduced irrigation footprint (in terms of land and extraction overall) and a consolidated irrigation industry – yet an industry that I hope is even more productive and profitable, with better mental health and still world leading, with a reduced level of farm exit. With proper economic assistance, and appropriate rural community investment and environmental policies, rural communities will hopefully be more viable – and areas where people will choose to live.

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