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MURRAY–DARLING BASIN AUTHORITY

The 2020 Basin Plan Evaluation

Vulnerabilities to climate change in the Murray–Darling Basin

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Contents

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Acknowledgement of the Traditional Owners of the Murray–Darling Basin
The Murray–Darling Basin Authority pays respect to the Traditional Owners and their Nations of the Murray–Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

The guidance and support received from the Murray Lower Darling Rivers Indigenous Nations, the Northern Basin Aboriginal Nations and our many Traditional Owner friends and colleagues is very much valued and appreciated.

Aboriginal people should be aware that this publication may contain images, names or quotations of deceased persons.

Introduction

Climate science for the Murray–Darling Basin now predicts with a high level of confidence that temperatures will rise and, in the southern Basin, winter rainfall will decline. Projected reductions in water available for consumptive use and environmental flows are exacerbated in several ways by the other impacts of climate change, in particular:

- Increased variability (longer droughts, more intense wet periods, other extreme events) will challenge water users and ecosystems to sustain themselves at low levels of water availability for longer and to adapt to the impacts of more extreme weather events.
- High evapotranspiration rates mean that there will be less water in the landscape with more water being required to irrigate crops effectively.
- Water quality issues, particularly salinity and black water events, are expected to be more prevalent, reducing the fit for purpose nature of water supplies, and impacting communities, industry and the environment.

These changes mean that the environments, industries, businesses and communities that have depended on the historical hydrology of the Basin for their development and survival must also change.

The MDBA is initiating a program to support adaptive water management in the Murray–Darling Basin. The vulnerability assessment presented in this report is part of the first phase of this program. This assessment will be used to target more detailed work on: the implications of a changing climate for the Basin Plan objectives; to understand how to stay on track to achieve the objectives, and where they may need to be re-examined in the face of climate uncertainty, and; where effort is required to develop policy and management options to increase adaptive capacity. This work will contribute to ongoing adaptive water management across the Basin and build the evidence base to inform the legislated review of the Basin Plan in 2026. The MDBA will be working with the community, state partners, water representative bodies and scientists.

This report sets out the results of a high-level qualitative scan of how Basin Plan objectives relating to Basin communities, water-dependent industries, water markets, ecological outcomes and First Nations people may be vulnerable to the impacts of climate change. The assessment used different methods to appropriately scan for vulnerabilities in each of these themes at the Basin-scale using the available evidence and in consultation with relevant experts.

The results of this assessment are presented along with the preliminary identification of research, water management and policy development needs that have emerged when considering the factors underling vulnerabilities and adaptive options. However, these suggestions are based on a single line of evidence (this assessment) and will be considered in conjunction with other work being undertaken to inform the design of the MDBA's climate change work moving forward.

The MDBA's assessment of vulnerabilities, guided by the Climate Compass framework, was a high - level scan; and therefore had the following limitations:

- Vulnerabilities were often assessed at a macro-level, with readily available information. Further consultation on the results of this high-level assessment are expected to be conducted in the next stages of the MDBA’s climate change program; and will inform more detailed assessments of priority cultural, social and economic vulnerabilities.

- This assessment does not consistently capture the significant spatial differences in vulnerability experienced across the Basin. Climate science information at finer spatial scale is being developed by CSIRO and will inform impacts and vulnerabilities at the local scale in the next stage of the MDBA’s climate change program.
- Cultural vulnerabilities and those socio-economic vulnerabilities experienced by First Nations of the Basin were assessed at a very high level. This approach was undertaken with respect to cultural sensitivities; and the consultation already occurring on the development of water resource plans. In the next stage of the MDBA’s climate change program, a more detailed assessment should be undertaken, designed and led by First Nations themselves so as to be culturally appropriate, with support from the MDBA.
- The vulnerability of the MDBA’s River Murray operation was excluded from this assessment. A more detailed vulnerability assessment of the MDBA’s River Murray operations will be undertaken in the next stage of the MDBA’s climate change work program, in consultation with the Joint Venture arrangements. This will require specific climate change scenario data and modelling and will need to be sequenced once this prerequisite work is completed.

Effective climate adaptation will require a multi-agency and multi-disciplinary approach. State water agencies have already invested significant time and energy into climate adaptation, and industry groups are continuing to build momentum towards on-ground climate adaptation and future climate response. The MDBA’s role will be to work with partners on a Basin-scale approach, and to help the wider community better understand the projected future climate as part of their preparations.

Socio-economic vulnerabilities

Assessment summary

The limited available literature on climate change vulnerabilities for irrigated industries, agriculture and Basin communities reveals that a changing climate will serve to increase the range of other pressures that Basin communities face. The recently released draft assessment report on the social and economic conditions in the Basin (ISEAP, 2020) notes that technological change, shifts in consumer demand, and changing trade patterns, along with climate change and water reform, have created a complex array of factors profoundly impacting business and communities in the Basin at a pace that is outrunning their ability to adapt.

The limited knowledge base of socio-economic impacts of climate change is a reality of the diversity of Australian regions, whose climates will vary, and whose local industries and communities will respond differently to these variations. The ongoing development of the information base about these changes will need to be at the local scale to ensure adaptation solutions are appropriate to their context and take account of the level of adaptive capacity in these places and communities.

Evidence suggests it is likely that larger regional centers and regional cities that are less dependent on irrigation and are better serviced and more connected to population centers outside the Basin, will be much more insulated from climatic changes, as they have been over the last two dry decades.

The largest irrigation districts of the Southern Basin are likely to be impacted by both the most significant predictions of reduction in local runoff (Bureau of Meteorology 2019), combined with water trade and likely high prices shifting more of the available water downstream towards irrigation areas with (current) higher value permanent horticultural plantings. Further contraction of the lower value irrigation activities which support key industries in these areas can be expected.

Analysis by ABARES found that when compared with the current market scenario, future water market scenarios are estimated to have allocation prices that are an average of 28% higher, and above $200 per ML in eight out of the ten years in the southern basin. Under even drier conditions, allocation pricess could be expected to be 50% higher on average than what is currently being seen in the market (Gupta, et al., 2020). While water supply is sufficient to meet estimated demand from horticultural plantings in all scenarios tested by ABARES, in practice there remains risk of supply shortfalls within each water year, particularly if future conditions are drier than modelled or trade constraints are tightened. The growth in water demand in the lower Murray, due to maturing almond trees, is also likely to lead to greater pressure for inter-regional water trade, more frequently binding trade limits and large differences in prices between catchments.

Water markets will also be challenged by climate change. As limits to trade become increasingly binding, governments will come under increasing pressure to further restrict or further free trade within the Basin from the different economic interests. The industry transitions predicted under the extreme dry climate change scenarios may threaten overall market stability and function.

In the Northern Basin, the outcomes are less clear as the impact on summer rainfall is less certain. However, the remote irrigation communities in south-western New South Wales and south-western

Queensland are amongst the most climate change vulnerable small and regional towns in Australia (Beer, et al., 2013). Smaller and more remote towns generally will find holding and growing their populations even more difficult in a drier, more extreme climate, undermining the sustainability and growth potential of their local and regional economy.

The social and economic objectives of the Basin Plan are largely dependent on the achievement of the ecological objectives, as functioning ecosystems providing a range of services and benefits to communities and industries to support a healthy working Basin. For example, maintaining connectivity flows throughout the river system maintains water quality by keeping contaminants mobile and flushing them from the system. In turn, good water quality supports fishing activities that provide social and economic benefits for communities (connection to Country for First Nations, and recreational and tourism activities). Poor water quality has significant technological and financial implications for potable water treatment and can be so poor as to remove its value for stock and domestic use. The water quality issues related to consumptive and recreational uses of water are explored in the ecological vulnerabilities section of this report.

The cost-benefit assumptions inherent in the Basin Plan rely heavily on the maintenance of ecosystem services over the coming decades to provide these cumulative benefits. However, the benefits will be compromised by prolonged dry periods with low flows, connectivity issues and relatively limited water available for environmental watering to enable maintenance or improvements in ecosystem services. The cumulative benefits to amenity, tourism, recreation and agriculture from ecosystem services are therefore also highly vulnerable.

Irrigation and other agricultural industries

The Basin Plan seeks to maintain water-dependent industries in the Basin by providing water that is fit-for-purpose for irrigated agriculture and enabling an efficient water market to give businesses greater flexibility and opportunities to better manage water availability risks. Ultimately, the Basin Plan seeks to support water-dependent industries in the Basin by provider greater certainty about water availability and maintaining the ecosystem services that underpin a healthy working Basin.

Climate change implications

Climate change presents a combination of challenges for irrigation in the Murray–Darling Basin. These challenges are particularly clear in the southern Basin where reduced winter rainfall in combination with a drier landscape leads to a reduction in the water available for consumptive use. Similarly challenging for irrigation businesses will be the concentration of rainfall in more extreme wet years combined with longer, more severe droughts. Less and more variable rainfall is likely to result in high water prices, compounding challenges for irrigators to sustain livelihoods. ABARES analysis suggests that 3% change in average rainfall results in 17% increase in temporary water market prices in the southern Basin (Gupta, et al., 2020). Along with decreased availability of water, there is potential for increased salinity levels and other sources of water quality degradation making water less fit for purpose.

The likely reductions in economic returns resulting from reduced water availability, increased salinity, increased evapotranspiration and increased extreme events in the southern Murray–Darling is revealing of the varying longer-term outcomes for irrigation in the Basin under climate change.

At a regional level, these changes in water availability lead to significant shifts in irrigation water use; recent experiences demonstrate this trend, where more of the available water is being traded to areas on the lower Murray to maintain horticultural plantings more able to support higher water costs.

Considering the on-farm and trade adaptation options available to irrigation industries, under relatively small reductions in availability the flow through implications for profits are fairly contained, as was seen in the millennium drought where large reductions in water availability led to more limited profit impacts. For example, during 2005-06 and 2007-08 water use decreased by 57% but the gross value of irrigated agricultural production fell by only 13% (ISEAP, 2020). However, under more extreme climate change scenarios large reductions in water diversions will result in similar or larger scale reductions in profit (Qureshi, et al., 2013). As the climate changes and intense dry periods become more frequent, larger scale reductions in profit for irrigation industries may occur as the consumptive water pool reduces.

This suggests the existence of tipping points in irrigation industries beyond which the environmental conditions and business costs driven by climate change (and flow through economic and social impacts for connected communities) would be beyond the ability for even large businesses in traditional irrigated industries to absorb, making the impacts much more severe than anything experienced in the last two decades of dry years. Past this tipping point, a radically different, opportunity based annual irrigation industry could emerge following a very challenging economic transition (Quiggan, et al., 2010).

These findings of alternative pathways, depending on whether adaptive capacity thresholds are breached, were also reflected in earlier work which modeled the impacts of reduced consumptive water availability in the Murray–Darling Basin:

> *Deterministic analysis suggests that as water becomes more scarce, the proportion of water allocated to horticultural crops should increase, since these are the crops which yield the highest ratio of output value to water input. A state-contingent analysis yields the opposite conclusion. Horticultural crops generally require a consistent supply of water. Climate change is associated with an increase in the frequency of droughts, when the shadow price of water is very high. The result is that the cost of securing a stable water supply for horticultural crops increases.*
>
> *The increased frequency of droughts leads to an expansion of 'opportunity cropping' activities, in which irrigation is used in years of high water availability and is replaced by dryland production activities in years of low water availability. In the model described here, opportunity cropping activities that use irrigation water in Wet and Normal states, but not in Drought states, tend to expand as a result of climate change*. (Quiggan, et al., 2010)

Taking these results together, it is clear that water policy, including the Basin Plan, will need to be capable of enabling the management of significant shifts in industry mix and in the scale of irrigated agriculture in regions as climate change reduces the water available for consumptive use.

In the near term, under existing arrangements, a continuation of the movement of water use down the southern Murray–Darling is likely, reducing the irrigation undertaken in key Victorian and NSW irrigation districts upstream and further exacerbating the current tensions between States and regions of the Basin. However, if global mitigation action has limited effects and variability becomes too extreme, reliably of supply to these permanent plantings in the lower parts of the Southern Murray–Darling will also be affected and water use may shift towards more opportunistic annual cropping and a very different industry mix in potential new geographic locations. This will challenge river operators to adapt to ensure water demands can be met in new patterns of use at new locations.

In considering the vulnerabilities of irrigated agriculture to climate change it is worthwhile to also note the wider impacts that a drier, more extreme climate will have for dryland agriculture as these are the opportunities that will become more important as irrigated agriculture contracts or changes in line with water availability.

A study (Crimp, et al., 2010) focusing on livestock industries identified that the key biophysical impacts associated with climate change in the Murray–Darling Basin (MDB) include:

- declines in pasture productivity
- reduced forage quality
- livestock heat stress
- greater problems with some pests and weeds
- more frequent droughts and more intense rainfall events
- greater risks of soil degradation.

Recently released ABARES work brings together evidence of change in cropping and beef industries over the last two dry decades:

> *Controlling for non-climate factors, we find changes in climate since 2000 have reduced average annual broadacre farm profits by 22%, or around $18,600 per farm.*
>
> *While beef farms have been less affected overall, with a reduction in average profits of 5%, some beef farming regions have been affected more than others, particularly south-western Queensland.*
>
> *Cropping farms generally face greater climate risk than beef farms, while mixed-cropping livestock farms sit in-between these extremes. There is a trade-off between risk and return: cropping farms face higher risk but also generate higher average returns.*
>
> *There is also strong evidence of adaptation and management practice change helping to reduce the sensitivity of farms to dry conditions over time which have reduced the impact of a drier climate in the last two decades.* (Hughes, et al., 2019)

This evidence emphasizes that the economic pressures within irrigated industries are also being experienced in the wider agricultural sector in Australia. These will place Basin communities under additional pressure as the sector adapts to change.

In terms of agricultural productivity in the Northern Basin, the outlook is much less clear. Nearly all the work to date has focused on modelling Southern Basin outcomes. In the North, uncertainty about the trends in summer rainfall under different climate change scenarios as well as the largely unregulated rivers makes it more difficult to assess likely trajectories for agricultural industries, and irrigated agriculture in particular. This is a significant gap in understanding the likely outcomes for consumptive water use in the Basin as the climate changes.

Knowledge, management and policy implications for irrigation and other agricultural industries

Understanding what impacts climate change will have on water availability in the context of different climate change scenarios will greatly assist water-dependent industries to make informed business and investment choices; and will help communities plan for and adapt to the uncertain changes climate change will bring. Supporting this adaptive capacity will help ensure the Basin Plan's objectives of viable Basin industries and communities is progressed.

