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**

*Above: The Darling river at Bourke in drought conditions.*
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## 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).

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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.

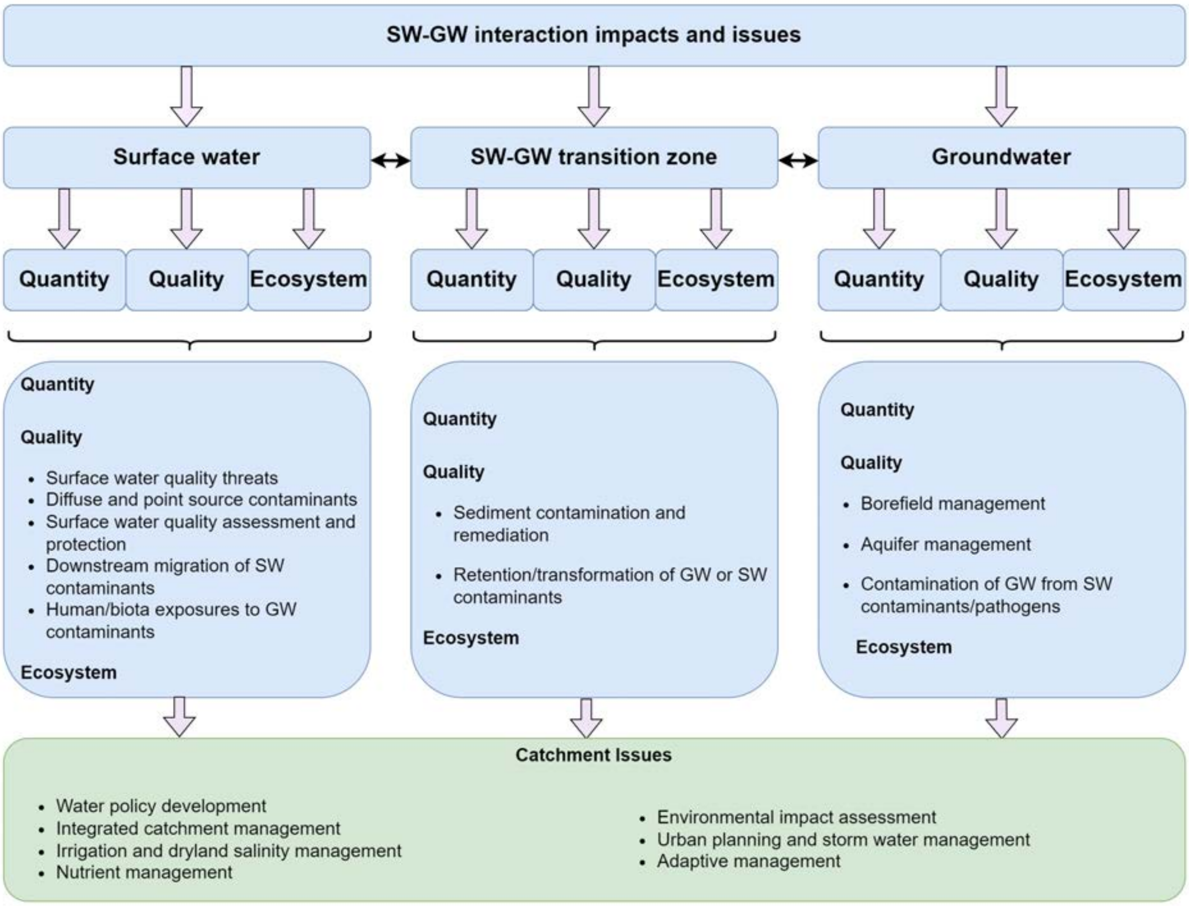

Figure 2: Framework for SW-GW interaction impacts for the MDB, with a focus on water quality (adapted from Conant, Robinson et al. 2019)

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.

