Issues in managing a large river at a Basin scale

A report prepared for the
Murray–Darling Water and Environment Research Program

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Rebecca E. Lester[1], David Robertson[2], Joel Bailey[3] and Lara Palmer[3]

[1]Centre for Regional and Rural Futures, Deakin University, [2]CSIRO Land and Water, [3]Murray–Darling Basin Authority

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The authors pay 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.

Location:

Geelong Waurn Ponds Campus

Locked Bag 20000

Geelong Victoria 3220 Australia

For more information about CeRRF, Deakin University, visit the website www.deakin.edu.au/cerrf

EXECUTIVE SUMMARY

Australian Government agencies are required to manage the Murray–Darling Basin as a whole, considering future climate change and facilitating adaptation to ensure a healthy, working Basin. This presents challenges and opportunities, given the scale of the Basin, the plurality of uses and value that exist within in and the uncertainties associated with what the future may hold. This issues paper identifies current strengths, challenges and opportunities associated with Basin-wide management and then proposes a framework for Basin-wide monitoring and management to foreshadow future Commonwealth capability expansion.

There are a range of core strengths that provide the basis for greater capacity to manage the Murray–Darling at a basin scale. Since the inception of the Basin Plan, substantial progress has been made, by State and Federal Governments, to increase their capacity to monitor, manage and evaluate values and vulnerabilities within the Basin. Other stakeholders have developed the capacity to improve science to underpin the management of the system. Current strengths include the ability to manage at the catchment and sub-catchment scale, where much previous management has been focused. Annual and seasonal planning is also a current strength, as is our extensive knowledge of, and ability to model, hydrology. Finally, capability is best developed focusing on actions that are under the direct control of managers.

Despite the core strengths and focus on increasing capability in recent years, some challenges remain. Monitoring of the Basin as a whole is a challenge, due to its scale and the range of bioregions it covers, for example. Long-term monitoring and assessment requires time to accumulate, as well as new capability. The plurality of values and vulnerabilities across the Basin means that there are many responses that need to be considered and the impact of future climate and plausible adaptation options are uncertain, many and varied. Many of those adaptation options will involve actions outside the direct control of managers and there is an urgent need to better involve the community and First Nations in decision making and to address past errors that have tended to foster mistrust. Finally, there are real challenges associated with attempting to manage under deep uncertainty.

Opportunities exist to help to meet these challenges. Enhanced integration, across value types, would assist in the identification of synergies and trade-offs. This would help in the management of the Basin across the quadruple bottom line of economic, social, environmental and cultural values and to break down the false narrative of the dichotomy between a robust economy and a healthy environment. Partnering across lines of influence would provide the opportunity to extend the sphere over which the impact of management was felt. The many stakeholders and institutions that work and live in the Basin bring different perspectives, skills and abilities that, together, will enhance the ability of Basin communities to adapt to future climates. Finally, there is the opportunity to embrace uncertainty in decision making. The science of decision making under deep uncertainty has developed approaches such as robust decision making and dynamic adaptive planning which offer pathways to identify decisions that are likely to be satisficing under many plausible futures or to take initial decisions but have a set plan for assessing response to those decisions and adapting as needed. A risk portfolio approach could also be useful, where some actions that are low risk but possibly also low gain are included alongside higher risk but higher gain options and clearly communicated as such.

To address some of the challenges and opportunities, as well as build on the existing strengths, we propose a framework for management at a Basin-scale. The values held by different stakeholders in the Basin will overlap and intersect. They may change through time and among locations and will

certainly vary in their vulnerability to changing future climates. Mapping and understanding these values and vulnerabilities is the first step, followed by understanding and prioritising which of those values can and should be protected where it is unlikely that all can be protected – this must be based on a robust and open conversation with the community. To maximise the likelihood of protecting those values and vulnerabilities, adaptation will be required, but it is often unclear what the most effective adaptation might be and how it will interact with other adaptations and actions already underway or to be implemented. Modelling can be used to assess the efficacy of proposed actions under a range of future climates and conditions, seeking to understand the impact of actions within MDBA's control and those that are not. The outcomes of such modelling can be used to inform communities and decision makers as to the possible impact, or under what range of plausible futures that option is satisficing. This approach can be augmented by the use of clear causal networks that make the causal and correlative relationships used in modelling transparent. These will assist with the critique of the process, enable it to be updated as new knowledge arises and facilitate communication. Thus, the approach would seek to be a tool able to be used to develop trust in the process used to assess the possible impact of future climates or adaptations and provide a basis for robust discussion of priorities and options with the community.

Ongoing investment will continue to develop capability to address the challenges and knowledge gaps associated with the holistic management of the MDB. MDBA has identified a range of science needs, including the development of a climate adaptation framework, review of existing methodologies and better connections between First Nations knowledge and Basin water management, among others. MDBA-coordinated programs such as MD-WERP, the Integrated River Modelling Uplift, as well as other State, Commonwealth and partner-led programs will seek to address these knowledge needs. Additional consideration may be needed to facilitate the development of additional tools to capture responses in social, economic and cultural values, integrate those values to explicitly identify trade-offs and synergies, reduce the current complexity in the number of indicators that are used to represent outcomes, to communicate the basis for decisions effectively and to embed frameworks to support decision making under deep uncertainty.

Management of the Murray–Darling Basin will continue to evolve. This will be in response to a changing climate, as we grow our understanding of the processes and drivers affecting values in the Basin, and as communities and ecosystems adapt. Recent years of fire, flood and pandemic have shifted Australia's perception of the uncertainty associated with the future, creating an opportunity to have deep conversations with communities about the future of the Basin and how best to respond. Adaptive management, based on clear links between monitoring, evaluation and future policy, with tenets of decision making under deep uncertainty underpinning the approach, will be needed to assess the efficacy of that planned response. There will be challenges associated with the management of the Murray–Darling Basin under a changing future climate. Difficult decisions will be needed regarding values that may not be able to be supported under that future and how best to deal with those people, industries and ecosystems that may be displaced as a result. But the same change will also bring new opportunities for different, more effective and more holistic ways of living and creating livelihoods in the Basin. In the end, successful Basin-wide management of the Murray–Darling will require open, respectful and effective communication with the community, as they decide what they would like the future of the Basin to be.

TABLE OF CONTENTS

1. INTRODUCTION

Australian Government agencies are required to manage the Murray–Darling Basin (MDB) as a whole, considering future climate change and facilitating adaptation to ensure a healthy, working Basin. The MDB covers 1 m km^2, including sub-tropical through to arid zones, irrigated and dryland agriculture and urban centres. Thus, any attempt to manage at that scale presents a significant challenge.