It will also be important to ensure that policy and management mechanisms are sufficiently flexible to avoid creating barriers to adaptation and instead support efforts to adapt in a timely way. Testing water management frameworks and instruments for their suitability and performance under different climate change scenarios and ensuring relevant statutory plans are updated and have regular review points to consider new information will be important. This work should also inform risk management approaches, to ensure strategies to address climate uncertainty are relevant and working.

These arrangements will be particularly important to understand at a catchment scale so that the likely changes in local conditions are reflected in local rules and arrangements and involve Basin communities in informed decision-making regarding the trade-offs that will likely need to be made.

Understanding the ecosystem services that support water-dependent industries will also help to better manage climate impacts, including where improvements in farming practices could better protect these services such as as soil and floodplain productivity and boosting populations of pollinating species.

Water trade

The socio-economic objectives of the water trade provisions under the Basin Plan are to support operationally efficient water markets, minimise transaction costs and support the availability of a range of water products in the market. This is achieved by the Basin Plan's water trade components requiring adjustment of State trading arrangements to:

- address significant restrictions on surface water trade, for both entitlements and allocation trade
- improve the availability of water market information, and
- improve governance of water trading rules, to give confidence to the market.

Water trade is the key mechanism for facilitating on-going adjustment by water users to changes in the consumptive pool. It is also the adaptive capacity mechanism that most enables the Basin economy to manage the impacts of climate variability and climate change[1].

Climate change implications

Under the more extreme climate change scenarios, it seems likely that water markets may not provide an adaptive solution, as markets could be challenged to facilitate more radical shifts in industry scale and extent if climate change pushes water reliability to the point where even permanent plantings cannot secure or afford sufficient water.

Recent work has argued that water users under pressure from high prices may resort to increasing levels of water theft if monitoring and compliance is ineffective. It also suggests that investment decision-makers could create a 'rural debt bomb' which may ultimately have to be met by national interventions, as the insurer of last resort (Loch, et al., 2019). The pressure to respond by changing water trade rules if this occurs will be immense.

Together these pieces of work identify the sensitivity of water trade to climate change. There is uncertainty about whether restrictions on trade will remain as per the Basin Plan or whether political pressure may lead to market intervention. The recent public and political pressure for changes in water trade rules from communities whose users have sold water down river and subsequently in dry periods observe full rivers carrying that water away from their stressed communities are a precursor for more significant social and economic issues that will arise as trade facilitates even more significant shifts in these regions.

Similarly, significant shifts in water availability may lead to very low security water products being used differently or rendered worthless if they no longer provide reliable access to water necessary to support business operations. This could reduce the range of products available on the market.

Overall, water trade will be subject to significant testing of its operational boundaries in response to climate uncertainty, and likely public and political pressure to change or restrict trade from the users most affected by reduced water availability and sustained higher prices. However, there is significant capacity to better explore the scenarios under climate change including the learnings from the last two dry decades and make institutional reforms to better adapt the market to function effectively under climate change.

Knowledge, management and policy implications for water trade

Building a better understanding of likely water market behaviors and stress points under climate change scenarios through extensions of recent modelling work will help explore appropriate market rules, products and regulatory settings. This knowledge will help to prepare the market (regulators; policy makers and participants) to respond and ensure they remain an effective component in this critical adaptive management mechanism.

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[1] Interim findings from the ACCC inquiry into Murray–Darling Basin water markets were released in August 2020 after the development of this assessment report. The ACCC interim report provides additional detail on the effectiveness of water markets and future vulnerabilities.

Basin communities

The fundamental tenet of the Basin Plan is for a healthy working Basin, ensuring communities sufficient and reliable water supplies that are fit for a range of purposes including domestic and stick, recreational and cultural use, and confidence in their long-term future.

Climate change implications

Basin communities will be vulnerable to direct impacts of climate change as well as being impacted by the connected changes in ecosystem services and local and regional economies. Few studies focused on climate change and regional communities in Australia are available, however a thorough review of literature relating to climate change and country towns (Beer, et al., 2013) identifies the critical sensitivities for Basin communities. These include:

- increased pressure on health services, as some diseases and some risk factors spread to a larger proportion of the Australian land mass. Services that may already be stretched in country towns will then face greater difficulties in meeting needs
- infrastructure in some country towns will be found to be inadequate because of extreme events, or long-run pressures such as increased demand or more rapid deterioration. Examples of likely infrastructure deficits include:
    - road and bridge infrastructure in the face of greater levels of flooding
    - electricity supply as a consequence of more frequent and extreme heat waves
    - emergency services (including/predominately volunteer-run services) required to respond to a growing number and range of events.
- reduced rainfall and reduced river flows affecting communities dependent upon irrigation
- tourism is potentially very vulnerable to the impacts of climate change as it often relies heavily on both quality of life and natural amenity, which may be at risk as a consequence of climate change
- potential impacts on mental health as communities are confronted by both more challenging climatic conditions and an increased incidence of emergencies
- labour market change as economic activity is affected by climate change.

Included in the analysis by Beer (2013) was a vulnerability assessment undertaken by generating a standardised score for each of Australia's almost 2000 non-coastal urban settlements with a population of 200 persons or more. The results of this work show that smaller, more irrigation dependent and more remote communities will find adapting to climate change the most challenging. Available evidence suggests that Basin communities are amongst the most vulnerable towns in Australia to climate change including:

- remote indigenous communities, particularly those in the far western areas of the Basin
- Goodooga in the Northern Basin (the 19th most vulnerable town nationally)
- Dirranbandi, identified as one of the top 20 most vulnerable towns in Queensland
- most of the top 20 most vulnerable towns identified in NSW (e.g. Brewarrina and Collarenabri)
- many of the most vulnerable towns identified in Victoria (e.g. Robinvale, Gunbower and Leithville)
- the Riverland towns of Waikerie, Renmark, Barmera, Berri and Loxton in South Australia.

In contrast to the communities above, Albury-Wodonga and Toowoomba are amongst the least vulnerable places both in their states and nationally, reflecting the advantages that larger, less primary industry dependent and better serviced communities have in adapting to climate change.

Emphasising the vulnerability of many Basin communities is a recent quantitative assessment of climatic extremes and population flows in the Murray–Darling Basin which demonstrates that extreme climatic events and lower rainfall have a clear negative association with population flows in the Basin (Bakar & Huidon, 2018). Climate change will almost certainly create a range of pressures for communities that make it more difficult to retain population.

In contrast, the larger, more diverse and better-connected regional cities and towns in the east and south of the Basin are expected to have significant adaptation capacity and continued growth. This is supported by a studied commissioned as part of an independent assessment of social and economic conditions in the Basin , which found that inner regional areas near to cities are more resilient than outer regional and remote communities which are more dependent on agriculture (Schirmer 2020).

Further impacts on communities are expected in relation to supplying critical human water needs through extended dry sequences. Specific tiered rules for ensuring critical human water needs in the regulated Southern Murray–Darling system are designed to provide an explicit pathway to prioritise the meeting of critical human water needs under low and extremely low water availability scenarios or specific water quality triggers. These Tiers are yet to be enacted and tested but this may change if the current historically extreme dry conditions persist in the Basin.

The challenges experienced in securing sufficient water for many towns in the Basin during the drought also suggest there will be a need to invest in nearby storage of additional water for critical human needs in communities whose supply is vulnerable to extended low flow conditions or the development of other new solutions. This need for water security planning and investment was echoed in the independent assessment of social and economic conditions in the Basin, who recommended the development of regional pilot programs for alternative urban water supply sources (ISEAP, 2020).

Overall, the vulnerability assessment for regional settlements including those in the Basin suggests that regional communities already under pressure from lower social and economic outcomes, structural economic change (such as farm aggregation) and demographic challenges (such as population ageing) will be the most vulnerable to the negative community impacts of climate change. This vulnerability is entrenched as a consequence of different levels of adaptive capacity in the form of access to infrastructure, services, social capital and financial capital. The independent assessment of social and economic conditions in the Basin highlighted this vulnerability, noting that people living in these areas are facing acute social and economic issues, including poor mental health, household distress and financial hardship (ISEAP, 2020). This lack of capacity is particularly stark for First Nations people, who experience socio-economic disadvantage disproportionately to the rest of regional Australians.

The socio-economic objectives of the Basin Plan are also dependent on the ecological objectives which include maintaining appropriate water quality and restoring and protecting ecosystem services and functions that underpin amenity, tourism, recreation and services to agriculture (MDBA, 2017).

The 2017 Evaluation assessed the four outcomes of ecosystem services that directly or indirectly affect social and economic outcomes: amenity; recreation; tourism; and services to agriculture. This assessment noted:

> *The ecological condition of many Basin rivers and wetlands has improved over the last five or so years in response to a general improvement in Basin rainfall and an increase in flows associated with environment watering.*
>
> *The improvement in environmental conditions has contributed to improved social and economic outcomes, with benefits in the form of improved amenity and recreation opportunities, job and income growth in the tourism sector, and benefits to farming and other consumptive water users from improved water quality.*
>
> *On balance, there are multiple lines of evidence supporting the view that water recovery to date under the Basin Plan is contributing to improved environmental outcomes, with positive flow-on effects to Basin residents and visitors and to key industries like tourism and recreational fishing.*
>
> *While benefits are likely to be comparatively modest in scale and scope at this point, this is consistent with expectations at the time the Basin Plan was developed.*
>
> *Over time, and as more water is recovered and used for environmental purposes, it is expected that the flow-on benefits to people will accumulate.*
>
> (MDBA, 2017)

This excerpt is revealing of how sensitive these socio-economic objectives are to climate change. In common with water quality objectives, the assessment shows that their status is reliant on successive years of more favourable (wet) climatic conditions which are expected to be less prevalent as the climate changes. Expected cumulative benefits over time will be compromised by prolonged dry periods with low flows, connectivity issues and relatively limited water available for environmental watering to enable maintenance or improvements in ecosystem services.

The result of this vulnerability is that new and difficult trade-offs for regions and the Basin as a whole can be expected, and the current settings of the Plan will need to reflect the decisions that are made to ensure Basin communities are climate ready and adaptable.

Knowledge, management and policy implications for Basin communities

A better understanding of the ecosystem services critical to the health of Basin communities and the consequences to those services under likely climate change scenarios is needed and must be effectively communicated to all communities. This will then enable water managers to better prioritise ecosystem services support, through both river operations and environmental water use. There are also opportunities to strengthen the requirements for climate risk management strategies in water resource plans beyond water condition and availability, to consider broader ecosystem services, and monitor performance at managing these risks.

Further assessment of the cumulative socio-economic benefits expected to be provided by ecosystem services under climate change should also be undertaken to continue to understand the balance between water recovery and the relative gains from any changes to the consumptive pool. Any options for shifting the Basin Plan's water sharing arrangements must involve informed decision-making by Basin communities to ensure trade-offs between the environment, ecosystem services and water-dependent industries are understood and accepted.

For communities whose water supply is vulnerable to extended low flow conditions, exploration of alternative solutions to provide water for critical human water needs should be pursued. For example, there may be a need to include greater drought contingencies in storage, invest in new storage or alternative water sources. Infrastructure solutions are also likely to play an important role.

More broadly, research is needed to more comprehensively identify the unique climate change vulnerabilities of Basin communities, including those not linked to the management of water under the Basin Plan. Then, increased investment will be needed to build the capacity of communities to plan and adapt to the changes. Planning for community recreation/amenity, tourism and other economic diversification strategies will help communities and industries respond to a drier future.

First Nations vulnerabilities

Assessment summary

First Nations peoples have been adapting to climatic changes and its effects on the environment for millennia. The contemporary notion of climate change is often perceived as the most recent of many challenges First Nations face in maintaining their culture, economic viability and ability to care for Country.

First Nations are considered uniquely vulnerable to the impacts of climate change compared to non-Indigenous Australians. Distinctive cultural, socio-economic and geographical factors contribute to a high level of exposure and sensitivity to the impacts of climate change. While cultural knowledge and strong social networks place First Nations well to successfully adapt, the current scale and pace of environmental change means that First Nations communities, like other Basin communities, will need substantial support to improve their adaptive capacity.

First Nations people's identity and culture is intricately tied to their traditional land and waters, encapsulated in the concept of 'Connection to Country'. Consequently, the ecosystem changes driven by a more variable climate are likely to significantly impact the wellbeing of communities connected to them.

The MDBA's Aboriginal Weather Watchers project, undertaken by the MDBA from 2016-2019 to build knowledge on the impacts of weather on Aboriginal people (particularly on Aboriginal uses and values of water-dependent natural resources), reinforced that there is a strong relationship between water availability and First Nations wellbeing, described in the following diagram:

The majority of the Basin's forward climate change scenarios predict that water availability is likely to reduce, continuing the trends that First Nations have experienced since modern river regulation. While further research needs to be undertaken to understand specific vulnerabilities, the predicted impacts of climate change provide further justification for the current priorities being pursued by First Nations representative bodies, such as cultural flows and improved inclusion in environmental water management.

The impacts of climate change for First Nations peoples are complex and multidimensional. Non-climate related stressors relating to existing social and economic disadvantage, such as lower levels of health, income, and education, are likely to exacerbate the sensitivity of First Nations peoples to climate change impacts while also compound the challenges in adapting.

Partnerships with other government and non-government organisations, research entities and local groups will be important for effective, long-term and flexible adaptation. The MDBA is committed to support First Nations to adapt to changes in the water management space through ongoing partnerships with NBAN and MLDRIN.

Climate change implications

> "*Water is our lifeline for Aboriginal people. That's our life source, the river. That's part of us, that river. When anything happens, it affects it. When we see* [kangaroos] *dying out, that's part of us saying we're going too. It's a belonging. We belong to the earth. Our totems are things we need to look after. Other people have taken them away…It's not water in the tap that's important. Water in the river is what's close to our heart. It is a belonging.*" (Aboriginal Weather Watchers project participant)

First Nations peoples have been observing environmental changes for generations, and Traditional Owners in the Basin have noted that the rate of change is accelerating – what was once observed over hundreds of years is now being observed over decades.