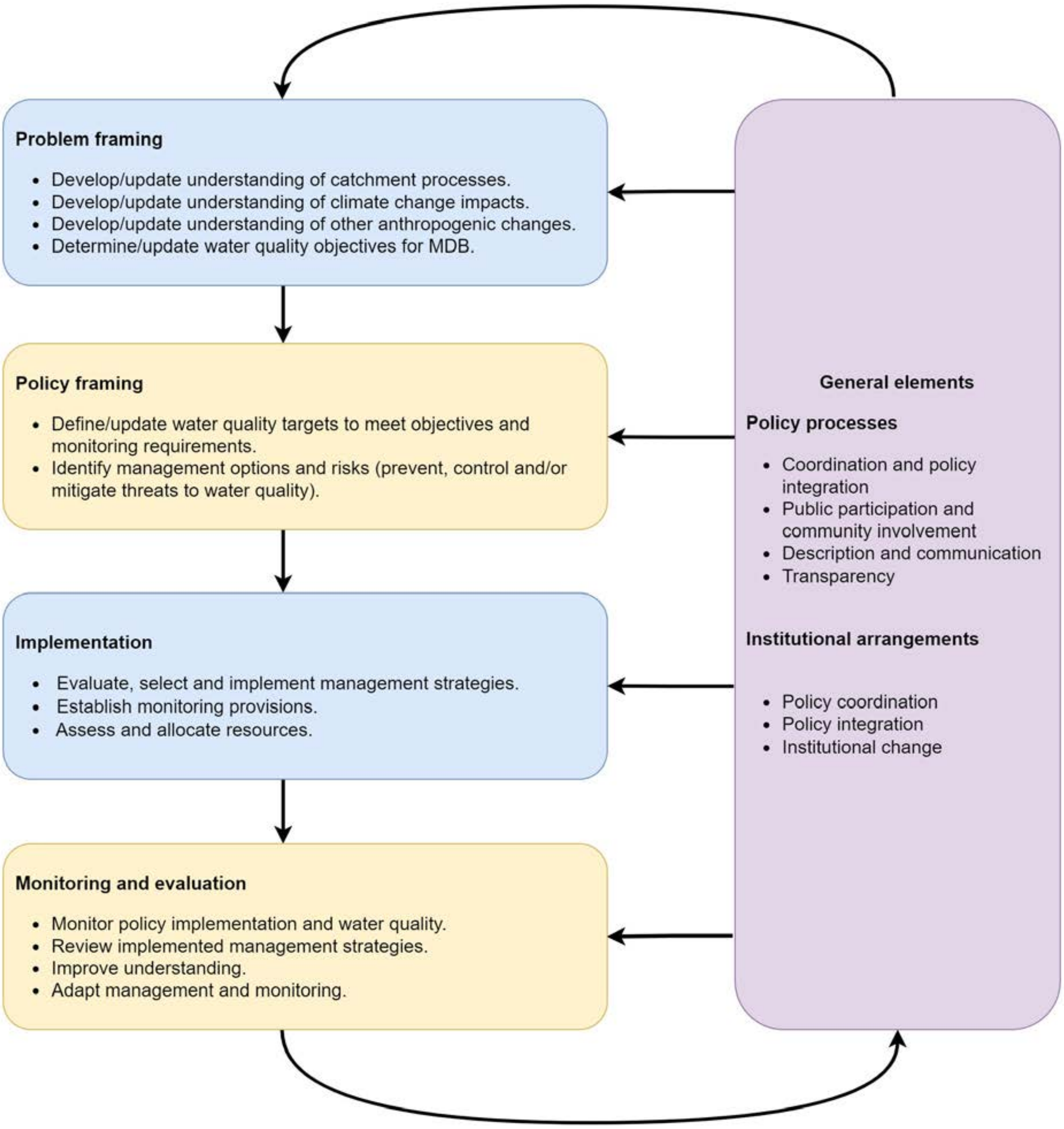

Figure 3: Simplified water quality policy framework for the MDB (adapted from Bennett 2008, Dovers and Hussey 2013)

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).<br>• DO >50% saturation. |
| Water Resource Plans (States) | • Irrigation infrastructure salinity targets 95% of the time over a 10-year period.<br>• Sodium adsorption ratio < that which would cause soil degradation.<br>• Water dependent ecosystem targets for 21 Target Application Zones for turbidity, Total Phosphorus, Total Nitrogen, DO, pH, temperature, pesticides, heavy metals, other contaminants.<br>• 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.