The Murray–Darling Water and Environment Research Program (MD-WERP) is an Australian Government initiative to strengthen the scientific knowledge of the Murray–Darling Basin. The Murray–Darling Basin Authority act as the Commonwealth coordinators, in collaboration with the Commonwealth Environmental Water Holder and the Department of Climate Change, Energy, the Environment and Water. The Climate Adaptation Theme of MD-WERP will generate a range of knowledge, tools and capacity to assist with this process, as will the other themes within MD-WERP. Despite this, past experience has demonstrated that research programs can fail to influence management and policy for a range of reasons, despite best intentions. These reasons can include mutual lack of understanding of processes and constraints, a lack of acceptance of tools by end users and a mismatch between the scale of research and the scale at which decisions are made.

This project will seek to avoid these pitfalls and will focus on synthesising outputs and learnings from the main research activities across the Climate Adaptation Theme. The Theme has a particular emphasis on maintaining strong links between researchers and the users of the information – thus, the project will ensure that co-design is followed by co-development and co-application. To assist with this task, we here hypothesise a framework for managing the MDB at the Basin scale. We will later revise this framework based on the outcomes of MD-WERP and synthesise the results and findings across the Climate Adaptation Theme to create management-oriented recommendations at a scale directly relevant to upcoming processes such as the Basin Plan review.

This issues paper identifies current strengths, challenges and opportunities associated with Basin-wide management and then proposes a framework for Basin-wide monitoring and management to foreshadow future Commonwealth capability expansion. In developing this, we are focused on ensuring transparency around decisions made as a part of planning for, or delivery of, MD-WERP's Climate Adaptation Theme, clarity regarding scope and ensuring that research occurs in a manner that is most suited to uptake by policy makers and practitioners.

Thus, the intention of this document is to create a framework for thinking about the management of the Murray–Darling Basin at a Basin scale, exploring how planning, management and monitoring are connected and to identify current strengths, challenges, knowledge gaps and future opportunities that will contribute to ongoing improvement in MDBA's ability to meet the objectives of the Basin Plan.

2. CURRENT MANAGEMENT STRENGTHS

There are a range of core strengths that provide the basis for greater capacity to manage the Murray–Darling at a basin scale. Since the inception of the Basin Plan, substantial progress has been made, by State and Federal Governments, to increase their capacity to monitor, manage and evaluate values and vulnerabilities within the Basin. Similarly, other stakeholders have also continued to develop their capacity and there has been much investment in the science to underpin decision making. The investment and efforts continue with ongoing capacity building occurring. One example is via a recently-announced modelling uplift within the MDBA to enhance the hydrological modelling capability, specifically with a view to enhancing basin-wide modelling capabilities. Another is MD-WERP, which aims to fill key gaps in the science to underpin the Basin Plan review in 2026 – what are the likely effects of future climate on values and vulnerabilities, can we better characterise flows at each end of the hydrograph, how might environmental values respond to low flows and how can we better characterise and support social, economic and cultural values in the Basin. These two new programs complement other initiatives at Federal, State and local levels.

Catchment and sub-catchment scales

Historically, management has focused on catchment and sub-catchment scales (or across multiple neighbouring catchments). As an example, key management documents are developed at this scale, such as Long Term Watering Plans, which often span neighbouring catchments but identify targets and assets at the catchment scale (e.g. see Victorian plans available at water.vic.gov.au/waterways-and-catchments/rivers-estuaries-and-waterways/environmental-water/long-term-watering-plans). This focus on management of catchments has created a strength at managing for this spatial scale, whereby processes and interactions at catchment and sub-catchment scales are often well understood and well documented. Many monitoring programs focus on this scale (e.g. monitoring of Selected Areas to evaluate the use of held environmental water; (Wassens et al., 2020) and models are frequently built and calibrated to aid decision making at that scale (e.g. Yang et al., 2017). The impact of actions such as the application of environmental watering are often well understood and individual managers and other stakeholders have deep personal knowledge and experience of how particular catchments and sub-catchments function and respond. Thus, there is a wealth of experience, knowledge, data and tools to inform decision making at this scale.

Annual and seasonal planning

Similarly, historically, much of the planning of water allocations and releases has occurred at an annual timescale or shorter. This has partly been driven by the instruments used for that planning (e.g. annual environmental watering priorities available at mdba.gov.au/publications/mdba-reports/basin-annual-environmental-watering-priorities) using that timeframe, but also by the availability of forecasts for weather and rainfall. Rainfall forecasting, in particular, has historically been unreliable at longer timeframes, and so has hindered a longer-term focus (Abbot and Marohasy, 2015). Shorter timeframes (e.g. seasonal) have also been used extensively, often to adjust annual plans as conditions on the ground became apparent (i.e. did actual rainfall match forecast rainfall) and so seasonal planning has become another strength, with well-developed instruments, forecasts at that time scale and models to support decision making.

Hydrology

Hydrological understanding, models and tools are key existing strengths in the management of the Basin. Hydrology is the science that describes the movement of water through the landscape, including the conversion of rainfall to runoff, transmission of streamflow through rivers, processes that influence storage volumes and inundation extents. Decades of investment and research have led to generations of hydrological models across all parts of the Murray–Darling Basin. While most of these models exist at the catchment scale, whole-of-Basin modelling was built and implemented for the development of the Basin Plan (Yang et al., 2017), and then applied in the Sustainable Diversion Limit Adjustment Mechanism and the Northern Basin Review. This capability is being consolidated and enhanced as a part of the Integrated River Modelling Uplift.

The strength in knowledge surrounding hydrology, its key role as a driver of condition for other variables and its links to management levers have resulted in hydrology targets being used as a proxy for condition for other values and vulnerabilities in the Basin. For example, environmental targets are set using return intervals for particular flow indicators (e.g. flooding to a certain extent; as documented in Long Term Watering Plans, for example, see water.vic.gov.au/waterways-and-catchments/rivers-estuaries-and-waterways/environmental-water/long-term-watering-plans). So, while there is much to continue to learn around the hydrology of the Basin (e.g. particularly under very low flows or at times of flood), hydrology is one of the better developed areas of science that underpin decision making in the Basin.

Actions under direct control of managers

Management in the MDB is complex. The Australian Constitution assigns legislative power for water and environment to the state and territory governments, with the Commonwealth Government formally responsible for oversight, facilitation and investment in the national interest, particularly for transboundary rivers such as the MDB (Hart et al., 2021). These arrangements have been modified a number of times, most recently with the passage of the Commonwealth Water Act 2007, where Basin state governments agreed to cede some of their powers, agreeing that the Commonwealth Government would take a larger coordinating role to integrate management of Basin water resources (Hart et al., 2021). Thus, management of the MDB is shared between the States of Victoria, New South Wales, South Australia, Queensland, the Australian Capital Territory and the Australian Government. Practically, the management of the MDB requires State and Commonwealth governments to work together on issues of water sharing, river operations and, increasingly, environmental watering (Hart et al., 2021).