Findings of the Aboriginal Weather Watchers program indicates that Aboriginal people are already experiencing the increasing temperatures and average rainfall reductions predicted by climate change models. All participants of the study noted that it was hotter and drier, with longer periods of extreme heat, compared to when they were younger. First Nations peoples have noticed a significant increase in the frequency of dust storms, an extreme weather event fuelled by dry conditions and low rainfall.

A scan of existing literature informed the initial identification of a suite of factors that uniquely influence the vulnerability of First Nations peoples to climate change impacts. This information has been expanded upon through engagement with NBAN and MLDRIN, and information from the Aboriginal Weather Watchers Program. These factors are listed below and linked with specific examples of vulnerabilities.

Socio-economic status

Existing levels of socio-economic disadvantage will place First Nations peoples at a higher level of exposure and sensitivity to the impacts of climate change. Important socio-economic markers include average levels of income, health, education, housing and access to essential services. These markers are often interlinked and interact to compound vulnerability. The flow-on effects caused by exposure to heat stress is an example of how climate change impacts First Nations.

Extreme weather periods, such as heat waves, require work schedules to be cancelled, delayed and sometimes accumulated once conditions ease. This may increase financial risk for First Nations peoples who are more likely to have less disposable income for electricity bills and limited access to good quality, potable water. Poor housing and infrastructure further reduces the ability for people to recover from an extreme weather event.

Livelihoods

First Nations peoples often have high reliance on ecological systems to sustain livelihoods and traditional food systems. Environmental degradation driven by climate change will see reductions in biodiversity and altered species abundance, distribution, and migration. The drying up of permanent water holes, and rivers as the "*driest I've ever seen*" (observed by Aboriginal Weather Watchers participants) is an example of the significant environmental change already occurring. The sequential impact on species distribution is highlighted in an observation from another participant; *"birds are not here anymore like they used to be. Koala: we haven't seen many of them anymore. Snakes: we used to get about 5 a season. I only seen one this year and it was a python."*

Shifts in animal populations due to climate change has flow on effects for the availability of Indigenous foods and medicines. This has implications for peoples' access to food and can result in a greater reliance on store bought food, which may have economic and dietary impacts. Similarly, the flowering and fruiting of native flora is impacted by climate change, as some fruits dry out and others taste bitter. This affects the potency of native flora that is used as bush medicine.

Unpredictable weather and seasonal changes will also increase pressure on the ability to maintain and diversify people's livelihoods on or near traditional lands.

Heritage, culture and identity

The cultural heritage of First Nations is strongly tied to traditional lands, and the responsibility to protect these areas is an integral part of identity. Protecting these areas may become increasingly difficult under climate change.

An example of climate change impacts on culture is the inability to collect bark or spinifex resin for coolamons due to species unavailability. In dry and hot conditions, further restrictions on cultural burning may put important cultural sites at risk, as well as key plant species which require fire to regenerate. Associated impacts of drought conditions include the increased unwillingness or inability of Elders to spend time on Country, reducing opportunities for intergenerational knowledge sharing on cultural practices.

Wellbeing and health

The holistic notion of health in Indigenous cultures means that the individual and collective health of a community is intrinsically tied to the health of the environment. This is captured in the saying 'healthy country, healthy people'. When speaking about dry conditions, participants of the Aboriginal Weather Watchers Program stated that "*it just impacts your whole wellbeing and it impacts your cultural side of things"* and another, *"rivers were everything".* As a result, First Nations peoples are often more vulnerable to health impacts from climatic changes because of their close relationship with the environment. For example, the sight of totem animals in poor condition causes significant distress because it means people cannot carry out cultural obligations.

This may lead to increases in diseases due to lifestyle changes, and increased medical risk resulting from more frequent extreme weather and climatic shifts. Peoples emotional, spiritual and social wellbeing is likely to be affected by these climate change impacts, leading to increases in mental health issues.

Mobility and location

First Nations have a strong sense of place that is closely tied to their culture, identity and health. These ties significantly limit the ability of many First Nations peoples to leave areas as a response to climate change impacts, or exacerbate psychological and social stress if required to relocate. First

Nations communities are spread throughout the Basin, often in regional and semi-remote areas, which are more likely to feel more directly the extreme impacts of climate change than urban areas.

Damage to infrastructure from extreme weather, such as roads melting or cracking in extreme heat, significantly impacts people's mobility for both employment and cultural purposes. Location also influences a number of related health and wellbeing factors, such as access to safe drinking water, bush tucker, bush medicines, and essential services.

The deep spiritual connection with traditional lands is emphasised by the need to be close to Country even in times of hardship. A participant from the Aboriginal Weather Watchers Program describes cultural activities to help make it rain, saying that they would "*go to river and talk to the Mundagudda* [Rainbow Serpent]. [They] *talk to land and listen for the language…we can tell Country it is still loved and respected and ask for help, for the dryness, for all things living*".

It is important to note that the specific nature and extent of vulnerabilities in First Nations communities will differ, and some will have better capacity to adapt. In addition, many of these vulnerabilities will be simultaneously influenced by other drivers of change affecting First Nations communities, such as the expansion and automation of the agriculture industry, and reduction in access to essential services for remote communities.

Knowledge, management and policy implications for First Nations

First Nations maintain that any form of adaptation should be founded in enabling interaction with Country, as this is inextricably linked with culture and wellbeing. While adapting to the impacts of climate change requires an integrated, whole-of-government response, the MDBA can faciliate adapations in the water management space, and offer support for complementary initiatives at a broader government level.

Deeper engagement with First Nations representative bodies (MLDRIN and NBAN) in future stages of the Climate Change Program should be aimed at better understanding the specific climate change related vulnerabilities for First Nations in the Basin. An improved understanding of the relationship between climate, hydrological factors, and cultural outcomes will be an important line of inquiry for any future research plans.

Further engagement should assist in differentiating impacts driven by climate change from other drivers and exploring opportunities to support Basin communities' transition from vulnerability to greater adaptive capacity. It will also be important to understand coping mechanisms that currently may occur due to climate change impacts, such as an increase in store bought foods and associated lifestyle diseases in response to reduced bush tucker availability. Collecting this type of information should enable MDBA to better understand its role in supporting First Nations to adapt to the impacts of climate change in Basin water management. However, ensuring legal protection of information provided by First Nations should be prioritized in any research process.

To understand the adaptive capacity of First Nations communities, the independent assessment of social and economic conditions in the Basin recommended the development of a program for First Nations groups to build a baseline and track social and economic conditions and outcomes from water reform. In a climate change context, the availability of data to characterize communities and monitor changes could be a valuable resource for First Nations groups to influence adaptation pathways.

While MDBA requires more specific information of First Nations vulnerabilities to understand adaptation needs, MDBA should consider supporting the development and communication of local Indigenous knowledge to characterize their experiences of climate change and the potential ecological implications. This local observational knowledge is not only a valuable input into environmental water management, but it can also be a source of information to better articulate adaptation needs and co-design options for communities. The Aboriginal Weather Watchers project and 'citizen science' opportunities are examples of these types of initiatives that MDBA could support.

Water literacy is also an essential part of being involved in Basin water management. Improving literacy of technical terminology will ensure that First Nations people have better capacity to effectively contribute to water management decisions. This knowledge-sharing should be two-way, with reciprocal sharing of terminology between cultural knowledge holders and river operational knowledge holders. Access to climate change information is also essential for assisting communities to understand the implications of climate change and inform discussions on adaption options.

Recommended management actions are similar to current initiatives being pursued by MLDRIN and NBAN, as climate change will exacerbate the challenges already faced by First Nations. The priority initiative for MLDRIN and NBAN is attaining water rights (cultural flows) through the Aboriginal Water Entitlements Program (which the MDBA does not deliver). However, MDBA can continue facilitating opportunities for First Nations communities and bodies to partner with Government to deliver environmental water that has cultural objectives and outcomes. Examples of these initiatives include but are not exclusive to:

- Inclusion of MLDRIN and NBAN representatives in environmental water decision making forums, such as the Southern Connected Basin Environmental Watering Committee (SCBEWC). This demonstrates a shift towards more inclusive decision-making arrangements.
- Working with local and regional governments to undertake Aboriginal Waterway Assessments (AWAs) to better articulate local Aboriginal values and watering needs. An example of the application of the AWA tool was at the Millewa forest in November 2018 with the NSW Government. Input provided by Aboriginal community members helped inform targeted environmental water delivery to sites in the forest that are of ecological and cultural value. The improved health of the environment increases biodiversity and provides opportunities for sustainable use of cultural resources by Aboriginal people. This highlights how collaboration between community and government bodies can help maintain connection to Country and Culture.
- The First Nations Water Guidance Project, whereby formal engagement is undertaken to identify Aboriginal objectives for consideration in the Basin's annual environmental watering priorities. The pilot project is being undertaken to inform the 2020-21 water year. This project demonstrates progress in recognizing Indigenous knowledge to support water planning and decision-making.

Complementary natural resource management initiatives are also needed to adapt to the impacts of climate change. The Dewfish Demonstration Reach in the Condamine catchment is an example of how effective partnerships with Indigenous rangers can optimize the impacts of available water. This river restoration program resulted in significant increases in native fish numbers after extensive re-snagging, riparian fencing and carp removal activities. Increased Indigenous rangers programs should continue to be a priority initiative at a Basin scale.

Enabling opportunities for First Nations peoples and knowledge to be better integrated in decision-making on Basin plan policies will be a key aspect of supporting climate change adaptation for the MDBA. While the Basin Plan establishes specific avenues for First Nations advice, such as WRPs, inclusion and participation in other aspects of water reform are needed to ensure real outcomes are achieved in the long-term.

Notable progress towards more inclusive governance arrangements includes the passing of legislation in 2019 for a new Indigenous Authority member, and the appointment of the first Aboriginal Chair of the Basin Community Committee in late 2019. Enabling access to decision-making forums provides the opportunity for First Nations perspectives to be meaningfully incorporated and key climate change adaptation initiatives progressed in the water management space.

Knowledge sharing and capacity building opportunities that can be facilitated within MDBA’s remit should be pursued, as these can in turn enhance the platform for First Nations groups to pursue enduring goals such as improved access to Country and water resources.

Ecological vulnerabilities

Assessment summary

Climate change is a two-speed problem for ecological communities. There is the slow-burn, gradual shift in climate that will mean that species and ecosystems will be forced to function outside their optimal conditions (temperature ranges, rainfall patterns etc.). Then there are the high-impact extreme events, the frequency and/or magnitude of which are predicted to be greater than previously experienced, such as larger flooding events and more frequent and intense bushfires. The 2019-20 bushfire season has shown the catastrophic impact these events have on species populations and habitats. How long and how well ecosystems recover from such events is not yet clear.

What is clear is that both these slow-burn and high-impact events will, in combination, make it difficult for Basin ecological communities to thrive in the good times and recover from the bad. The result of many of the ecological vulnerabilities identified is this report is not the imminent extinction of species, but initially, the reduction of their ability to contribute to the healthy functioning of the river system. In the longer term, some species viability may be tested.

A critical aspect of climate change impacts not well understood is how, as ecosystems respond to climate stressors (either short or long term), their ability to provide ecosystem services is also compromised. There is insufficient knowledge of the complex requirements of certain species, or the interdependent relationships that comprise ecosystems, to know when tipping points are reached as conditions compromise ecosystem function.

Healthy ecosystem function is also dependent on species diversity; both the diversity of species that play various functional roles within an ecosystem, and the intra-species genetic diversity which allows them to adapt to changing environments over time. Without both forms of diversity, the important processes performed by species within ecosystems may begin to breakdown overtime.

Climate change will add to the ecological vulnerabilities already experienced from 200 years of over-extraction and river regulation in the Basin. Knowledge of environmental watering requirements continues to develop, and watering events are providing real outcomes for Basin species and ecosystems. However, without increased knowledge of ecosystem interdependencies and species requirements, including how ecological communities will persist under new climate averages and recover from climatic extremes, there is a great risk that Basin ecosystem tipping points will be reached. Even with this knowledge a fundamental lack of water and high-impact events may result in tipping points being reached; and significant improvements in management capacity will be needed to avoid compromising ecosystem functions.

The detailed results of the vulnerability assessment are set out below against the key ecological outcomes anticipated under the Basin Plan.

Connectivity

River connectivity is critical to many ecosystem functions and the associated ecological services provided. The expected outcomes for connectivity throughout the Basin include maintaining base flows, increasing tributary flows, increasing flows to Murray Mouth, maintaining surface water-groundwater connectivity, and maintaining and where possible reinstating the connection between rivers and their floodplains.

Flow reliance and other factors at play

Creating and maintaining connectivity through the river system relies on various types of flows. Baseflows, freshes and larger flows create longitudinal connectivity along the river and its tributaries. Baseflows are important for connecting rivers during periods of low inflow, allowing fish and other aquatic species to continue to move through the river and access resources as well as manage water quality.

Freshes provide natural cues for some species to migrate to breed and also ensure water quality is maintained by mobilising sediment, salt and nutrients so they do not concentrate. Large flow events can flush these sources of water quality degradation out of the river system and enable the wider dispersion of species to avoid reductions in genetic diversity that the isolation of populations can create.

Larger overbank flows also provide lateral connectivity; joining rivers to their floodplains to prompt food web productivity and cycle nutrients and carbon between floodplain soils and rivers. These large flows provide access to unique habitats for many Basin species and may also provide vertical connectivity by recharging groundwater systems close to the river channel.

Baseflows are also a form of vertical connectivity between surface water and groundwater, where groundwater may contribute to baseflows in some river reaches and be recharged by surface water flows in other reaches. Rainfall, evaporation, infiltration and recharge rates are key determinants of inflow to rivers and changes in these factors will have implications for maintaining connectivity. Changes to catchment vegetation as a result of land use change and fire regimes will also alter catchment hydrology and hydrogeology, which will have flow on effects for connectivity.

The impacts for connectivity in regulated and unregulated systems will vary markedly, given regulated catchments have storages which can be used to maintain flows.

Climate change implications

Longitudinal connectivity

The duration and intensity of dry periods is likely to increase as a result of climate change, which will challenge the capacity of water managers and the river system to maintain baseflows through these periods. With extended dry periods, the demand for water during periods of low availability is likely to increase. This will put pressure on low flows and baseflows to provide water for critical human and environmental water needs as well as maintain connections through the system to allow species to move to find food resources for as long as possible, and then maintain drought refugia. This was demonstrated starkly in recent times as record-breaking temperatures and rainfall deficiencies across much of the northern Basin contributed to the Darling River and many of its tributaries being reduced to a series of disconnected waterholes.