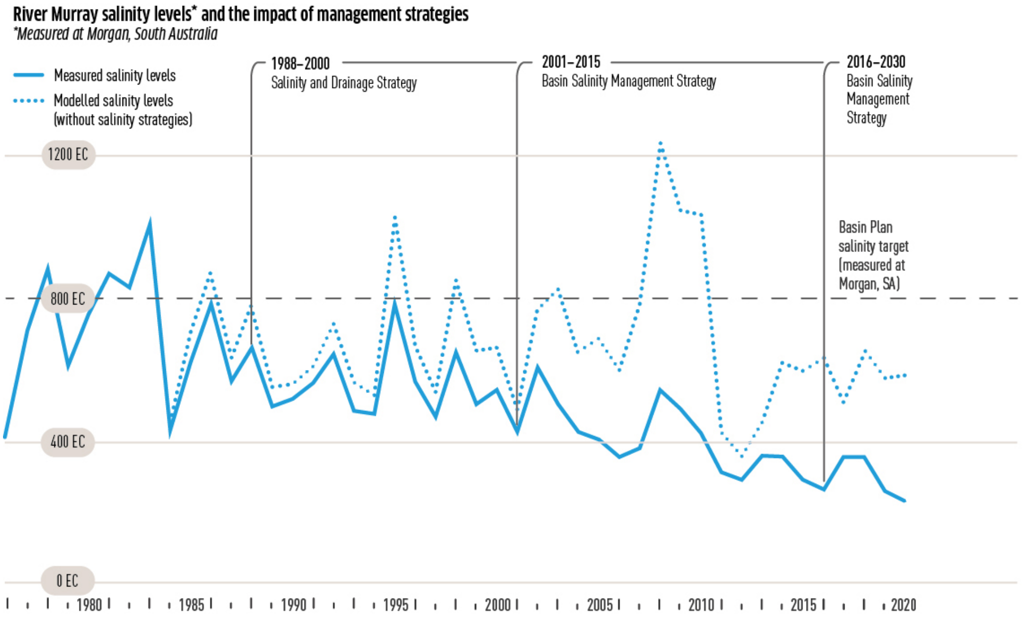

Figure 4: Decreasing salinity in River Murray at Morgan, measured in Electrical conductivity (EC) units (MDBA 2020a) [Licensed under a CC BY 4.0]

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.<br>Extent: Wilcannia Weir Pool to Mungindi.<br>Species: *Anabaena circinalis* (now renamed *Dolichospermum circinale*).<br>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.<br>Extent: Lake Hume to Corowa.<br>Species: *Anabaena circinalis, Anabaena flos-aquae, Aphanocapsa sp, and Cylindrospermopsis raciborskii.*<br>Toxins: No details. | (Baldwin, Wilson et al. 2010) |
| 2009 | >1,000 km Murray River and tributaries | Timing: Early Mar 09 to early May 09.<br>Extent: Lake Hume to upstream of Euston.<br>Species: *Anabaena circinalis, Microcystis flos-aquae,* and *Cylindrospermopsis raciborskii.*<br>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.<br>Extent: 500 km in Murray and Edwards rivers, with a small package of bloom infested water moving downstream for 650 km.<br>Species: *Anabaena circinalis.*<br>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.<br>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.<br>Species: Chrysosporumovalisporum occurred for the first time in these rivers.<br>Toxins: No measurable toxins. | |
| 2017/18 | | "Widespread blooms, especially in the Lower Darling".<br>No further details. | MDBA (2020a) |
| 2018/19 | Menindee Lakes and Lower Darling River | Timing: Nov 18 to Jan 19.<br>Extent: Menindee Lakes and 40 km in Lower Darling River.<br>Species: *Dolichospermum circinale*<br>Toxins: No details.<br>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<br>Extent: Lower Darling River for 600 km.<br>Species, Toxins: No details.<br>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**<br>High salinity adversely impacts drinking water quality, agricultural production, ecosystems, infrastructure and industries requiring good quality water (MDBA 2022).<br>Salinity occurs naturally in groundwater, which is mobilised by irrigation, land clearing (dryland salinity) and mining.<br>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).<br>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.<br>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.<br>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**<br>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.<br>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.<br>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.<br>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**<br>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).<br>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.<br>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.<br>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**<br>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.<br>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**<br>Temperature variations in rivers resulting from summer heatwaves warming low flows or cold water released from dams harm river fauna and flora (MDBA 2022).<br>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).<br>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.<br>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.<br>Higher water temperatures will increase consequential threats including toxic cyanobacterial blooms and blackwater events (see below).<br>Higher temperatures will also increase the potential for pathogens. |