In order to achieve this shared management, managers have two sets of levers – actions under their control. These levers are either physical (i.e. dams, weirs, pumps, levees) or they relate to rules regarding water sharing. For example, the Sustainable Diversion Limit is a long-term lever that identifies a sustainable level of take from the Basin to balance environmental and consumptive uses. The purchase and allocation of held water for environmental purposes is an action that is directly under management control, as is the management system constraints. Management options that use one or more of these levers are relatively straightforward to implement from a practical perspective (and setting aside differences in opinion as to how these should be utilised). In contrast, actions that fall outside the direct control of managers are far more difficult to capture, or attempt to influence to achieve Basin Plan objectives.

In addition to the role of government, there are substantial economic and cultural interests in the Basin. Despite Aboriginal Nations being the first inhabitants of the MDB over tens of thousands of years, the recognition of cultural water needs is in its infancy. There are more than 46 Aboriginal Nations that live within the MDB but, until recently, they have largely been excluded from the management of water in their Basin (Hart et al., 2021). That is changing, albeit slowly. Agriculture is the main economic driver of the MDB, utilising 85 % of the available land, more than 95 % of the water diverted from rivers and reservoirs and contributing approximately $24 billion per year to the

Australian economy (Hart et al., 2021). Pasture, rice, fruit and nuts and grapes are the dominant crops in the southern MDB while cotton is the dominant crop in the north (Hart et al., 2021). In addition, 2.2 million people now live in the Basin, with more than 4 million people depending on its water resources (Hart et al., 2021). Many of the activities associated with social, economic and cultural interests fall outside the direct control of water managers but influence the patterns of water use within the MDB and must be accounted for in the basin-wide management of a system like the MDB. This creates a complex set of interconnected interests that must be considered, ranging from the responsibility of individual landowners or Traditional Owner groups to industry groups or governments, adding to the challenges of managing a large river at basin scale.

3. CURRENT MANAGEMENT CHALLENGES

Despite the considerable progress that has been made to increase the capability of managers to achieve the objectives of the Basin Plan, challenges remain. These are predominantly associated with incorporating a greater range of values and vulnerabilities in considerations, expanding the spatial and temporal scale of management capability and including the impact of future climates and adaptation options.

Basin-wide monitoring

Extensive monitoring is currently undertaken across the Basin, to establish baselines and to understand the impact of interventions (e.g. under the Commonwealth Environmental Water Office Flow-MER program; flow-mer.org.au). Monitoring occurs to establish the amount of water in the system, storage volumes, condition of environmental and other assets and social, economic and cultural wellbeing. It is not feasible to monitor all elements of the Basin in all locations so, for the most part, monitoring occurs at specific high-value locations (e.g. Selected Areas) and at specific times (e.g. following interventions) (see flow-mer.org.au as an example). This creates challenges for management at a basin-wide scale because of the need to extrapolate from monitored locations and times across the Basin, as well as to understand how the condition of monitored entities may relate to other entities that are less well monitored, or not monitored at all.

Efforts to reduce the challenge of monitoring a large and complex system often focus on using species or sites as ‘representative’ of condition more broadly but these approaches can be misleading if not used carefully. For example, birds, fish and vegetation tend to be very well monitored in parts of the Basin and are often assumed to act as an ‘umbrella’ for the condition of other groups that are less well monitored such as frogs, reptiles and invertebrates. ‘Umbrella’ species are those whose conservation is intended to confer protection on many co-occurring species, but the concept’s efficacy is questionable (Roberge and Angelstam, 2004). A common alternative, ‘keystone’ species is often a species maintaining the stability of an ecosystem but there is considerable confusion in the definition of the concept. Further, using the approach risks selecting species because they are iconic, rather than based on a scientific validation that they do, in fact, maintain ecosystem stability (Cottee-Jones and Whittaker, 2012). Thirdly, the use of ‘representative’ locations to assess condition at broad scales is common but assumes that variation among locations is trivial compared with the larger scale – an assumption that is frequently demonstrably false – thereby creating challenges in the extrapolation of findings (Downes, 2010). Thus, as commonly applied, these are often not scientifically defensible methods for reducing complexity in an unbiased manner and new approaches are needed to facilitate robust decision making at a basin scale.

One approach to extrapolation of monitoring in space and time is to develop relationships between highly detailed monitoring at specific locations and specific times and lower resolution data that exist across the basin and through time. The increase in the number and resolution of satellite-derived products creates an opportunity to develop such relationships. These can then form the basis of a nested series of understanding, where the satellite-derived data can provide a foundation for extrapolation of monitored condition in other locations and at times that are not monitored. Such relationships would then need to be continually validated to ensure that responses on the ground were related to the extrapolated expectations, but this could be a powerful approach to basin-wide monitoring.

Long-term monitoring and assessment

The Murray–Darling is recognised as one of the most variable major river systems in the world (Hart et al., 2020). Weather systems in the Basin show clear annual and interannual (up to decadal patterns) that influence the availability of water, including on long time scales (Bond et al., 2021). This tendency to long-term systematic variation in weather means that there will be similar long-term variability in hydrology (Bond et al., 2021) and that other values and vulnerabilities will also vary on those time scales. This degree of variability creates challenges in understanding how values and vulnerabilities are likely to change as a result of future climates and adaptation.

Existing long-term data are invaluable for projecting future responses to change, but these relationships always contain uncertainty — for all parts of the river-dependent ecosystems, industries and communities, water is an important driver, but it is not the only driver. For instance, water availability is vital for irrigation industries, but other drivers also influence such as a changing global economy, intensification of land use, and weeds and pests, among others (Riddiford, 2021). To assist with this challenge, paleoclimate records over 10,000 years have been constructed for NSW (DPIE, 2020). These can provide context for the recorded weather and hydrology of the Basin. Similarly, paleoecological data can provide context for the condition of some parts of the Basin. First Nations knowledge can provide a long-term understanding that is lacking otherwise (Mackenzie et al., 2017). However, in other cases, understanding long-term patterns and changes is not possible or has not occurred. Continuing to identify and gather sources of long-term data can assist in understanding what future change may arise. For example, historical ecology uses historical records to build an understanding of past, otherwise undocumented changes in ecological condition. A common example is the use of fishing trophies and related information to document reduction in the size class of fish species over decades, or restaurant menu items to identify species distributions (McClenachan et al., 2015). Continuing to identify, collect and interpret available long-term data sets will provide context for modern monitoring and evaluation data.