As dry periods increase in length, the frequency of the medium to large flows that provide connectivity and re-wetting of the system will also reduce. The extent to which these flows provide connection down the system may also reduce due to other factors such as catchment vegetation, fire regimes and increased evaporation rates. Increased periods of disconnection with downstream reaches and terminal wetlands will cumulatively impact on environmental functions including distribution of nutrients and carbon/energy, dispersal and migration opportunities, and flushing sediment, salt, and nutrients. The overall impacts of anticipated changes to connectivity flows are that species populations become increasingly isolated, have fewer habitat options, reduce in abundance and genetic diversity, and thereby decrease the resilience of ecosystems and populations.

The limited ability to buffer these flow regime changes with environmental water delivery in unregulated reaches increases the vulnerability of these systems significantly.

While environmental water is available in regulated systems to provide longitudinal connectivity, these systems will be vulnerable in terms of the variability of these longitudinal flows. Regulation of rivers has reduced the natural variability in flow regimes, in general reducing freshes and bank full flows and removing the natural wetting/drying cycle that some species rely on for different lifecycle stages. The impact of these changes on ecosystem processes will in turn cumulatively affect the distribution and abundance of species dependent on flow variability, be it to enable migration to new feeding grounds or those that require flows to provide cues and conditions to breed and recruit.

Further alterations to the flow regime may be needed to meet consumptive demands for water, depending on how climatic changes decrease inflow, and how water availability and land use change shift use patterns. Increases in storage capacity and subsequent release of less small and medium flows, and possible further changes in the seasonality of flow releases, could eventuate to provide water security for consumptive users. While significant work has been underway for some time to adjust river operation arrangements to accommodate environmental water use, as environmental conditions and consumptive use patterns change, there will be a need to understand the implications for environmental water users and ensure rules are updated to accommodate the different water use and delivery needs of environmental water holders.

Lateral connectivity

Climatic changes in rainfall and other factors affecting inflow such as changes in catchment hydrology will likely reduce the frequency of overbank and flood events. It is also possible that the inundation extent, duration, seasonal timing and other characteristics of large flow events may change. This will have implications for floodplain species such as colonial nesting birds and floodplain specialist fish, who have adapted to a particular range of environmental conditions determined by these inundation events. Changes in flood frequency will also change important riverine processes such as nutrient, carbon and sediment cycling, and the productivity of aquatic food webs. There are also significant water quality implications to changes in these processes as demonstrated in the Murray river in 2016. The particularly long spell since a previous flow of that magnitude had allowed the buildup of a high carbon load (in the form of leaf litter) on many floodplains, the subsequent large influx of organic carbon during the 2016 event contributed to a hypoxic black water event and in turn the death of many aquatic organisms.

The ability to provide flow to the actively managed floodplain (riparian, near-channel wetland and anabranch ecosystems) in regulated systems will be vulnerable to reductions to environmental water availability under climate change. These impacts will vary across the Basin according to changes in inflow to storages, the mix of license types in the environmental water portfolio available in the system, and the ability of portfolio holders to coordinate the use of their available water. Floodplains are also physically disconnected from these large flows by levees and other infrastructure, and planned work to remove these constraints will need to progress to ensure lateral connectivity can be achieved.

Inundation of higher floodplains relies on very large unregulated flow events and cannot be achieved with environmental water alone. With predicted increases in the duration of droughts, the period between watering events for these areas will increase. It is likely that over time these areas will transition to new ecosystems less dependent on river water. There is limited information predicting how these ecosystems may change and their consequent interactions with the lower floodplain and river system.

In unregulated systems where there is limited regulation infrastructure to actively deliver water to floodplains, predicted longer periods between large flow events will disconnect these river systems from their floodplains for extended periods. Extraction rules that protect unregulated flows in these systems will provide inundation when events do occur, however it is likely that these systems will change in response to a new regime of inundation.

A range of other climate driven factors will also influence inflows and change flow regimes, such as the impact of vegetation changes on catchment hydrology including the impacts of increased bushfires, changes to groundwater recharge rates, and increased temperatures and resulting evaporation rates.

Vertical connectivity

Hydraulic relationships between groundwater and surface water systems is important for several reasons, such as ensuring saline groundwater or rising groundwater tables do not mobilise salts into freshwater systems or lead to dryland salinity; to provide connectivity with groundwater dependent ecosystems; and to maintain baseflows to rivers during dry periods or provide recharge to groundwater systems from rivers in some reaches.

Connections between surface and groundwater systems are particularly vulnerable to climate change due to the lack of baseline knowledge of hydraulic relationships, the immaturity of water resource management frameworks to manage surface water and groundwater in an integrated way, and the likelihood that demand for groundwater resources will increase as surface water availability decreases.

Reduced rainfall and the associated expected decreases in the frequency of overbank/unregulated events will impact on groundwater levels, as these events provide recharge to some groundwater systems. Other interacting factors such as vegetation and land use changes can also impact on catchment hydrogeology and are not clearly understood in many areas of the Basin.

Rules are in place in some areas to manage groundwater extractions, maintain groundwater pressure, and protect groundwater recharge. However, water resource management frameworks still largely consider surface water and groundwater systems separately due to a lack of information about hydraulic relationships. As demand for water from ground and surface water sources will increase as the climate becomes hotter and drier, risks to hydraulic relationships may increase, and there will be a need to ensure licencing and river operations rules can appropriately recognise and manage these risks.

Knowledge, management and policy implications for connectivity

There is need to understand the likely changes to connectivity flows under climate change scenarios, including understanding the changes to factors that affect inflows such as rainfall, evaporation, soil infiltration, groundwater recharge, floodplain geomorphology, and impacts of vegetation changes (e.g. land use change, bushfires). Improvements in knowledge of how water moves across floodplains in unregulated systems will also help to understand how to manage the impact of lateral disconnection.

A more comprehensive baseline knowledge of groundwater/surface water connections and hydraulic relationships is also needed before risks to maintaining vertical connectivity under different climate change scenarios can be identified.

There is also a need to forecast the likely changes to the environmental water available under different climate change scenarios, to understand any implications for achieving connectivity. In unregulated systems, it will also be important to test the performance of water sharing rules under likely climate change scenarios to protect flows that contribute to connectivity, including baseflows, low flows, first flushes and floodplain harvesting, given these are the main management instruments in these systems.

Likewise improving water management frameworks to manage surface water and groundwater sources as connected systems in areas where there is a high level of connectivity will be important to maintain connectivity as climate change impacts these hydraulic relationships.

There may also be opportunities to better codify arrangements for providing connectivity through coordinated, system-scale use of all available water, to ensure connectivity can be achieved as effectively as possible.

Understanding likely changes to water extraction for consumptive use under different climate change scenarios will be important to ensure river operations can continue to adapt to changing patterns of consumptive demand without reliability impacts to environmental water holders or creating barriers to environmental water delivery. This information could also be used to stress test the ability of existing long-term average caps and water allocation frameworks to manage extraction under climate uncertainty. Understanding these likely patterns of water use behavior will also help target compliance activities to ensure water flows and levels are protected.

Exploring new water resource management mechanisms or identifying improvements to existing approaches to order to better manage climate uncertainty (e.g. drought reserves, conservative allocation policies, contingency planning processes) should also be pursued as part of an adaptive management approach.

Water quality

A key objective of the Basin Plan is to maintain appropriate water quality for cultural, environmental, social and economic activity. This means that the water resources must remain fit-for-purpose. To contribute to the maintenance of water quality and salinity throughout the Murray–Darling Basin system, the Basin Plan includes objectives for water-dependent ecosystems, water for human consumption, irrigation water, recreational water, water quality characteristics, and includes the salinity targets set in the Murray–Darling Basin Agreement.

Flow reliance and other factors at play

River flow is crucial in managing a number of causes of water quality degradation. Mobilizing and flushing salt out of the Murray mouth, intercepting saline groundwater and preventing salt from concentrating locally, through the maintenance of connectivity flows (baseflows, freshes and larger flows) has underpinned salinity management in the Basin over the last three decades. River connectivity also benefits the management of other sources of water quality degradation such as excess sediment and nutrients and pesticides, by preventing their concentration in local environments.

Overbank flows are also important for maintaining water quality, as frequent inundation of the floodplain transports organic matter into the river system and boosts regular organic matter decomposition on the floodplain. Without frequent removal from the floodplain, organic matter will accumulate and wash into the river system during large flood events. This increases the risk of hypoxic blackwater events as the organic matter is broken down by bacteria and depletes oxygen from the water.

The connections between surface water and groundwater systems are also critical for managing water quality. This connectivity plays an important role in protecting river systems by ensuring that freshwater lenses form over saline groundwater and, if salt does move into rivers, it remains mobile and cannot concentrate.

However, groundwater-surface water connections can also enable transportation of nutrients, pesticides and other contaminant loads from groundwater into rivers. This can occur where the use of irrigation water has increased nutrient inputs or other contaminants into groundwater systems. Maintaining hydraulic properties of groundwater systems, such as pressure, is important to ensure saline or poor-quality groundwater does not intrude into higher quality groundwater and surface water sources.

Other climate driven factors that influence water quality include temperature, which increases the risk of algae blooms and intense rainfall events which can increase the pollutant load entering river systems. The potential changes in water chemistry that may result from climate change are largely unknown, making it difficult to predict what will happen to water quality.

Other non-flow factors which impact water quality include land management practices that create excess sediment and nutrient runoff, and the regulation of various other point and diffuse pollution sources.

Climate change implications

The ability to provide water quality that is fit for purpose will be vulnerable under future climate projections and will challenge the ability of river operators to maintain suitable water quality for productive and consumptive use, and to minimise impacts on aquatic ecosystems.

Less inflows and longer dry sequences are predicted, making flushing events potentially smaller and less frequent. This will reduce the ability to flush out salt from the river systems and meet the water quality objectives. These types of extreme events could also lead to low dissolved oxygen water in thermally stratified water bodies and potentially increased sedimentation and can expose acid sulfate soils which lower water pH when flows return.

As inflows to surface water systems are reduced and dry sequences are extended, groundwater systems are likely to play an important role in providing baseflows to maintain connectivity. However, the reduced availability of surface water will also increase demand on groundwater systems to supply water for consumptive If left unchecked, this could have significant impact on groundwater levels and reduce connectivity to surface water systems.

However, more intensive rainfall events are also possible, which would increase erosion and surface runoff during rainfall events and result in other water quality issues. Other extreme events such as bushfires are also likely to be more frequent and intense, contributing to poor water quality issues when post-event rainfall events occur.

Some of the more specific water quality issues for different uses of water are outlined in the sections below.

Water-dependent ecosystems

Water quality for water-dependent ecosystems relies on larger flows to maintain adequate water quality and groundwater connectivity to maintain baseflows to keep contaminants mobile and drought refugia. Increases in the number and duration of low/cease to flow periods will impact the ability to dilute contaminant levels. This altered flow regime could also expose acid sulphate soils in some areas, which will lower pH levels in the water when flows return.

Other predicted flow related impacts of climate change are likely increases in extreme rainfall events, which may result in large amounts of bank erosion and subsequently increase turbidity.

A non-flow related factor which will impact water quality for ecosystems include changes in natural temperature ranges, which affect the health and biological processes of some species.

Other factors which may not be affected by climate change but will impact on water quality include inappropriate irrigation practices, or changes in the locations and techniques used in irrigation, which may have implications for salt and nutrient loads and water chemistry.

Other water quality impacts that may arise from the likely changed conditions described above, such increased mortality rates among native species, as they are often less resilient than invasive species.

Water for human consumption

Water quality for human consumption will be particularly vulnerable to predicted increases in low/cease to flow periods, which will allow contaminants to concentrate in surface water sources and increase treatment requirements or render the water unsuitable in some circumstances. Similarly, increases in water and air temperatures coupled with increase nutrient loads will promote the development of cyanobacteria and more intense rainfall events will increase runoff pollution loads, having implications for water treatment.

Potential changes in water chemistry pose a risk to water quality for consumptive use, as these changes could alter the composition of pathogens in raw water for treatment, increasing treatment requirements and production costs of potable water.

Irrigation water

Maintaining water quality suitable for irrigation will become challenging, as low/cease to flow periods are expected to increase and the frequency of freshes to decrease, making it difficult to dilute or remove sources of water quality degradation from river systems. An increase in the risk of water quality problems arising from acid sulphate soils also exists under possible climate change scenarios.

Climate change is also likely to impact on groundwater systems by affecting recharge rates, surface water connectivity and contamination levels. This could have a flow on effect to irrigation water quality as groundwater often plays an important role in both providing a water resource for irrigation and diluting salt in some areas. Depending on the capacity of the groundwater system, these impacts might only be visible in the medium to long term.

Other non-flow related factors that will impact on irrigation water quality include increases in air and water temperature which promote the development of cyanobacteria. Potential changes in water chemistry could also impact on irrigation uses by altering the sodium absorption ratios, under certain circumstances could cause damage to soil structures.

Water for recreation

Recreational water quality will be impacted by increases in the frequency of intense rainfall events. Increases in air and water temperatures as well as nutrient loads can increase the risk of toxic cyanobacterial blooms which prevents the recreational use of Basin’s water resources.

Recreational use also supports the Basin’s significant eco-tourism industry. This industry will be challenged under any conditions that reduce the natural aesthetic of the Basins waterways (such as poor water quality conditions) and the health of the Basin’s terrestrial and aquatic species.

Knowledge, management and policy implications for water quality

Water quality degradation will need to be managed with greater coordination to make optimal use of the increasingly limited water resource. Understanding the implications of different climate change scenarios on water availability, catchment hydrology and connectivity will be important to identify and manage impacts on water quality. Increasing knowledge of ecological processes such as the riverine response to salt and organic matter mobilization, as well as predicted climatic changes such as heat waves and extreme events, will help to assess and manage the risk of water quality degradation.

A better predictive capacity to understand the likely occurrence and nature of extreme events, and improving water monitoring capabilities, will help river managers and water authorities maintain water quality at acceptable levels in line with the Basin Plan objectives. The response to fish deaths which occurred across the Basin during the 2018-19 summer demonstrated how all relevant agencies at state and Commonwealth levels can successfully coordinate efforts and pool resources when required. Further development of multi-jurisdictional protocols for responding to all types of water quality emergencies will help to ensure these responses are fast, effective and efficient.