| Water quality issue | Predicted threat to MDB water quality and implications |
|---|---|
| **Low DO levels**<br>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**<br>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.<br>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.<br>Under climate change conditions the concentration of cyanobacterial toxins in waterways is expected to increase (Reichwaldt and Ghadouani 2012).<br>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.<br>Baldwin (2021) identified the need for detailed three-dimensional hydrodynamic models for large MDB wter storages to help manage and prevent blooms. |
| **Blackwater events**<br>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).<br>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.

## References

Al-Tebrineh, J., et al. (2012). "Community composition, toxigenicity, and environmental conditions during a cyanobacterial bloom occurring along 1,100 kilometers of the Murray River." *Applied and environmental microbiology* **78**(1): 263-272.

ANZECC ARMCANZ (2000). Australian and New Zealand guidelines for fresh and marine water quality. *Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra*. **1**: 1-314.

Azevedo, S., et al. (2002). "Human intoxication by microcystins during renal dialysis treatment in Caruaru-Brazil." *Toxicology* **181**: 441-446.

Baldwin, D. S. (2021). Water quality in the Murray–Darling Basin: The potential impacts of climate change. *Murray-Darling Basin, Australia: Its Future Management*, Elsevier: 137-159.

Baldwin, D. S., et al. (2010). "Influence of extreme drawdown on water quality downstream of a large water storage reservoir." *River Research and Applications* **26**(2): 194-206.

Beavis, S. G., et al. (2023). "Water quality risks in the Murray-Darling basin." *Australasian Journal of Water Resources:* 1-18.

Bellamy, J., et al. (2002). "Integrated catchment management: Learning from the Australian experience for the Murray-Darling Basin." Brisbane: CSIRO Sustainable Ecosystems. January. 2002

Bennett, J. (2008). Final discussion paper on implementation of the National Water Quality Management Strategy (NWQMS). Canberra, Australia, Australian Government, Department of the Environment, Water Heritage and the Arts.

Biswas, T. K. and L. M. Mosley (2019). "From Mountain Ranges to Sweeping Plains, in Droughts and Flooding Rains; River Murray Water Quality over the Last Four Decades." *Water Resources Management* **33**(3): 1087-1101.

Blackmore, D. (1995). "Murray-Darling Basin Commission: A case study in integrated catchment management." *Water Science and Technology* **32**(5-6): 15-25.

Bowling, L. and P. Baker (1996). "Major cyanobacterial bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions." *Marine and Freshwater Research* **47**(4): 643-657.

Bowling, L. C., et al. (2013). "Effects of hydrology and river management on the distribution, abundance and persistence of cyanobacterial blooms in the Murray River, Australia." *Harmful Algae* **30**: 27-36.

Bureau of Meteorology (2020). Trends and historical conditions in the Murray-Darling Basin. A report prepared for the Murray-Darling Basin Authority by the Bureau of Meteorology. Bureau of Meteorology: Melbourne, Australia, 18pp.

Bursle, E. and J. Robson (2016). "Free living amoebae and human disease." *Microbiology Australia* **37**(1): 20-24.

Bycroft, B. (2017) Better practice catchment water planning for Australia. *Water e-Journal. Online Journal of the Australian Water Association* **2**, 11 DOI: org/10.21139/wej.2017.027

Carmichael, W. W., et al. (2001). "Human fatalities from cyanobacteria: Chemical and biological evidence for cyanotoxins." *Environmental Health Perspectives* **109**(7): 663-668.