Plurality of values and vulnerabilities

The values of the Basin are many, dynamic in space and time, and vary among actors. “Value can usefully be thought of as the co-product of the asset that is valued and the person valuing it – it is not a property of either on their own” (Wahid et al., 2022). Across those values, there are different levels of susceptibility to future climates, creating a diverse range of vulnerabilities as well (Wahid et al., 2022). While this presents challenges to management and adaptation to future climates, it is also a symptom of the rich tapestry of the Murray–Darling Basin and a value in and of itself that needs to be maintained and adapt as future climates manifest.

Among the plurality of values and vulnerabilities, we are better able to describe and model some than others (Wahid et al., 2022). Irrigation values and vulnerabilities are among the best understood. Environmental values, in some instances, are well understood and substantial investment has occurred to better characterise those values and vulnerabilities. Despite this, our understanding of environmental values and vulnerabilities is patchy in space and time and across different taxonomic groups. It is also relatively poor at higher organisation levels (i.e. we have better knowledge for individual species or populations than how whole communities or ecosystems may respond).

Other values and vulnerabilities, however, are less well understood. Social and cultural values are poorly documented and can be difficult to quantify, so do not easily fit the quantitative framework that is typically utilised (Wahid et al., 2022). Economic values and their vulnerabilities, beyond irrigation, are also often poorly understood. Tools to capture those values and vulnerabilities are lacking, adding to the difficulty in including consideration of those values in decision making processes.

Impact of future climates & plausible adaptation

The Murray–Darling Basin's climate is changing. While the climate has natural variability and is prone to extremes, evidence provided by both the CSIRO and Bureau of Meteorology identify the climate of the Basin is changing (BOM and CSIRO, 2020). For example, from 2017-20 the Basin experienced the driest 3-year period on record, characterised by extremely low inflows, towns running out of water, mass fish deaths, extensive bushfires and significant water quality issues. Since then, records have regularly been broken regarding the amount of rainfall experienced, with widespread flooding occurring in the MDB at the time of writing. The preponderance of scientific evidence indicates that the future Basin will be warmer compared to historical records, and it is also likely to be drier and include more frequent droughts and extreme weather events.

Understanding the likely effects of this changing climate is a challenge. Future climate change will affect different values and vulnerabilities differently, likely with differences among bioregions and across other dimensions (Wahid et al., 2022). The adaptive capacity of parts of the system to respond to climate change is often unknown and responses are likely to include threshold and other non-linear responses, making the use of past behaviour to inform future projections difficult (Cook et al., 2014). Further, rainfall remains one of the more uncertain variables modelled by global climate models, adding to the uncertainty and complexity (Abbot and Marohasy, 2015). Based on current trajectories, the world is on track for an average temperature rise of between 2.1 °C and 3.9 °C by 2100 (Kemp et al., 2022). Observations have been tracking at or near to the worst-case scenarios presented by the IPCC (Kemp et al., 2022), and this may indicate that climate change is occurring more rapidly than anticipated, or possibly that decadal-scale climate variability is poorly resolved by the models. Added to this, the rate and scale of global action to a net zero carbon future is also uncertain (Kemp et al., 2022).

Adaptation to future climates will be needed. Adaptation will be undertaken by a range of actors and take many forms (Lyle, 2015). Governments will respond with policy settings designed to support the objectives of the Water Act and the Basin Plan, among other objectives. Communities will continue respond to adapt to new conditions, potentially with movement of population and changes in social structures (Lyle, 2015). The agricultural sector will respond, by changing crops and varieties grown and adopting new technologies (Lyle, 2015). First Nations communities will continue to adapt, as they have for thousands of years (Nursey-Bray et al., 2019). Ecological systems will adapt and evolve, with changes in the distribution and abundance of species, some will go extinct, and diseases are likely to be more prevalent (Moore and Schindler, 2022). These adaptations will build upon past strategies to adapt to the fluctuations in climate and flows that are part of life in the MDB. Communities and regions have dealt with past drought, for example, by changing crop types or intensity, trading water or temporarily shifting to other livelihoods (Wahid et al., 2022). Species and communities rely on refuge habitats, drought resistant phases and adaptive plasticity, among other strategies, to withstand adverse conditions (Ackerly, 2003).

Adaptation to climate change is also a sequential process. It will not be limited to one action by one actor (Lyle, 2015). Multiple actions will be taken, in sequence or simultaneously, potentially by multiple actors (Lyle, 2015). Some sequences of adaptation options will be complementary, increasing the efficacy of adaptation overall. Others will be antagonistic, making adaptation less effective through poor coordination or unforeseen interactions (Lyle, 2015). Such combinations of actions may present an opportunity for governments to intervene to mitigate maladaptation.

Understanding combinations of adaptation options and how they will combine to create a response in values and vulnerabilities is a challenging task.

Finally, it is important to acknowledge that our ability to adapt to future climates is also uncertain. Some adaptation will be effective at mitigating the impacts of climate change. Other values will not be able to be maintained and recognising those values that will not be able to be maintained and understanding how to respond to that reality is a further challenge that will involve difficult conversations with communities and stakeholders about acceptable pathways to deal with those challenges.

Interactions

The Murray–Darling Basin has a complex range of values that interact in space and time (Gawne et al., 2018; DeFries et al., 2004). For example, maintaining productive and resilient water-dependent industries will alter land use patterns that is likely to affect water-dependent ecosystems which, in turn may alter ecosystem services such as pollination and regulation of water quality which then affect water-dependent industries. Exactly how these interactions occur is likely to depend on their condition, location in the Basin (e.g. arid zones may respond differently from temperate zones) and many other factors (DeFries et al., 2004). Feedback loops are common (see Thorslund et al., 2021 for an example regarding feedback in drivers of freshwater salinisation).

Historically, decision making has been siloed, with different managers responsible for decisions relating to environmental watering and irrigation entitlements, for example (Boxelaar et al., 2006). As a result, in many instances, decisions within the Basin are made considering one or a few of these values and vulnerabilities, with the implicit assumption that each is independent of the others underpinning that approach. More recently, the interconnectedness of the system has been increasingly recognised, with the Basin Plan 2007 focused on the need to balance multiple interests (Hart et al., 2020). Systems thinking provides a theoretical framework for incorporating the trade-offs and synergies among value types that reflect that interconnectedness (Gómez Martín et al., 2020). However, the tools to support decision making often continue to reinforce traditional silos reflecting different scientific disciplines. Many existing tools are not able to consider likely interactions between value types at appropriate scales, but are focused on a single set (e.g. ecology or hydrology). The use of such tools to support future decision making is likely to result in suboptimal or even counterproductive management decisions where interactions are important, and so integrated approaches are needed (Gómez Martín et al., 2020; Kelly et al., 2013).