Agreement on a baseline understanding of water quality risks can be used to test and refine river operation arrangements to maintain water quality, particularly through extended dry periods to provide critical human and environmental water needs under future conditions. Similarly, broader water quality management frameworks, including risk management strategies and regulatory arrangements, could also be tested and improved.

Knowledge of water quality risks under climate change will also help to plan and prepare water management and treatment infrastructure to ensure water quality can be managed during/post-extreme events, guide investment in new technology (e.g. water filtration/treatment, plant breeding) to better enable domestic and economic uses of water to continue under a range of future climate change scenarios.

The indirect impacts of climate change on water quality, such as altered fire regimes, catchment vegetation changes and changes to water chemistry, also need to be explored, in recognition that these may create new water quality issues in the future.

Water quality is often linked to land use management. Each Basin state has a range of management and regulatory options available to reduce water quality degradation associated with point and diffuse sources and poor land management practices. The Basin Plan provides opportunities for Basin states to better integrate water resource management and land management practices through the water resource planning process, although the inclusion of land management measures to address water quality is options. There are opportunities to explore how Basin Plan water management measures can be further integrated with land management measures.

Vegetation

The expected outcomes for vegetation in the Basin-wide environmental watering strategy are to maintain the extent and maintain or improve the condition of water-dependent vegetation. As flow management is the primary mechanism for achieving these outcomes under the Basin Plan, the outcomes are expected to be achieved only where environmental water can be delivered.

Flow reliance and other factors at play

While most vegetation species in the water-dependent ecosystems of the Basin utilise any water available (rainfall and groundwater), rivers are critical to their long-term persistence. Periodic inundation of riparian and floodplain areas not only provides water to aquatic ecosystems such as wetlands and anabranches, but also wets the soil profile, cycles nutrients and carbon to and from the soil and river and is important for lifecycle stages of some plant species. Overbank flows and larger floods are critical components of the flow regime which provide this periodic inundation.

During dry periods groundwater resources are utilised by vegetation, either through access to the groundwater table or groundwater contributions to baseflows in rivers and water levels in wetlands.

For submerged vegetation species in river channels and the Lower Lakes and Coorong, small freshes and freshwater inflows are also important for maintaining water quality and can be important for lifecycle phases of some species.

In addition to the above flow requirements, various other factors will impact the ability to improve the condition and maintain the extent of water-dependent vegetation in the Basin. These factors include grazing, invasive species, soil salinity, vegetation clearing, air and water temperatures, evaporation, fire regimes, and sea level rise.

Climate change implications

As average rainfall is expected to decrease across most of the Basin, many vegetation communities will be highly vulnerable to a loss of water resources, including rainfall, inundation from flooding and decreased groundwater levels due to decreased recharge and possible increased extraction for consumptive use.

Many vegetation species in the Basin are adapted to a wetting and drying regime. However, as dry sequences are likely to increase under climate change, the threshold of conditions vegetation species can persist within will likely be exceeded. This could impact on the health of vegetation, diminish the habitat characteristics needed to support other species, and over time impact the viability of vegetation communities by decreasing recruitment and community structure.

Conversely, the possibility of more intense storm events could increase the duration of some flood events, disrupting the life stages of some species (e.g. submerged vegetation). Changes to bushfire regimes and increased incidents of water quality degradation may also impact on lifecycle stages of vegetation species and the health of vegetation communities, including their ability to recolonise after natural disasters. This may result in reductions in the extent of these species.

These impacts on vegetation communities will occur over extended time periods and may result in reduced biodiversity, protracted extent of vegetation communities, and some areas will transition into different vegetation communities. Such changes in vegetation will also have implications for other species that rely on particular vegetation assemblages or characteristics to provide suitable habitat.

While vegetation communities exist in mosaics across the landscape that shift in vegetation composition and structure in space and time, rapid shifts in climate and the increase in extreme events may reduce the health of key vegetations communities and impact on the ecological processes that enable vegetation communities to transition and persist in the landscape under changed climatic conditions. For example, likely air and water temperature increases and shifts in seasonal conditions will impact some vegetation species, which rely on seasonal temperature cues for germination. Understanding the dynamism of vegetation at species, population and large spatial and temporal scales will be important knowledge to underly management efforts to maintain diverse and functional habitat across the Basin.

The unique vulnerabilities of structural groups of vegetation are detailed below, including some the implications for important habitats of the Basin.

Forests and woodlands

Dominant overstory species that form the floodplain forests, woodlands and riparian vegetation communities of the Basin include black box, coolibah, and the culturally important river red gum. These species provide roosting and nesting habitat for some waterbird species and are important habitat for many other terrestrial species.

While these species can cope with extended drought periods by accessing groundwater, they rely on regular flooding to re-wet the soil profile and provide conditions suitable for recruitment. This regular inundation ensures there is age diversity in the population of a vegetation species, as well as ensuring the health of individuals.

Forests and are likely to experience reductions in the frequency of flooding. Predicted increases in temperatures and evaporation will further decrease these species access to water during dry periods. Changes in groundwater levels may also eventuate, further removing access to vital water resources.

Woodlands high on floodplains, which tend to be dominated by black box or coolibah species, are particularly vulnerable to climate change as environmental watering is unlikely to reach these areas due to the volumes available and constraints preventing inundation other than during large uncontrolled flooding events.

Impacts on forests and woodlands will likely occur over time as mature trees die and the seed stock and younger recruits diminish. In some areas this will result in decreased habitat value these vegetation communities provide for terrestrial species or reductions in the area of suitable habitat. In other areas the dominant species may change or the forest or woodland transition to a different type of vegetation community.

In terms of the habitat these forests and woodlands provide, the health and characteristics of these habitats may also change, having an impact on associated fauna species. The increased disconnection of these floodplain habitats from the main channel will also disrupt carbon and nutrient cycles and have implications for the breeding opportunities of many fish species that are important for aquatic food web productivity. All these impacts have implications for the overall health of river systems.

In addition to vegetation clearing, grazing and invasive species impacts, this vegetation is utilised in some areas for timber and other wood products. Sustainable forestry practices as well as land management will be needed to maintain the health, extent and viability of forests and woodlands.

Shrublands

Lignum is a woody shrub that grows in the riparian and floodplain areas of the Basin. This vegetation provides important habitat for many Basin species, and in particular provides critical breeding ground for colonial nesting birds such as the straw-necked ibis.

These shrublands require regular inundation to maintain their health and provide the habitat characteristics that support other species. With likely reductions in the frequency of the overbank flows and larger floods which provide this inundation, the health and extent of these shrubland areas are likely to decrease. This will have flow-on impacts for all floodplain fauna species, including many waterbirds who rely on this habitat for breeding.

Lignum is particularly vulnerable to a number of other non-flow factors. Lignum is readily destroyed by fire, so changed fire regimes will reduce the extent of this habitat and allow weeds to colonise floodplain areas. Vegetation clearing has also had a significant impact on these shrubland communities as it is extensive in productive floodplain areas largely on private land. Invasive species such as feral pigs damage the shrubs as well as the soil structure, limiting recolonisation. Lignum also relies on air temperature cues for lifecycle phases of the plant, so changes in temperatures may have an adverse effect on recruitment rates.

Non-woody vegetation

Non-woody vegetation species in the Basin include species that fringe water courses or grow within river channels and wetlands including, grasses, sedges, rushes, and herbs. These species rely on consistent water availability and various components of the flow regime to provide suitable water levels and quality to maintain the condition of plants and enable recruitment.

Non-woody vegetation occupy habitats where water availability and persistence during dry spells is most reliable. The shallow-rooted, soft tissue and often ephemeral nature of non-woody vegetation means that they are particularly vulnerable to changes in water availability, and they will be first to respond when conditions change. Favourable conditions need to persist long enough for flowering and seed set, otherwise the seedbank will be quickly depleted.

A secondary impact of water availability is water quality. Expected reductions in the frequency of freshes will increase water quality degradation throughout the system by removing the regular flows which keep salt, nutrients and sediment mobilised and moving through the river system. Likewise decreases in the frequency of large floods will reduce the amount of flushing of the river system and increase the loads of these key causes of water quality degradation. During extended dry periods, the risk of poor water quality will also rise as baseflows cannot be maintained to manage water quality and the periods of cease-to-flow conditions will increase.

For non-woody vegetation in near-channel habitats such as wetlands and anabranches, reductions in the frequency of larger flows (overbank and floods) will reduce regular freshwater inflows and increase the incidents of poor water quality in these habitats. Large floods are required to flush poor quality water and built-up organic matter from these areas. These flows are also important for providing inundation levels that enable submerged species to grow, so reductions in these flows will likely reduce the extent of non-woody wetland and floodplain vegetation.

Reduced freshwater inflows from the Lower Lakes to the Coorong will impact on the ability to maintain areas of *Ruppia tuberosa* seagrass, which provides food and habitat for many estuarine species including protected migratory shorebirds. Reductions in these flows will make managing salinity and water levels to provide suitable conditions for seagrass to grow difficult. Estuarine species will also be impacted by any increases in sea levels and extreme events such as storm surges, which will impact on the extent of submerged vegetation. If other factors such as flow conditions and non-flow factors discussed below have decreased the condition of these vegetation communities, their ability to recolonise after such events may also be reduced.

Several other factors may change as a result of climate change and effect the condition and extent of non-woody vegetation in the Basin. Changes to fire regimes may increase the incidents of poor water quality by increasing the frequency of runoff events following fires and the loads of sources of water quality degradation. Changes in air and water temperature may push conditions to the limit of plants tolerance ranges, decreasing their condition and growth, thereby reducing their extent over time. A number of these factors may also contribute to greater prevalence of invasive species which compete with native species, such as filamentous algae which can bloom in large enough quantities to smother other species, reducing light permeability and dissolved oxygen levels.

While not directly driven by climatic changes, grazing practices also impact on wetland vegetation and will need to be carefully managed if these non-woody species are to be maintained.

Knowledge, management and policy implications for vegetation and habitat

Given the dependence of water-dependent vegetation on most components of the flow regime, it will be important to manage environmental water to ensure these components can be maintained as much as possible. This will require a better understanding of the trajectories and rates of change in ecosystems, so available water resources can be used to manage transitions between ecosystem types, and changes in the distribution of ecosystem types in the landscape. Understanding the impacts of climate change on the likely availability of water in environmental water portfolios under different climate change scenarios will be key to informing planning for watering over multiple years and through dry periods.

As the ability to achieve the expected outcomes for vegetation is likely to be limited to areas where water can be provided, removing constraints to environmental water delivery and better targeting the use of all water to achieve multiple outcomes will be important. Identifying a priority subset (comprehensive, adequate and representative) of water-dependent ecosystems across the Basin that could be maintained as the climate changes could be explored, alongside understanding how ecosystems transition between types, as a suite of management approaches that could be employed to ensure the Basin remains ecologically healthy. This would require an understanding of the watering requirements that would support these ecosystems under various climate change scenarios and an assessment of whether sufficient environmental water is available to meet these watering requirements.

Vegetation and habitats in unregulated systems will be particularly vulnerable to changes in wetting and drying regimes, as there are limited mechanisms to actively water these areas. However, water extraction rules can protect water for the environment in these systems when flows do occur. Testing how adequate existing rules will be in protecting important flow components under predicted flow regime changes will be needed to protect the vegetation communities in these areas.

The management of non-flow factors impacting water-dependent vegetation will be also important interventions for alongside flow management. Improving coordination of water management with other natural resource and land management activities will help to optimise the outcomes achieved for vegetation.

Waterbirds

The expected outcomes for waterbirds in the Basin-wide environmental watering strategy are to increase the breeding and abundance of birds and maintain current species diversity. In the Coorong and Lower Lakes the expected outcome is to maintain the numbers of four key migratory shorebird species. Waterbirds require a mosaic of suitable feeding, roosting and breeding habitat to be maintained across the Basin to support healthy populations.

Flow reliance and other factors at play

Key components of the flow regime to provide feeding and roosting habitats, and suitable breeding conditions for most waterbirds include overbank and large flooding events. These events maintain riparian areas and inundate wetlands and other floodplain habitats that provide food, shelter and nesting sites, as well as provide cues that trigger breeding events. Regular overbank flooding is also needed to keep wetland habitats primed to support future breeding events. Seasonal flooding in the Coorong and Lower Lakes is also important to provide foraging habitat for migratory shorebirds. During droughts, waterbirds also rely on baseflows to maintain critical refugia with food and shelter.

As well as suitable watering regimes, non-flow factors impact on key waterbird breeding and feedings sites, such as land clearing protections, fire regime management, and land and natural resource management practices. Other factors such as invasive species management and appropriate hunting regulation and compliance enforcement will be needed to minimize impacts on mortality rates to ensure viable bird populations can be maintained.

Other changes associated with climate change will also have significant direct impacts on bird breeding and recruitment. Changes in natural cues may shift the timing and frequency of breeding events, reducing breeding success rates. More frequent heat waves and associated disease outbreaks will also likely increase mortality rates.

Climate change implications for waterbirds

The frequency of large-scale flooding events is likely to decrease under climate change. This will reduce the breeding opportunities for many waterbird species. It is unclear whether the reductions in inflow expected under climate change will provide regular inundation at a suitable frequency to maintain the vegetation needed to support breeding events when suitable flooding events occur.

While many waterbirds species can opportunistically move to find feeding and roosting habitat, expected increases in drought duration will increase reliance on refugia, and competition for resources at these sites will likely increase. The ability to support waterbird populations through droughts will rely on the maintaining key habitat sites in good condition across the Basin. This is particularly important for some species of colonial nesting birds and migratory shorebirds, who are conditioned to use specific sites.

There is also a possibility in some areas that increases in the magnitude of flooding events will be a feature of the extreme events predicted under climate change, such as level rise in the Coorong and

Lower Lakes and more intense rainfall events. This will also create vulnerabilities for waterbirds by producing inappropriate inundation for the vegetation species relied upon for feeding or nesting resources, or other forms of habitat degradation. Natural disaster recovery and habitat restoration work will be important strategies to manage these vulnerabilities.

Environmental water can be used to provide regular overbank flows in some areas to maintain suitable habitat, and can also be used to extend the duration of flood events to enable waterbirds time to successfully breed. However, the volumes of environmental water available in the Basin are usually not sufficient to provide the initial inundation needed to trigger a significant breeding event.