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

Clune, T. and M. Eburn (2017). "Blue green algae in the Murray Darling Basin: a case for Commonwealth leadership." *Australian Journal of Emergency Management* **32**(3): 46-51.

Colloff, M. J. and J. Pittock (2022). "Mind the Gap! Reconciling Environmental Water Requirements with Scarcity in the Murray–Darling Basin, Australia." *Water* **14, 208**: 16pp

Conant, B., et al. (2019). "A framework for conceptualizing groundwater-surface water interactions and identifying potential impacts on water quality, water quantity, and ecosystems." *Journal of Hydrology* **574**: 609-627.

Crawford, A., et al. (2017). "Use of three monitoring approaches to manage a major Chrysosporum ovalisporum bloom in the Murray River, Australia, 2016." *Environmental Monitoring and Assessment* **189**(4): 202.

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

DeRose, R., et al. (2003). Patterns of erosion and sediment and nutrient transport in the Murray-Darling Basin. Technical Report 32/03, CSIRO Land and Water, Canberra.

Dovers, S. and K. Hussey (2013). Environment and sustainability: a policy handbook. Sydney, Australia, The Federation Press.

Evans, M. C. (2021). "Re-conceptualizing the role(s) of science in biodiversity conservation." *Environmental Conservation* **48**(3): 151-160.

Evans, M. C., et al. (2017). "Embrace complexity to improve conservation decision making." *Nature Ecology & Evolution* **1**(11): 1588-1588.

Grafton, R. Q. (2021). "Policy review of water reform in the Murray–Darling Basin, Australia: the “do’s” and “do’nots”." *Australian Journal of Agricultural and Resource Economics* **63**: 26.

Grose, M., et al. (2021). Regional Fact Sheet Australasia. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani et al. Cambridge, United Kingdom, Cambridge University Press.

Hart, B. T. (2016). "The Australian Murray-Darling Basin Plan: challenges in its implementation (part 1)." *International Journal of Water Resources Development* **32**(6): 819-834.

Huisman, J., et al. (2018). "Cyanobacterial blooms." *Nature Reviews Microbiology* **16**(8): 471-483.

IPCC (2022). Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P. R. Shukla, J. Skea, R. Slade et al. Cambridge, United Kingdom and New York, USA.

Jochimsen, E. M., et al. (1998). "Liver failure and death after exposure to microcystins at a hemodialysis center in Brazil." *New England Journal of Medicine* **338**(13): 873-878.

Kingsford, R. (2023). How did millions of fish die gasping in the Darling - after three years of rian? *The Conversation*. 20 March 2023 Carlton Australia, The Conversation Media Group Ltd.

Lawrence, J., et al. (2022). Chapter 11 2022: Australasia. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change H.-O. Pörtner, D. C. Roberts, M. Tignor et al. Cambridge, United Kingdom, Cambridge University Press.

Mekonnen, M. M. and A. Y. Hoekstra (2015). "Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water." *Environmental Science & Technology* **49**(21): 12860-12868.

Mekonnen, M. M. and A. Y. Hoekstra (2018). "Global Anthropogenic Phosphorus Loads to Freshwater and Associated Grey Water Footprints and Water Pollution Levels: A High-Resolution Global Study." *Water Resources Research* **54**(1): 345-358.

Mobius, W. (2012). CS 037: Hypoxic Blackwater event in the River Murray following inundation of the Murray-Darling Basin, 2010-2011. Adelaide, Australia, SA Water: 10pp

Murray-Darling Basin Authority (2020a). The 2020 Basin Plan Evaluation.. C, Murray-Darling Basin Authority, Canberra, Australia 166pp

Murray-Darling Basin Authority (2020b). The 2020 Basin Plan Evaluation. Plan Implementation Evidence Report. December 2020., Murray-Darling Basin Authority: Canberra, Australia 186pp.

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

Murray-Darling Basin Authority (2022). "Water quality." Retrieved 1 April 2022, from https://www.mdba.gov.au/water-management/mdbas-river-operations/water-quality.