Statistically, when considering analyses with interactions, it is necessary to interpret any interactions before considering main effects in isolation of those interactions (McClelland and Judd, 1993). This is because, where an interaction occurs, the effect of one variable depends on the value of the other (McClelland and Judd, 1993). Thus, it is necessary to understand both factors to be able to understand a likely response. For example, if fish spawning is a function of both water temperature and flow rate, and those two factors interact, attempting to predict fish spawning from flow rate alone will only be accurate when water temperatures are also appropriate. Thus, any decisions made attempting to induce spawning by manipulating flow rates may succeed if water temperatures are appropriate by chance, but are likely to fail if water temperatures are not appropriate. This can create confusion because the same flow manipulation will be successful in some circumstances but not in others, because of the unaccounted-for interaction.

The number of possible interactions is impossibly large. Attempting to capture them all and manage accordingly is simply not possible. But some actions can be taken to reduce the likelihood that interactions and feedback loops will result in negative management outcomes. The first is to introduce experimental rigour in the delivery of management actions (Poff et al., 2003). Where multiple equivalent locations could be selected for a particular action, the exact location should be chosen randomly. This enables the results of that action to be extrapolated to other locations within the set of equivalent locations, rather than being limited to the single place. Explicit hypotheses for the outcome of actions should be documented, along with possible factors that may influence the outcome (Lester et al., 2020). Those factors should be monitored along with the response of interest. The outcomes should then be documented, so that the results of multiple actions through time, under different conditions, can build to create a far more nuanced understanding of when actions are most likely to achieve desired results, and when they are not – a sophisticated application of adaptive management. Through time, this will lead to a far deeper understanding of the most important interactions occurring and allow more successful management of values and vulnerabilities (Lester et al., 2020).

Actions outside direct control of managers

Policy settings to implement the Basin Plan lie within the control of governments and government agencies, such as the MDBA. However, many of the drivers of future condition (e.g. future climates, stressors), the plausible adaptation options, and the possible actions to respond lie outside the direct control of those organisations (Lyle, 2015). This represents an enormous challenge for MDBA – how to fulfil its statutory obligations and meet its objectives under the Basin Plan when so much is outside its control. Relying on levers and adaptations that are within the control of MDBA is unlikely to be sufficient to protect values and vulnerabilities in the face of future climate change. Thus, addressing this by finding a meaningful path to facilitate adaptation that is outside its direct control will, to some degree, determine the overall level of success in adapting to future climates.

Community involvement

An ongoing challenge associated with the management of the Murray–Darling Basin is how best to involve the community in decision making. The rapid implementation that was needed during the introduction of the Basin Plan and the focus on water reform in the absence of other mechanisms to alleviate some of the negative impacts of water reform on Basin communities created a lack of trust in MDBA, which was widespread among some sections of the community (Colloff and Pittock, 2019). In some, perhaps many, instances, this lack of trust persists.

Contrasting discourses (or worldviews) exist regarding the Basin Plan. These vary in the weight given to human domination of nature versus a need to accept environmental constraints on society (Colloff and Pittock, 2019). There is contention about how successfully they have been considered in the past. Colloff and Pittock (2019) suggest that a series of frank conversations about what values, rules and knowledge are common among stakeholders is needed to avoid further disconnection. Focusing on how decisions are made, the limitations to those methods and possible alternatives is needed (Colloff and Pittock, 2019). Such a re-framing of the decision-making process would enable novel options by including new societal and personal values, rules and forms of knowledge that have previously be discounted or excluded (Colloff and Pittock, 2019).

MDBA have signalled an intent to approach future management of the Basin rather differently. They have already implemented a number of approaches to increase community involvement in decision making in the Murray–Darling Basin. De-centralisation of MDBA offices and staff aims to create closer connections between those staff and Basin communities. Reference groups provide input and comment on issues of relevance. A greater focus on the social and economic impacts of the Basin

Plan also assists to create opportunities to involve the community in a meaningful manner to have input into the management of the Murray–Darling Basin. Commitment to the inclusion of First Nations values and knowledge is evident (see below).

There are two clear ways in which communities can have input into the management of the Basin. The first is via stakeholder participation in natural resource management. Stakeholder participation, via participatory processes, is based on the assumption that effective management is more likely when resource users have a role in making decisions and benefiting from resource use (Ingles et al., 1999). This empowerment and the creation of partnerships is intended to strengthen collaborative management systems (Ingles et al., 1999). The participatory process is intended to increase the skills, confidence and self-reliance of resource users to engage in sustainable development (Ingles et al., 1999). The second way in which communities can have input is via participatory evidence generation. Citizen science is a powerful tool that has increased in its influence on natural resource management in the last decade or so (McKinley et al., 2017). Citizen science currently informs natural resource management, environmental protection and decision making (McKinley et al., 2017). It can improve natural resource management by providing evidence that would otherwise not be collected and by encouraging public engagement and action (McKinley et al., 2017).

Both processes involve trade-offs. Participatory consultation processes are time and resource intensive, both for government and community members, and there are degrees to which those community members can influence decision making (Ingles et al., 1999). Citizen science can be seen to be inferior to conventional science and so its use can be controversial (McKinley et al., 2017). However, when carefully tailored so that the process of participation matches the need for scientific or public involvement, both are effective methods for seeking the views of community members and engaging them in the management of the shared resource.

The context of decision making is important, though. MDBA has statutory obligations under the Basin Plan, the Water Act 2007 and the MDB agreement. Thus, there are clear limits in terms of the types of actions that it can undertake. This can create challenges when interacting with the community, as many of the activities and actions that may be advocated by the community may be outside the control of MDBA. As a result, there is a risk of creating unrealistic expectations as to what is able to be tackled. Care is needed to frame interactions with the community to acknowledge the scale and scope of issues that are raised while creating realistic expectations as to the actions that can be taken and creating mechanisms for appropriate communication of progress or ongoing contributions from the community into decision making. Despite these challenges, community involvement is critical to create ongoing social licence for sustainable management of the Basin across the range of values and vulnerabilities, recognising that this is likely to have impacts on Basin communities, particularly under a drier future climate.

First Nations participation

In addition to challenges associated with the involvement of the community as a whole, there are specific and pressing additional challenges associated with the involvement of First Nations in water management.