The ability to water key waterbird sites varies across the Basin. Some sites can be both actively and passively watered with environmental water, but in others there are both physical and policy constraints to the ability to inundate floodplains to water the diverse habitats utilised by waterbirds (e.g. wetlands, lignum shrublands, forests). For some sites in unregulated systems, predominantly in the Northern Basin, watering can only be achieved passively by protecting large unregulated flows from extraction through access license conditions and/or embargos.

Removal of non-flow stressors such as invasive species and inappropriate land management practices will be needed to maintain habitat quality and extent more generally, as flow-based management interventions alone are unlikely to be able to maintain the extent of habitat area, or specific sites, that can support viable bird populations.

With regard to the ability to increase waterbird populations when conditions are suitable, different functional groups of species require different conditions to breed, so maintaining their abundance across the basin will require some unique habitat characteristics. These characteristics and the flow and non-flow factors which affect them are described below.

Large waders

Species of large waders require wetlands for feeding and breeding, and hence will be vulnerable to expected reductions in the frequency and extent of overbank flows and large floods, which inundate these ecosystems to drive floodplain food webs and water suitable nesting vegetation. Large waders have adapted to variable environments and move to take advantage of suitable breeding conditions. To increase the abundance of these species, suitable wetland and nesting habitat will need to be maintained throughout the Basin to enable these species to move to take advantage of suitable conditions to breed. This will also be impacted by vegetation clearing activities, so land management along with flow management will be needed to ensure the habitat needs of large waders is met.

The ability to improve breeding and abundance of large waders is also dependent on other factors which impact mortality rates, such as increases in heat wave periods and increased predation. The number of natural breeding events may also be affected by climatic changes like seasonal temperature changes and shifts in rainfall patterns. Invasive species management may help to decrease predation rates, but climatic changes will need to be addressed through maximising breeding events through the use of environmental water to build population abundance to balance with any increases in mortality.

Colonial nesting birds

Colonial nesting birds breed in large colonies when conditions are suitable, generally when flood events have inundated floodplains to create booms in food resources. Likely reductions in the frequency and extent of these events will reduce these breeding opportunities, and while colonial nesting birds can move to take advantage of suitable conditions, there has already been an observed decline in the population of these species across the Basin due to river regulation, which has already reduced the frequency and extent of these large flow events. Changes in seasonal temperatures and rainfall patterns may also decrease the number of breeding events by removing natural cues for breeding. The volumes of environmental water available in the Basin are not sufficient to provide the initial inundation needed to trigger a significant breeding event but may be used to prime the system ahead of a suitable flooding event, or to extend the duration of the event to avoid nest predation and abandonment.

To support successful breeding events, suitable vegetation will need to be maintained in these breeding grounds, particularly for nesting and roosting. It is currently unclear whether regional variations under a climate change future will provide a suitable frequency and extent of overbank flow events to maintain this habitat, or what impact changing fire regimes will mean for the ability to maintain this critical habitat in the Basin at any one time. Decision making around the use of environmental water will need to be made at a landscape scale and across multiple years to ensure suitable overbank flow events can be provided to maintain a mosaic of these habitats across the Basin, so they are available when conditions are suitable for a breeding event. Managing the impacts of bushfires and vegetation clearing will also help support the maintenance of this important habitat characteristic.

However, it is thought that some species or populations of colonial nesting birds have site fidelity and so are unlikely to move to different sites to take advantage of suitable breeding conditions, making their abundance in the Basin particularly vulnerable. Targeted management interventions will be needed to protect the key breeding sites for these species, including both environmental watering and habitat protection strategies.

The ability to improve the abundance of colonial nesting birds will also be impacted by increases in the regularity and duration of heatwaves, increased pollution, pesticides, predation rates, and disease (botulism) as these changes will likely increase mortality rates. Suitable land management practices will help reduce some of these stressors to increase the resilience of colonial nesting birds to cope with the direct impacts of climate change.

Migratory shorebirds

Migratory shorebirds rely heavily on feeding grounds in the Lower Lakes and Coorong. Many of these species are small so their energetics make them susceptible to any depletion in food resources, and they are conditioned to visit particular sites on their migratory paths. Preserving these species will require the maintenance of a suitable inundation/drying regime to provide the mudflats, shallow water, and vegetation that provide their food resources. Wetting these habitats relies on freshwater inflows from large flow events and climatic changes are likely to reduce the frequency of these inflows.

Water quality issues that affect the health of these feeding habitats are also likely to increase under climate change, including algal outbreaks from high nutrient inflows and the risk of hypersaline conditions during extended droughts. These impacts will need to be managed through the provision of environmental water and careful management of water level oscillation to support the development of vegetation in these feeding grounds, which is particularly important for migratory shorebirds. This will rely on connectivity to be maintained throughout the Murray–Darling system to provide end-of-system flows at appropriate times.

Increased inundation through sea level rises and changes in the frequency and intensity of storm systems are also possible impacts on feeding grounds from climate change. These events will disrupt the lifecycle of the vegetation in these habitats, potentially reducing food resources for migratory shorebirds in these areas.

There are also other non-flow factors which will impact on migratory shorebird numbers directly as a result of climate change, such as increases in heat waves, which may increase mortality rates.

A range of other factors will also impact on the ability to maintain migratory shorebird species. These factors may or may not vary as a result of climate change, and include invasive species, predation rates and habitat loss through inappropriate land management practices. No-regrets management interventions such as invasive species management (including predators), habitat protection and food augmentation could be used to reduce the impact of these factors regardless of climatic change.

It should also be noted that the migratory nature of these shorebirds means they are also heavily reliant on the condition of other (international) habitats and migratory flyways. Developing objectives and investing in the protection of migratory species should be considered in this context.

Ducks

While duck species are highly opportunistic, moving to take advantage of suitable breeding conditions, their numbers may also be affected by climate change. High mortality rates of offspring mean that duck species rely on large flood events to raise multiple clutches to maintain population viability. With the frequency and duration of these flood events likely to decrease, breeding and recruitment of ducks may not provide suitable numbers to counter the high off-spring mortality rates.

Like other waterbird species, ducks will also be sensitive to other factors that impact their ability breed and overcome mortality rates. These factors include predation, heatwaves, water quality events, disease and hunting.

Knowledge, management and policy implications for waterbirds

Given the vulnerabilities of waterbird populations discussed above, there is a need to understand the critical factors for successful breeding of key species and/or functional groups, such as: natural cues and timing for breeding events; important habitat characteristics for feeding and nesting; causes of mortality; how all these factors are likely to change under various climate change scenarios and what impact these changes are likely to have on breeding success and population numbers.

Identifying and monitoring the key waterbird sites across the Basin will also be critical to ensure environmental water management can be used effectively to maintain feeding, roosting and breeding habitat and provide refugia during drought.

There may also be a need to better coordinate planning for environmental watering and the use of available environmental water portfolios across multiple years; to maintain habitat at key waterbird sites and to extend flooding events to maintain a suitable frequency of breeding events to sustain a resilient population structure.

Ensuring flow management is complemented by other non-flow management interventions such as habitat protection and restoration will also be an important for achieving the Basin Plan objectives in relation to waterbirds. These other pressures (invasive species, habitat degradation) could significantly negate any gains made in healthy waterbird populations through water management interventions.

To enable these management approaches, there may be a need to review environmental water planning frameworks and delivery arrangements to ensure they facilitate landscape-scale watering events over multi-year timescales, and ideally are tied in with other non-flow management investments.

Native fish

The expected outcomes for native fish in the Basin-wide environmental watering strategy are for the current species to be maintained, the population structure of key species to improve, for increased movement and expanded distributions, and for improvement in the community structure of key native species.

Flow reliance and other factors at play

River flows of certain volumes, durations and timings are critical to achieving the expected outcomes for native fish. Flows support key life cycle components of native fish such as movement and migration, spawning and recruitment. Flows are also critical in providing a variety of native fish habitats as well as supporting complex ecosystem-scale processes that in turn generate food resources and support native fish growth and survival. For example, freshes provide breeding and migration cues, flow variations create suitable in-channel habitats, large unregulated floods provide connectivity upstream and to the floodplain to support food web productivity, and baseflows provide refugia to sustain fish populations during droughts.

Climate and weather patterns predicted for the Basin are highly likely to affect all flow types to varying degrees. Climate change is also like to exacerbate other factors that already threaten native fish, such as increases in the prevalence of alien fish species, poor water quality, and potential increases in in-stream barriers (e.g. additional weirs and dams to increase water management capacity).

There are also a range of non-flow factors which will increase the vulnerability of fish. These factors may or may not change as a result of climatic changes, but nevertheless place additional pressure on fish and the ability to achieve the expected outcomes for native fish. These factors include the maintenance of floodplain habitats (wetland, anabranches etc.) by managing vegetation clearing and grazing pressure, potential increases in numbers and distribution of invasive species, increases in predation opportunities and mortality, and limited migration due to river management infrastructure. Careful management of recreational fishing is also important to avoid over exploitation of key species such as Murray Cod and Golden Perch. The management of these factors would help to reduce the vulnerabilities of fish species, and unlike some other climate related factors such as water and air temperature are more easily addressed through management interventions.

Climate change implications for native fish

Climate change and its implications for flows and water quality, and how these in turn create vulnerabilities for the Basin's native fish populations, is not yet fully understood. However, there is clear evidence that key life cycle components of many of the Basin's native fish species will be affected by changes in climate and weather.

Riverine specialists

As inflows reduce in many parts of the Basin under climate change, and periods between wet and dry conditions increase, riverine specialists (fish species such as Murray cod; Golden perch) are likely to become more limited in their ability to move and migrate. This can be as a result of disconnections in the system such as when a flow rates drop below those required to overcome barriers to fish movement and when the river moves to a state of disconnected pools.

The inability of native fishes to move will constrain populations to certain areas, making them susceptible to poor water quality as refugia contract during droughts (e.g. disconnected waterholes). Longer periods of disconnection due to reduced inflows will also limit recruitment to other areas and, over time, reduce the age variability and genetic diversity in the local population, in turn decreasing their resilience to future change. Careful management of environmental water and extraction during these low flow periods can help maintain refugia. However, management options decrease in extended droughts as water allocations are reduced, high conveyance losses prohibit environmental water delivery, maintaining critical human water needs becomes the priority, and the risk of water quality events increases. Connectivity issues are perhaps more significant in the Northern Basin where conditions are generally drier for longer than the Southern Basin and there is less river regulation to enable environmental watering.

The return (for example after prolonged low-flow conditions) of longitudinal connectivity flows are important to rebuild fish populations along the river system through migration and breeding. These large-scale events are particularly important for some species, such as golden perch and silver perch, whose lifecycles involve migrating often over long distances to breed. These species will require system-scale management when large unregulated flows occur to provide breeding cues to migrate, connectivity to travel upstream, further cues in breeding grounds to spawn, then maintenance of suitable habitat and conditions for hatching/development of young.

Longitudinal connectivity flows also support a wide range of fish species that do not require system-scale connectivity to support recruitment. Longitudinal connectivity provides opportunities for isolated populations to disperse, providing opportunities for genetic mixing and improved resilience in the long-term. As the frequency of these large flooding events is likely to reduce, system-scale management will be needed to maximise the breeding opportunities from these events as well as reconnect isolated fish populations and ensure recruitment populations are dispersed throughout the river system.

The variability of smaller flows such as freshes and bank full flows are also likely to change in frequency and amplitude as a result of climate change. Such changes have already occurred in regulated systems and represent a particular vulnerability for riverine specialist fish species in the Southern Basin due to the high levels of flow regulation. Flow variability provides natural cues for migration and breeding as well as providing suitable flow conditions and inundating or creating habitats for nesting and nurseries such as snags, undercut banks and anabranches. The loss of these natural cues and flow variability has already, and will likely further, decrease breeding opportunities and impact fish population size as well as structure. Flow management may be able to artificially replicate these conditions in regulated systems but will require a careful balance between providing unseasonal high-flows to meet consumptive demands and managing for cold-water pollution. There is also evidence that managed flows cannot fully replicate the complex hydrological interactions in the landscape that support the habitat diversity of healthy river-floodplain ecosystems (Bond et al. 2014). Extraction rules may protect key components of the flow regime in unregulated systems when they occur but will not be able to address a change in the natural frequency of high-flow events.

Wetland and floodplain specialists

Many of the Basin's native fish species rely on the habitats and food resources on off-stream wetlands and floodplains, which can be replenished and accessed by lateral connectivity flows such as overbank and large flood events. Floodplain habitats support the many short-lived, wetland-specialist species (such as Murray hardyhead, olive perchlet, southern pygmy perch, and many others) and are also important for boosting food webs through the breeding and dispersal of these floodplain species, as well as cycling carbon and nutrients from the floodplain into the river system to drive productivity. The likely reduced frequency of inundation of these floodplains under climate change will have further significant impacts on these species which rely on submerged vegetation and other habitats and food sources that are provided by wetlands and floodplains. Further declines in these small-bodied, short-lived species will have flow-on effects to aquatic food webs, decreasing access to food resources and therefore increasing the vulnerability of all aquatic species, particularly large bodied fish species, water birds and other fish-eating species such as turtles.

Environmental water can be used to assist with the provision of overbank flows, and with the removal of constraints to floodplain inundation, environmental water can also be used to extend the duration of flood events to enable wetland specialists to successfully connect to important habitats and spawning areas. However, the volumes of environmental water available in the Basin are generally not sufficient to provide the initial inundation needed to trigger these high-flow connections.

Estuarine specialists

The Murray River's interactions with the Coorong and Lower Lakes, and the movement of water through the mouth of river into the Southern Ocean, are both critical for estuarine specialists (such as black bream and mulloway). Flows to the Lower Lakes and Coorong are required each year to maintain suitable estuarine habitats and flows to the sea. Periodic high flow years are important to refresh and inundate the higher fringing habitats of the Lower Lakes, provide widespread connectivity between the Lower Lakes and Coorong, and provide significant outflows to the sea to provide freshwater 'signals' for species that spend periods of their lifecycle at sea.

The inflows from these large-scale events create salinity gradients which prompt some estuarine fish species to breed or migrate and increase lake levels to inundate suitable breeding and feeding habitat, similar to the effect of floodplain inundation in freshwater systems.

The frequency of large unregulated events is likely to decrease under climate change and this effect could be compounded by increased demand for extraction of water during these events to compensate for reduced consumptive allocations over extended dry periods.

These large inflows of fresh water as well as more regular freshes are also critical to maintain salinity levels that are within the habitable range of some species. Provision of environmental water to maintain lake levels and dilute salinity between larger flow events will be important.