Murray-Darling Basin Ministerial Council (1994). The Algal Management Strategy for the Murray-Darling Basin. Murray-Darling Basin Commission Canberra, Australia: 33pp.

New South Wales Blue-Green Algae Task Force (1992). Blue-Green Algae. Final Report. D. o. W. Resources. Parramatta, Australia, Department of Water Resources: 193.pp

Prosser, I., et al. (2001). Constructing river basin sediment budgets for the National Land and Water Resources Audit. *CSIRO Land and Water Technical Report.* **15:** 2001.

Prosser, I. P., et al. (2021). "Adapting Water Management to Climate Change in the Murray–Darling Basin, Australia." *Water* **13**, 2504: 19.

Reichwaldt, E. S. and A. Ghadouani (2012). "Effects of rainfall patterns on toxic cyanobacterial blooms in a changing climate: Between simplistic scenarios and complex dynamics." *Water Research* **46**(5): 1372-1393.

RM Consulting Group Pty Ltd (2020). Review of water quality targets in the Basin Plan. Final Report, Murray-Darling Basin Authority., Murray-Darling Basin Authority: Canberra, Australia 108.

Stocks, J. R., et al. (2022). "Kills in the Darling: assessing the impact of the 2018–20 mass fish kills on the fish communities of the Lower Darling–*Baaka* River, a large lowland river of south-eastern Australia*." Marine and Freshwater Research* **73**(2): 159-177.

Svircev, Z., et al. (2019). "Global geographical and historical overview of cyanotoxin distribution and cyanobacterial poisonings." *Archives of Toxicology* **93**(9): 2429-2481.

Verhoeven, T. J., et al. (2023). Integrated cyanobacterial management at basin/catchment scale – addressing a significant global and Australian problem. New Water 2023. Sydney, Australia, Water Research Australia.

Vertessy, R., et al. (2019). Final Report of the Independent Assessment of the 2018-19 Fish Deaths in the Lower Darling. I. P. f. t. A. Government., Australian Governmen Canberra, Australia: 99pp.

Walker, G. and I. P. Prosser (2021). Water quality: Land use impacts on salinity, sediments, and nutrients. *Murray-Darling Basin, Australia. Its Future Management*, Elsevier: 109-135.

Wentworth Group of Concerned Scientists (2021). Wentworth Group Submission to the Productivity Commission, National Water Reform 2020, Draft Report. 24 March 2021. Available online: https://www.pc.gov.au/__data/assets/pdf_file/0005/274568/subdr152-water-reform-2020.pdf. Productivity Commission. Sydney, Australia: 8pp.

Whitworth, K. L. and D. S. Baldwin (2016). "Improving our capacity to manage hypoxic blackwater events in lowland rivers: The Blackwater Risk Assessment Tool." *Ecological Modelling* **320**: 292-298.

Whitworth, K. L., et al. (2012). "Drought, floods and water quality: Drivers of a severe hypoxic blackwater event in a major river system (the southern Murray-Darling Basin, Australia)." *Journal of Hydrology* **450**: 190-198.

Williams, K., et al. (2021). Australia state of the  environment 2021: land, independent report to the Australian Government Minister for the Environment. Commonwealth of Australia, Canberra, Australia.

Wilson, K. A., et al. (2009). "Setting Conservation Priorities." *Annals of the New York Academy of Sciences* **1162**: 237-264.

Young, W. J., et al. (2001). Modelling nutrient loads in large-scale river networks for the National Land and Water Resources Audit, CSIRO Land and Water.

Zhang, L., Chiew F., and Hatton T. (2024). Hydroclimate of the Murray-Darling Basin. In Radcliffe, JC and Flapper, T (2024) (Eds), *A Thriving Murray-Darling Basin in 50 years: Actions in the face of climate change*, Australian Academy of Technological Sciences and Engineering, Canberra ACT.

Zhang, L., et al. (2020). Plausible Hydroclimate Futures for the Murray-Darling Basin. A report for the Murray–Darling Basin Authority. CSIRO. Canberra, Australia. 34pp.