"For Aboriginal people, water is a sacred and elemental source and symbol of life. The resources provided by aquatic ecosystems are a pivotal part of spirituality and the cultural economy. The rivers are the veins of Country, carrying water to sustain all parts of the landscape. The wetlands are the kidneys, filtering the water as it passes through the land." (Mackenzie et al., 2017)

The history of dispossession and marginalisation of First Nations people has yet to be addressed in water allocation and management, although efforts have increased. Indigenous water entitlements in 2017 were less than 0.01 % of Australia's water allocations, compared with >20 % land ownership by First Nations at the same time (Jackson, 2017). Within the MDB, in 2020, First Nations organisations held just 0.2 % of surface water entitlements and, in fact, First Nations water holding *declined* by 17 % between 2009 and 2018 (Hartwig et al., 2020). This effective exclusion from water ownership extended to management, where First Nations peoples have been prevented from shaping water policy, despite its direct relevance to their cultural, social and economic wellbeing and that of their Country (Jackson, 2017).

The first step to addressing these challenges lies in meaningful participation of First Nations in the development of water policy and management direction. Policymakers must seek and act on input from First Nations representatives when designing and implementing management programs (Hartwig et al., 2020). The Australian Government has committed to advance access to water for First Nations peoples, including $40 million to purchase water entitlements, which is a welcome step (Hartwig et al., 2020). But much is left to be done, including removal of barriers in governance arrangements, economic and financial barriers to involvements, a lack of skills, capacity, education and employment, a lack of relevant data and information and the diversity, and lack of broader understanding, of cultural values and norms (Jackson et al., 2019).

There are more than 46 Nations in the MDB, each of whom have their own aspirations, goals, and visions for how water should be managed into the future. These voices must be heard, respected and influential in determining the future direction of management in the Basin. How to reduce the current inequities and structural barriers to create a meaningful, respectful and culturally-appropriate mechanism for First Nations participation remains a challenge.

Managing under uncertainty

Uncertainty is a major feature of any management at a basin-wide scale, particularly when trying to account for future climates and how values and vulnerabilities will respond. It is not possible to know what future climates will be exactly – indeed, because of the inherent uncertainties associated with the future, it is likely to be a mistake to attempt to predict the future then optimise management settings to that prediction. This is because we do not know how systems will respond hydrologically to changes in climate, nor how the environment will adapt (or not). Responses of governments, communities, stakeholders are also unknown. Further, these uncertainties compound across value types, in space and in time to create a decision-making environment under high uncertainty. Major changes in climate and physical conditions, such as those currently occurring in the MDB, alongside rapid but unpredictable socio-economic development mean that effective decisions must be made under uncertainty (Kwakkel et al., 2016). Deep uncertainty is a term that is increasingly used and is applicable here. It occurs when there is not agreement on a system and its boundaries, outcomes of interest and their relative importance, or decisions interact with the system and so are not independent (Kwakkel et al., 2016).

Explicitly considering uncertainty is an area that has long been neglected in both research and natural resource management (Ascough et al., 2008). It is often difficult to identify potential sources of uncertainty, harder to quantify and most difficult to incorporate into effective management strategies. As a result, many models are developed and data collected without adequately describing the uncertainty associated with each (Lester, 2019). Without explicit consideration of uncertainty, tools often create an unrealistic impression of precision, which can lead to unreliability in their application. In turn, this is likely to lead to a failure to achieve management goals, with a resultant loss of public confidence (Ascough et al., 2008).

In addition to quantifiable uncertainty, there are also unknown or unquantified sources of uncertainty. These include the impact paradigm-shifting events (sometimes called 'black swan' events) or tipping points that may influence the system (Cook et al., 2014). These are often unable to be modelled but should be considered in the interpretation of the findings. For example, the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (Solomon et al., 2007) excluded speculative estimates of the consequences of a collapse of the Greenland ice sheet on sea level rise because scientists lacked an understanding of the consequences of such a discontinuous change (Morgan, 2009). This means that simulations and projections from that work likely represented a conservative projection because of the inability to tackle highly uncertain events that would often have a large negative outcome (e.g. much larger sea-level rise than otherwise projected for the case of the collapse of the Greenland ice sheet). Similarly, there are other events for which we have few observations on which to base models (e.g. surface-groundwater disconnection which was not anticipated until it was observed; Saft et al., 2016), or have not anticipated (sometimes termed 'surprises'; Morgan, 2009). Additional measurement and observation will enable some of these phenomena to be modelled but collecting these observations will take time and resources. Thus, it is important to recognise that the range of possible futures is often wider than our range of simulated futures.

System variability is another type of uncertainty that can influence decision making – and one which is not addressed with additional data or better models (Ascough et al., 2008). For example, it is incredibly difficult to predict total rainfall for *next* year at a specific location because of year-to-year variability (Morgan, 2009). This type of system variability is particularly important for the MDB, because high variability in rainfall and flow is key characteristic of the system (Hart et al., 2021). The Murray–Darling is recognised as one of the most variable major river systems in the world and this variability is natural and has shaped many of the assemblages of plants, birds and animals that live in the system (Maheshwari et al., 1995). Thus, it is a critically important element in the system in and of itself, but one that increases challenges associated with its management.

To give an example, *Ruppia tuberosa* is an aquatic plant that is a key habitat and food resource in the South Lagoon of the Coorong (Lester and Macqueen, 2017). It relies on relatively high water levels and low salinities to persist and thrive. But low sea levels in Encounter Bay, driven by the timing of passing weather systems, lead to the hydrologic disconnection of the North and South Lagoons (Lester and Macqueen, 2017). When that disconnection occurs early in the season, the South Lagoon has longer to evapoconcentrate salts, leading to low water levels and extreme salinities. In contrast, when that disconnection occurs late in the season, water levels remain higher and salinities close to that of sea water. Thus, the need for environmental water to reduce high salinities alters depending on the timing of weather systems, but this timing is inherently uncertain in any given year (Lester and Macqueen, 2017). This presents a challenge as the same volume of environmental water would be insufficient to support *Ruppia* in a year when disconnection occurred early but overly generous in years where disconnection was delayed. Thus, a flexible approach to management is likely needed under high variability.

Another challenge associated with extreme variability is the length of observational record required to characterise that variability. A basic understanding of probability theory indicates that a longer record is needed to adequately characterise the low-frequency (i.e. rare or extreme) events adequately. For example, the current observational record for the MDB only contains one drought of the magnitude and duration of the Millennium Drought, so it is not currently possible to adequately characterise its return interval. This is compounded by observed non-stationarity in the record – that is, the climate in the MDB is not under equilibrium and is changing, making estimating the likelihood of extreme events even more challenging.

So, the degree of natural variability and the uncertainty that surrounds so many elements needed to inform decision making presents an enormous challenge that must be acknowledged and incorporated into tools that are developed but also decision-making processes.