Knowledge, management and policy implications for native fish

Given the management challenges resulting from expected climatic changes discussed above, there are some critical knowledge gaps which need to be addressed to ensure river management can reduce the vulnerability of native fish to climate change. Understanding the flow cues and breeding and recruitment conditions for key species, particularly when connectivity is needed, will enable environmental water holders and river managers to attempt to replicate these conditions as much as possible to ensure viable fish populations are maintained. Gaining a better understanding of the likely changes to non-flow factors as a result of climate change and improving the effectiveness of management interventions would provide management options in addition to flow.

There will also be a need to improve river management to ensure coordinated, system-scale delivery of all available water which can contribute to ecological outcomes as water resources decrease. River management arrangements also need to better accommodate the use of environmental water to ensure this water can be used as effectively as possible to support adaptation to new climatic conditions.

Effective use of environmental water will also rely on the full implementation of the Basin Plan requirements around constraints so that floodplain inundation can be achieved and important ecosystem processes maintained. This coordinated management capability, along with improvements in compliance, will need to extend to large unregulated events to ensure that connectivity is maximised. There would also be significant value in improving the integration of river management with other natural resource management activities to reduce the vulnerabilities created by non-flow factors such as land management practices and invasive species.

To achieve some of the increased management capability described above, there may be a need to review existing water planning and delivery frameworks and river operations arrangements and regulatory conditions to ensure to ensure decision-making explicitly considers how to reduce impacts of river regulation on native fish and facilitates system-scale use of water for multiple benefits.

Key insights

The following commentary presents some of the key insights that have emerged from the vulnerabilities assessment. These insights capture a range of complex issues which influence the vulnerability of Basin ecosystems, communities and industries to climate change. The insights provide key focal points for future work to ensure water management efforts in the Basin can respond to the realities of climate change.

Adaptation

One of the central goals of the Basin Plan is to maintain the resilience of Basin ecological systems, underpinning the assumption that with this will come the capacity for the Basin's ecology to adapt and persist under uncertain climatic changes. However, the magnitude of impact that climatic changes will have on Basin ecological systems under current Basin Plan settings is not yet clear, and the results of the vulnerability assessment suggest that some ecosystems will fundamentally change as flow regime changes occur.

Focus may need to shift to how to more actively support the adaptation of species and water dependent ecosystems. The results of the vulnerability assessment suggest it would be prudent for water resource management to plan for the transformation of some ecosystems, with a view to ensuring the functions they provide can be maintained or supplemented by management activities. This does not suggest however that the current focus on system resilience should be discarded. Rather, it indicates the need for innovative multi-approach solutions that combine water management with other actions.

Given the extent of climate variations that are now being experienced, there is a need to consider whether this prevalent resilience management approach will be sufficient to maintain healthy Basin ecosystems. The goal of a healthy working Basin may therefore need to be achieved by broadening the Basin Plan's objectives to not only aim for ecological resilience, but to support the adaptation of ecosystems to ensure the Basin as a whole continues to function ecologically.

The need for adaptation support extends to Basin communities, who are experiencing their own major shifts in regional economies and subsequent changes to the social fabric of towns and regional communities. The impacts of a decade of water reform under the Basin Plan, along with other significant economic and demographic drivers, are now being exacerbated by an extended drought. There is increasing certainty in the climate science that the conditions currently being experienced will be more common in the future. Basin communities need support to not only cope and recover from current conditions, but to plan and prepare for the variable conditions to come.

This need for support recognises the disparity of impacts felt across communities to date – be they related to climate change, water reform, or other socio-economic drivers – which are a direct consequence of their variable levels of adaptive capacity. Access to infrastructure, services, and financial capital, levels of social cohesion and other forms of social capital will determine how well communities are able to adapt to changing circumstances or respond to major upsets. Addressing these issues requires building the capacity of communities through information, learning, problem-solving and adaptive decision-making models at the local scale – much of which requires ongoing and significant financial support. While this goes well beyond the MDBA's immediate remit, policy interventions and financial assistance will need to work alongside the efforts of local and state institutions, if successful adaptation is to be realised.

In a changed climate where ecosystems, communities and industries may shift to new states regardless of Basin Plan management, or even broader Government interventions, the Basin Plan will need to evaluate whether adherence to its current strategy for achieving objectives is possible and if those objectives still represent the optimal balance of social, economic and environmental outcomes.

Ecosystem services

Functioning ecosystems providing a range of services and benefit to communities; be they recreation and amenity, maintaining spiritual connections and cultural practice, or natural resources that can be utilized for, or support, economic productivity. Thus, many of social and economic objectives of the Basin Plan are actually dependent on the achievement of the ecological objectives. The 2017 Evaluation identified and assessed four of the ecosystem services that directly or indirectly affect social and economic outcomes: amenity; recreation; tourism; and services to agriculture (MDBA, 2017). The 2017 Basin Plan Evaluation demonstrated how reliant these outcomes are on the regular occurrence of average or wet conditions in the Basin (MDBA, 2017). These conditions are much less likely under climate change.

The cost-benefit assumptions inherent in the Plan rely heavily on cumulative benefits to environments and ecosystem services over the coming decades. However, the expected cumulative benefits over time will be compromised by prolonged dry periods with low flows, connectivity issues and relatively limited water available for environmental watering to enable maintenance or improvements in ecosystem services.

The cumulative benefits to amenity, tourism, recreation and agriculture from ecosystem services are therefore also highly vulnerable. The result of this vulnerability is that new and difficult trade-offs for regions and the Basin as a whole can be expected, and the current settings of the Plan will need to reflect the decisions that are made to ensure Basin communities, industries and ecosystems are climate ready and adaptable. This will challenge the MDBA to develop new and innovative ways to generate lasting agreement within the Basin about the trade-offs made by future management arrangements.

These circumstances will also challenge the current management approach to Basin Plan ecological objectives, which target the protection and restoration of key species and water dependent ecosystems. Connectivity flows are a key management strategy as a means of achieving these objectives. However, direct objectives to provide ecological functions such as nutrient/carbon cycles, food web productivity, and salt flushing may drive not only a better understanding of these processes to support ecological adaptation but help to deliver the multiple benefits these ecosystem services provide industries and communities across the Basin.

Such as shift in management objectives will be challenged by a lack of scientific knowledge and immaturity of management arrangements to manage across catchments, water portfolios, and jurisdictional operational rules. As such, adopting a shift in management approach will require significant and collaborative adjustment of existing management frameworks.

Multiple outcomes

This assessment has revealed that the objective to optimize environmental, social and economic outcomes in the Basin is highly vulnerable, as climate change will reset the balance of costs and benefits expected under the current Basin Plan in ways that are not yet properly understood.

The fundamental purpose of the Basin Plan is to balance water use for consumptive and environmental use. However, these two uses are not mutually exclusive, and redressing the balance is about more that allocating volumes of water. As a drying climate shrinks water availability during longer dry periods, continual improvement will be needed to ensure all the available water is being to put to efficient and effective use, including achieving multiple outcomes for consumptive and environmental users alike, including the less 'traditional' consumptive users, such First Nations' peoples, and all communities who value the amenity, recreational opportunities, and other aspects of a healthy and integrated ecological and anthropogenic system .

In some areas, managing the environmental impact of decades of over extraction alongside the need to maintain ecosystem services will be challenging. Innovative solutions will be required in the realm of water management, but also in other areas. In this vein, other options may also need to be considered to supplement flow management or manage climate change impacts that flow management is ineffective at dealing with. For example, invasive species have significant impacts on ecosystem function, and flow regime management is ineffective on its own to manage these impacts. Complementary natural resource management practices such as invasive species control, land management, native vegetation and revegetation, and soil conservation therefore represent no-regrets management interventions that play an important and possibly critical role in enabling Basin ecosystems to cope with whatever climatic changes occur.

Collaborative management between river operators and catchment managers is already embedded in Basin Plan implementation and River operations. However, a framework to enable better integrated catchment management at a Basin scale may be needed to ensure system-scale flow management can be delivered to complement other management interventions. This would help achieve optimal outcomes from the water available.

Climate change raises complex questions about whether the environmental restoration objectives (and the flow on benefits for communities and economies) can really be achieved under the current Basin Plan settings. As a result, the overall objective of optimizing social, economic and environmental outcomes under the Basin Plan must be assessed as highly vulnerable to climate change, and new management approaches will need to be explored to ensure water resource management is as efficient and effective as possible.

Adaptive management framework

The central feature of the Basin Plan is the re-balancing of how water is shared between consumptive uses and the environment and building a framework that can adaptively manage this balance in a variable climate (MDBA, 2018).

The Basin Plan's adaptive instruments consists of water trade, adjustable Sustainable Diversion Limits and water sharing arrangements in the MDB Agreement, Basin Plan and Water Resource Plans (WRP) that respond to available water resources. While these governance measures are designed to function across a range of water availability, the system is vulnerable because it is largely untested under the full range of scenarios climate change may present.

The setting of Sustainable Diversion Limits (SDLs) for each catchment in the Basin and their subsequent expression within State Government WRPs provides for certainty around the levels of access to water. Because of Australia's highly variable climate, the amount of water available to allocate for consumptive use under the SDL changes from year to year and depends on storage levels and weather conditions. Governments can also adjust the Baseline Diversion Limit, through a water resource plan which will in turn change the SDL.

Longer term certainty is supported by clear pathways for how and when these may be adjusted in response to better or new information about water resources and the future (including climate change) and how necessary recovery of water from the consumptive pool for the environment may be undertaken. The specific arrangements for changes to SDLs are then designed to provide time for communities and water users to adjust to a new operating environment. Recently an objective of maintaining and improving socio-economic outcomes has been added to the remaining water recovery due to be completed under the Basin Plan (Murray–Darling Basin Ministerial Council, 2018).

SDLs themselves operate within a wider governance framework comprising the water sharing arrangements agreed by Basin jurisdictions under the Murray–Darling Agreement and the State water entitlement and water sharing arrangements that apply in each irrigation area as per the relevant water resource plans and enabling state legislation and governance arrangements. This means that in response to a changing climate, there are a series of pathways for policy changes to be enacted by governments and water management authorities to facilitate adjustment of the system.

Flexible water sharing and management arrangements are designed to respond to seasonally available water with diversion limits that can be changed in response to new information to share water between the environment and agriculture and to safeguard critical human water needs. Water trade enables water to move to more productive uses as water scarcity increases prices. Environmental water management can be altered and improved to better secure water quality and ecosystem services in a changed climate. Together these arrangements comprise a large and complex adaptive management system for the Murray–Darling Basin that has significant capacity to succeed in adapting the Basin to climate change.

These arrangements provide a comprehensive framework for managing the consumptive pool in a way that can adapt to variable climatic conditions and new information. However, in practice, the management arrangements that enable them are often still being established and/or remain relatively untested in the difficult climatic conditions that will be more prevalent under climate change. Some scientists also argue that no allowance has been made in the SDLs for long-term climate change to adequately partition water use adjustment for consumptive users and the environmental health needs of the river systems (Pittock, et al., 2015).

The recent experience in the Lower Darling is instructive. As the system was heavily impacted by the current drought, the outcomes delivered by water sharing arrangements proved ineffective in supporting the basic health of riverine ecosystems and safeguarding critical human water needs. The inquiry and response to recent fish deaths in the Lower Darling are revealing of the extent to which the Basin Plan and its associated instruments will be challenged by climate change (Vertessy, et al., 2019). The recommendations of the inquiry include significant changes to water sharing arrangements to better cope with the environmental and socio-economic impacts of low flow conditions in the future as well as additional structural adjustment programs to facilitate a shift in consumptive use in the region. In effect, the inquiry recommends a reset of the recently reformed water management arrangements as their practical implications for the environment and communities have become clear. As the practical consequences of governance arrangements become clearer in other regions, further substantial changes are likely unless the systems trade-offs are better stress tested for extreme dry conditions.

While the intent of reforms is clear and appropriate to provide capacity to manage water under climate change, the Basin plan’s key governance arrangements cannot yet be considered to be a stable, adaptive management framework that can be assured of delivering on the objectives of certainty under climate change. The framework’s practical capacity to deliver outcomes under the continued pressure of climate change remains relatively unknown.

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Appendix A: Assessment approach

There are a large range of approaches to conducting vulnerability assessments documented in scientific literature, government policy and strategy, and other guidance documents. Vulnerability assessments are conducted in the context of climate change as well as public health, natural disasters and socio-economic development issues. Assessment methods need to consider the specific information needs, purpose and decision-making context of the assessment (European Environment Agency, 2018). There are, therefore, no ready-made 'off-the-shelf' solutions to how to conduct a vulnerability assessment (German Corporation for International Cooperation, 2014).

The purpose of the vulnerability assessment is to canvass what Basin Plan outcomes are at risk of climate impacts across the Basin, describe why they are vulnerable, and describe the capacity to adapt to climate change to reduce the vulnerabilities. The assessment will provide qualitative descriptions of what is likely to be vulnerable to climate change in the Basin and identify the current adaptation opportunities to reduce these vulnerabilities. These assessment results will then enable prioritisation and further detailed assessment of vulnerabilities to be conducted under different climate change scenarios, and to explore the policy settings in the Basin Plan that can enable adaptive management of Basin water resources, in subsequent phases of the Climate Change Program.

Identifying *what* is vulnerable is critical to the assessment producing meaningful results, but vulnerability is a difficult concept to define and measure (Hinkel, 2011). The Intergovernmental Panel on Climate Change (IPCC) understands climate change vulnerability as a function of how **sensitive** something is when **exposed** to a potential hazard, and its ability to **adapt** to changes and impacts created by this hazard (Intergovernmental Panel on Climate Change, 2014).

For this Scan phase vulnerability assessment, the MDBA has decided to initially assess how vulnerable the broad objectives of the Basin Plan will be to climate change and climate variability. This will enable the MDBA to understand what impact a changing climate will have on the ability to achieve the objectives of the Plan, how to stay on track to achieve them, and where they may no longer be sensible objectives in the face of climate uncertainty. However, the objectives of the Basin Plan are high level. The MDBA's approach to conceptualising these objectives to enable a systematic assessment of ecological and socio-economic vulnerabilities is set out below.