4. FUTURE OPPORTUNITIES

Given the current capabilities, investment in future capability and ongoing challenges to management at a Basin scale, there are several key opportunities for MDBA at present. Taking advantage of these opportunities, to achieve greater integration of different values and vulnerabilities and at a greater range of scales, to partner with other programs with complementary aims and to embrace the challenge of management under deep uncertainty, will result in substantial benefits for management at a Basin scale.

Integration

Integration across environmental, social, economic and cultural research is key to successful management at a Basin scale (Kelly et al., 2013). Combining environmental, social, economic and cultural values provides real opportunity to understand the complex interactions and trade-offs that occur in space and time, and across different values and vulnerabilities (Gómez Martín et al., 2020). These trade-offs and synergies exist and are fundamental to understanding what adaptation is possible under drier future climates at a Basin scale (Kelly et al., 2013). Done well, such integration has the capacity to enhance the combined environmental, social, economic and cultural values of the Basin and so, a synergistic approach is needed (Gómez Martín et al., 2020), rather than the traditional paradigm of a healthy economy competing with a healthy environment. In reality, the conflict between environmental and economic outcomes is often a false dichotomy (Hiner, 2015). The interactions of environmental, economic, social, and cultural values are complex, they can both compete with, and act to fortify each other (Hiner, 2015).

Management in the Basin and elsewhere is difficult due to deep uncertainty both in future conditions but also in possible adaptation options (Kwakkel et al., 2016). The ability to assess environmental outcomes is relatively well developed for the MDB (e.g. links between hydrologic metrics and environmental outcomes are embedded in the Long Term Watering Plans developed by each state) while similar capability for social, cultural and economic outcomes is less so. There is an opportunity to utilise the strength of knowledge in those environmental indicators to enable a step-change in the capability of partners to undertake decision making under deep uncertainty using best-available science. This would facilitate management under a quadruple bottom line, as required by legislation.

Using a predictive modelling approach drawing on systems thinking theory, for example, it is possible to integrate across value types (Kelly et al., 2013). This provides the opportunity for predictive modelling to occur across those values types which then enables explicit trade-offs and synergies to be identified and maximises the likelihood of success of management decisions taken (Kelly et al., 2013). The research currently being undertaken as a part of MD-WERP provides an important step forward – research to identify environmental, social, economic and cultural values and vulnerabilities will inform that to characterise climate adaptation. Both will then link to research to improve river operations and enhance the suite of values identified. This integrative approach has the capacity to be embedded within decision making for the Basin to enhance the operations as a whole.

Similarly, indicator suites that are used to assess condition and outcomes can be revisited to consider integration across value types. Many of the current indicators used for environmental outcomes, for example, are structural in nature, in that they relate to the presence or abundance of species of interest at particular locations. These are often used additively, to combine to represent a desirable ecosystem. Alternative approaches exist that integrate across multiple components. One alternative for environmental outcomes is to consider indicators of ecological function – that is, processes that occur when an ecosystem is functioning as expected (Ticehurst et al., 2022). A second approach is to use diversity indices which explicitly capture combinations of species (Swingland, 2001). A third is to test whether sensitive locations provide a proxy for conditions in the Basin as a whole. The Coorong and Lower Lakes, for example, is frequently suggested as such a location, with the community advocating that "a river dies from the Mouth up" (ConservationSA, 2021). This sentiment represents the inherent unidirectional nature of rivers, where upstream condition will affect what occurs downstream. But these approaches and ideas have yet to be formally tested for the MDB.

While these examples are largely focused on a more integrated approach to environmental outcomes, the approaches can be extended to assess their ability to represent social, cultural or economic values thus providing a more holistic understanding.

Partnering across lines of influence

MDBA has long had a close, if nuanced, relationship with Basin states, aiming to manage the Basin in a sustainable manner as a whole. Similarly, it has had good relationships with other government entities. It may be fair to suggest that relationships with other stakeholders outside of government have been less well developed.

At the time of writing, there are a number of programs underway that have complementary aims in terms of seeking to create sustainable communities and environmental assets under future climates. For example, the Future Drought Fund initiative involves a raft of projects and programs, of which the largest is the Drought Innovation and Adoption Hubs, which aim to enhance community, agricultural and environmental resilience to drought (e.g. vicdroughthub.org.au). The National Environmental Science Program funds environment and climate research (e.g. dcceew.gov.au/science-research/nesp/hub-climate-systems). It aims to support decision makers, including from Indigenous communities, to build resilience and support positive environmental, social and economic outcomes. New entities (e.g. WaterTrust Australia; watertrustaustralia.org.au/) seek to act as independent water and catchment policy centres to influence the decision making process and how communities and other stakeholders engage with water policy, while the One Basin CRC (onebasin.com.au) is focused on developing collaborative policy, technical and financial solutions to reduce exposure to climate, water and environmental threats in the MDB. Other such initiatives also exist.

This plurality of initiatives and stakeholders in the water management and resilience space creates multiple opportunities. Firstly, collectively, the opportunity to have demonstrable impact across these programs is far larger than any single program could achieve. If MDBA were able to collaborate across programs such as these, this would provide a line of sight to thinking and intentions on decisions that are not within the MDBA's remit. Working with some of these groups offers the opportunity to develop a collaborative model for the future where MDBA participate in broader community and stakeholder discussions, comfortable in the mutual understanding of their respective powers and responsibilities but committed to achieving fair, mutually beneficial and desired outcomes across a range of values.

Thus, engaging across a broad spectrum of programs where water management is one element in a complex problem can act to build trust in MDBA activities and intentions. It tends to embed MDBA in a broader community and demonstrates its interest in the wellbeing and function of the Basin and Basin communities beyond its own remit. There is significant reputational advantage to be had in such an approach, which would tend to build social licence and enhance MDBA's ability to deliver on its core obligations, at the same time as contributing to a broader agenda and lead to better outcomes in the Basin.

Embracing uncertainty

We cannot know what the future will hold and it is not possible to eliminate all types of uncertainty in our predictions of the responses of values to future conditions (Marchau et al., 2019). Instead, we need to embrace uncertainty in our decision making – by creating management approaches that respond to conditions as they unfold and focus on no-regrets decisions that will result in benefit regardless of the conditions. In this context, we consider the explicit quantification of multiple types of uncertainty and assessment of sensitivity to others as necessary features in decision making tools. Where uncertainty has been documented (e.g. Lester and Macqueen, 2017; Lester et al., 2012) that uncertainty is large. The challenge then becomes how best to incorporate that uncertainty into future objectives and decision making.