Assessing ecological vulnerabilities

Ecological objectives have been translated into more specific objectives in a number of policy documents such as the Basin-wide Environmental Watering Strategy (MDBA, 2014) and the 2017 Basin Plan Evaluation (MDBA, 2017). These specific objectives are largely related to the ecological outcomes the Basin Plan aims to achieve, and further work has also defined measurable categories to monitor and evaluate the achievement of objectives. For example, the objective to maintain the diversity of waterbirds and improve numbers and breeding success is broken into categories of general types of waterbirds such as large waders, colonial nesting birds and migratory shore birds.

The specific objectives and categories assessed in this report are listed in **Error! Reference source not found.**.

The vulnerability assessment considers the sensitivity and adaptive capacity of these categories in relation to the specific objectives. For example, how vulnerable will the ability to improve breeding success (specific objective) of colonial nesting birds (category) be, given potential climate-driven changes to key factors that underly breeding success and the birds' capacity to adapt to these changes?

Table 1: Specific ecologcial objectives and categories assessed

Specific objectives	Categories
Ecological objectives	
HABITATS: Maintain and extend important habitats of water-dependent ecosystems and environmental assets	In-stream, riparian, near channel, floodplain, and estuarine habitats
VEGETATION: Maintain extent and improve condition of key vegetation communities	Redgum forests, redgum woodlands, blackbox woodlands, lignum shrubland, wetland vegetation, submerged estuarine vegetation, riparian vegetation
FISH: Maintain current species diversity, extend distributions and improve numbers and breeding success	Short-lived, medium-long lived, estuarine, floodplain specialist, and in-channel specialist species
BIRDS: Maintain current species diversity, improve numbers and breeding success	Large waders, colonial nesting birds, migratory shore birds, fish-eating birds, and ducks
WATER QUALITY: Basin water resources are fit-for-purpose for cultural, environmental, social and economic use	Water-dependent ecosystems, raw water for treatment for human consumption, irrigation water, recreational water quality, salt export
RIVER CONNECTIVITY: Maintain base flows; increase tributary flows and flows to the Murray Mouth; maintain surface water-groundwater connectivity, and maintain and where possible reinstate connection between rivers and their floodplains	Lateral, Longitudinal, groundwater-surface water, end-of-system flows

To assess the potential impact of climate change on Basin Plan ecological objectives, the vulnerability assessment sought to identify key factors underling the achievement of the objectives that are likely to change with a changing climate. The vulnerability of the objectives can then be assessed in terms of how sensitive their attainment will be to changes in these factors.

For example, to protect and restore water-dependent ecosystems, maintaining lateral connectivity between rivers and floodplains is critical. Factors that underpin the maintenance of lateral connectivity include over-bank flow events and removing physical barriers to water moving onto the floodplain.

The identification of factors focuses on flow regime components as well as non-flow factors. Separating out the flow-based factors will enable the MDBA to conduct more detail analysis of vulnerabilities in the next phase of the Climate Change Program, when an array of climate change scenarios has been produced. These scenarios will provide more details on how flow regimes are likely to change under the best available climatic projections (e.g. frequency, duration, extent of flow events). Identifying flow-based factors will enable the MDBA to test the management interventions that are within its remit in the next phase of the Climate Change Program. Identifying the contribution of non-flow factors to vulnerability is also important for understanding the full suite of management interventions that could support adaptation, either through amendments to the Basin Plan, or via other policy mechanisms.

This framing of vulnerability will allow the MDBA to understand how Basin Plan objectives will be vulnerable to climate change and variability and what flow management and other interventions need to be explored to determine the best adaptation options.

For the purposes of this vulnerability assessment, sensitivity is understood as how Basin Plan objectives will be affected by change in an underlying factor. For example, the ability to maintain floodplain habitats will be sensitive to any changes in overbank flow events but won’t be sensitive to changes in baseflows.

In the absence of climate change scenarios, the assessment will consider how likely changes in factors will impact the ability to achieve the objectives. For example, floodplain habitats will be sensitive to decreases in the frequency and magnitude of overbank flows, as these changes will result in longer dry sequences and less inundation extent and duration of these habitats. These qualitative statements of vulnerability will provide a better understanding of what creates the vulnerabilities likely to be experienced, which can be further explored through the CCP moving forward.

Vulnerabilities can be mitigated/reduced if there is capacity to adapt to the changes that are experienced. This assessment explores both the intrinsic capacity for ecosystems and species to adapt, and the extrinsic management interventions that could support adaptation. For example, some fish species can migrate to cope with reductions in flows, and the maintenance of connectivity between river systems will support this adaptive capacity.

This consideration of intrinsic and extrinsic adaptive capacity will enable the MDBA to understand what management options are available to manage vulnerabilities. These options can then be tested against the climate change scenarios in the next phase of the CCP.

The outputs of the assessment are qualitative statements about what likely climate change factors will create vulnerability to the achievement of Basin Plan objectives, and what adaptation options are available to reduce or mitigate these vulnerabilities.

Workshops with internal MDBA thematic experts produced statements of how Basin Plan objectives may be vulnerable under potential changes in climate. The MDBA’s external Communities of Practice were asked to provide feedback on whether the statements were accurate, and whether any major aspects of vulnerability had been missed. The results were then cross-checked with existing state-based climate vulnerability or risk assessments, any relevant scientific literature, and the interim results of related reviews and evaluations being conducted by the MDBA or external experts.

Assessing socio-economic vulnerabilities

As a scan phase assessment, the work on socio-economic vulnerabilities has been done rapidly based on existing literature. Similar to the ecological vulnerabilities, the assessment sought to understand how socio-economic Basin Plan objectives may be sensitive to likely changes in factors which underlie their achievement, and the capacity to adapt to these likely changes.

The recently released framework for evaluating the Basin Plan captures key management outcomes and objectives for the Basin Plan, including the key socio-economic objectives (see Figure 1). These outcomes and objectives are organised into five groups including whole of Basin Plan objectives and outcomes as well as environmental, water quality, sustainable diversion and water trading groups. These have been used to structure the socio-economic assessment process.

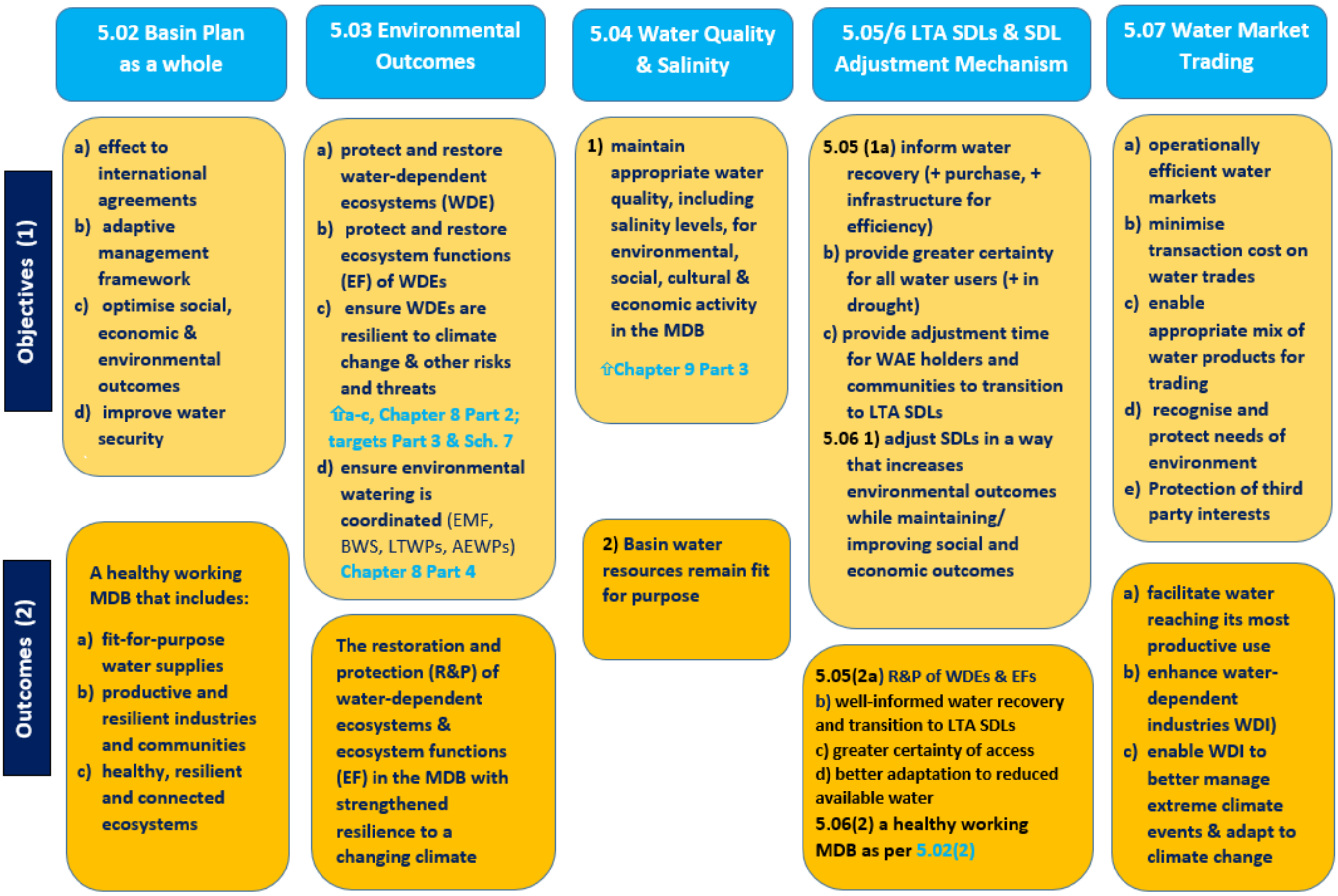

Figure 1: Management Objectives and Outcomes to be achieved by the Basin Plan (MDBA, 2019)

In relation to these socio-economic objectives, the central feature of the Basin Plan is the re-balancing of how water is shared between consumptive uses and the environment and building an adaptive management framework that can maintain this balance over time (MDBA, 2018). As such, the socio-economic objectives of the Plan are primarily aimed at facilitating progress to or attainment of systemic attributes such as certainty, adjustment, confidence, adaptive management and balance. A range of policy mechanisms (such as water trade rules) and direct and indirect effects of the Basin Plan's governance mechanisms aim to facilitate progress towards these socio-economic objectives.

Given this complexity of management impacts as well as the complexity of the Basin's socio-economic systems generally, the socio-economic vulnerability assessment will be undertaken by considering how various key factors shape the socio-economic systems experienced in the Basin. The socio-economic objectives and factors are listed in Table Table 2.

Table 2: Socio-economic objectives and factors

<table>
<tr><th>Objectives</th><th colspan="4">Factors</th></tr>
<tr><td></td><td>Catchment lens</td><td>Water Dependent Industry presence</td><td>Hydrologic/ Ecological factors</td><td>Other factors</td></tr>
<tr><td>Adaptive management framework</td><td rowspan="10">Northern Basin
Southern Basin</td><td rowspan="10">Cotton
Rice
Dairy
Vegetables

Permanent Horticulture:
- Grapes
- Almonds
- Citrus
- Apples, Pears and Other Fruit

Other Irrigated Crops</td><td rowspan="10">Connectivity
Fish
Water Quality</td><td rowspan="10">National and global climate change mitigation activities
Population size and remoteness
Dryland agriculture
Global markets for products and services
Technology and innovation
Industry employment and workforce trends
Climate variability
Levels of Investment in the Basin Economy and Communities</td></tr>
<tr><td>Optimise social economic and environmental outcomes</td></tr>
<tr><td>Improve water security</td></tr>
<tr><td>Maintain appropriate water quality</td></tr>
<tr><td>Social and economic benefits of environmental watering (amenity, tourism, recreation and services to agriculture)</td></tr>
<tr><td>Adjust SDLS in a way that increases environmental outcomes while maintaining/improving social and economic outcomes</td></tr>
<tr><td>Provide adjustment time for communities to transition</td></tr>
<tr><td>Operationally efficient water markets and minimise transaction costs</td></tr>
<tr><td>Enable an appropriate mix of water products</td></tr>
<tr><td>Recognise and protect needs of the environment</td></tr>
</table>

Each factor will be considered where relevant to the socio-economic objectives. The broader interaction of interdependent factors will be explored to understand how socio-economic systems are shaped by these influences, and what implications this may have for the system characteristics, the Basin Plan seeks to develop.

Each factor is described briefly below and will be considered as part of the vulnerability assessment to ensure a level of nuance and detail that can focus future work and research.

Catchment (Region): The Basin is made up of a series of variously connected catchments (regions) in which unique mixes of communities and economic activities are located. Climate change is also forecast to have different hydrological impacts in the different catchments (regions) of the Basin (CSIRO, 2008) leading to variations in the nature and combinations of vulnerabilities within the Basin. Regional variation has been considered at a high-level for this scan phase assessment, focusing on recognised differences between the northern and southern Basin. Further work to bring together the likely climate change impacts at a regional scale will be achievable once modelling work to understand the climate impacts on hydrology at the catchment scale is completed.

Industry mix, particularly dependence on Irrigated Agriculture: Some parts of the Basin economy are particularly vulnerable to changes in the Basin's hydrology as they are more reliant on economic activities that are substantially derived from the consumptive use of water. For example, the MDBA identifies a series of water dependent industries and irrigation dependent communities which have been a focus for monitoring the impacts of water recovery on the Basin economy and communities (MDBA, 2018) as these areas and industries are most directly vulnerable to changes in consumptive water availability. This factor will enable the relative industry vulnerabilities to be considered.

Hydrological and Ecological Factors: The ecological assessment identifies a series of categories for the Basin Plan's environmental objectives which need to be considered in this assessment. Three categories – fish, connectivity and water quality - link directly to the socio-economic objectives of the Basin including the direct and indirect socio-economic benefits of e-watering that have been measured in previous evaluations as well as the effective functioning of water markets and the consumptive pool.

Other Factors: A range of factors not influenced by the Basin Plan or hydrology of the Murray–Darling Basin will impact on the socio-economic vulnerability of the Basin. These include (but are not limited to):

- National and global climate change mitigation activities
- Population size and remoteness
- Dryland agriculture
- Global markets for products and services (such as irrigated output or crops)
- Industry employment and workforce trends
- Climate variability (as distinct from Climate Change)
- Levels of investment in the Basin economy (such as investment in water markets and agricultural businesses)
- Technology and innovation (such as water efficient production innovations)

The broad interaction of these other factors will be considered in the vulnerability assessment process.

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