There is likely to be a spectrum where, at one end, the future is uncertain but we have a strong understanding of the range of possible futures and probabilities associated with each future and a strong understanding of how our decisions will translate into on-ground responses, while at the other end of the spectrum, the future is still uncertain, but we have a limited understanding of that future and how our decisions translate to on-ground responses (Marchau et al., 2019). In the first scenario, it may be most appropriate to follow a highly quantitative, model-based approach in which we make long-term policy settings based on a strong understanding of future risk. In the latter scenario, it may be more appropriate to make a small number of decisions based on the information available but set up a flexible plan that will adjust regularly to the future as it unfolds.

There is a burgeoning field of study regarding decision making under deep uncertainty with many options for how best to approach the challenge, whichever end of the spectrum is most applicable. One such approach is robust decision making. Robust decision making is an iterative planning approach appropriate for decision making under deep uncertainty, where candidate strategies are tested across many scenarios (Kwakkel et al., 2016). The goal of robust decision making is for strategies to produce satisficing (or sufficient) results in as many scenarios as possible, with a focus on identifying trade-offs and conditions where strategies perform poorly to enable modification (Kwakkel et al., 2016). Thus, a small number of indicators is considered in many scenarios, in contrast to past approaches where many indicators are considered in few scenarios. For this to be effective, the indicators selected must represent responses in values for which the system is managed. An alternative is dynamic adaptive planning. Dynamic adaptive planning focuses on implementing an initial plan prior to resolving major uncertainties, with a view to adapt the plan over time as new knowledge becomes available (Walker et al., 2001). A key element in dynamic adaptive planning is that a monitoring program is developed, along with specific trigger values for revision of the current policy settings, to facilitate the adaptation as the future unfolds (Walker et al., 2001). There are other approaches which can be used singly or in combination to best fit the specific case (Marchau et al., 2019).

While there is a need for more nuance in our approach to decision making, we may also need to increase our tolerance for risk in that process. Decision making could be placed into a risk portfolio context, analogous to that used for financial management (Lester et al., 2020). As an example, (Edwards et al., 2004) take such an approach to the management of fisheries. Different management actions or adaptation options could be assessed with a possible 'return on investment' (or likely efficacy) and a relative risk identified for each. As identified above, there are likely to be many possible adaptation options or sequences of adaptation options and some of these could be assessed. Basin-wide decisions could then be made to explicitly create a balanced risk portfolio where some adaptations are implemented that are highly likely to succeed but may have a small relative impact (Lester et al., 2020). Other adaptations may have much larger possible impacts but be more uncertain and so contain greater risk. Appetite for risk could vary among regions, for different values and vulnerabilities, or even year-on-year. The advantage to taking such approach is that it creates an explicit understanding of uncertainty and risk (in a form that many individuals will understand) and, if that risk is clearly stated in advance and justified, is likely to create greater social licence for undertaking adaptation options. When actions are framed as having a degree of risk, and justification given for why the choice is made to proceed, rather than being considered a business-as-usual action, it is less likely that any lack of benefit would be seen as a ‘failure’ of action (Ascough et al., 2008) . Rather, acknowledging uncertainty, characterising it via modelling and sensitivity testing and balancing risk in decision making can become the new best practice and better utilise the best science available.

At a mechanical level, MD-WERP will improve our information base, strengthening our ability to infer on-ground response to water planning. But by adopting a strong link between the researchers and the practitioners — co-development and co-application — we are ensuring that the information is used appropriately, and it will inform which part of the spectrum is most appropriate to adopt for future adaptations of the Basin Plan, despite the deep uncertainty under which decisions must be taken.

5. PROPOSED FRAMEWORK FOR MANAGEMENT AT A BASIN SCALE

Management of the Murray–Darling Basin is challenging. It involves understanding the range of values across social, economic, environmental and cultural spheres that need to be maintained or enhanced. The scale of the Basin, and differences in values across space, time and stakeholder groups, adds complexity. Understanding what future climates in the Basin may look like, and which values are likely to be vulnerable to future climates frames what is possible for future management. As climate change progresses, along with the advent of other interacting external stressors (e.g. changes in global commodity markets, supply chains), managers, communities and individuals will undertake a range of adaptation actions – either deliberately after careful consideration of the plausible future impact, or in an *ad hoc* manner. Many of these adaptation options will occur simultaneously, overlap, and counteract or enhance each other. Thus, the landscape for managers is complex and consideration of how best to navigate this complexity is warranted.

Values and vulnerabilities

The purpose of water management is to ensure that the resource is managed effectively in line with community values and expectations. Community values in the first half of the 20th Century were directed towards nation building, irrigation industry support, and economic return for communities. However, community values have adjusted over recent decades to recognise the importance of good water quality, a sustainable river-dependent environment, and the incorporation of First Nations and their cultural needs — water planning has responded to these changes in community values.

Management at a basin scale is correspondingly designed to maintain and enhance values within the Basin. There are well-defined objectives set out in the Basin Plan, specifically a healthy working river that supports productive and resilient water-dependent industries, healthy and resilient ecosystems and communities with access to sufficient and reliable water supplies (Basin Plan, 2012). These objectives are designed to encompass a range of values across the Basin. Values are those things within the Basin that we, as a society, community or individual, hold dear, if considered from a human-centric perspective, or have some intrinsic worth from a broader perspective. Values can span productive industries, healthy ecosystems and healthy communities (Wahid et al., 2022). Cultural values are overlain across those spheres, but also encompass additional dimensions including custodial, identity and social cohesion values among others (Mackenzie et al., 2017). Individuals will each hold different sets of values and those values may vary in space and time in response to context (Wahid et al., 2022). For example, during drought, access to water for stock may be a priority value but this may not be top-of-mind in other contexts. Similarly, values have shifted substantially during the COVID-19 pandemic as a result of unprecedented, and often unimagined, circumstances and now frequently include freedom of movement, freedom of exercise and freedom to construct a livelihood, as well as health and wellbeing of individuals and families.

Values within the Basin will overlap and intersect. For example, productive and resilient water-dependent industries are reliant on both healthy and resilient ecosystems (Wahid et al., 2022) and communities with access to sufficient and reliable water supplies to some extent. A buoyant economy may be a value that sits within that of productive and resilient water-dependent industries, and productive agriculture may sit wholly within that. Similarly, there will be many other values that will overlap and intersect with these examples. First Nations cultural values recognise the intersection of these spheres in holistic manner that recognises and celebrates this intersection (Mackenzie et al., 2017). "*The inextricable connectivity between identity, spirituality and water gives Aboriginal people a unique role in water resource management*" highlights this intersection (Mackenzie et al., 2017), p12.). One representation of these is as a series of concentric and overlapping rings (Figure 1). Defining these values is a necessary first step in understanding how future climate and proposed management and adaptation options will affect those values, as was undertaken in the rapid assessment by Wahid et al. (2022).

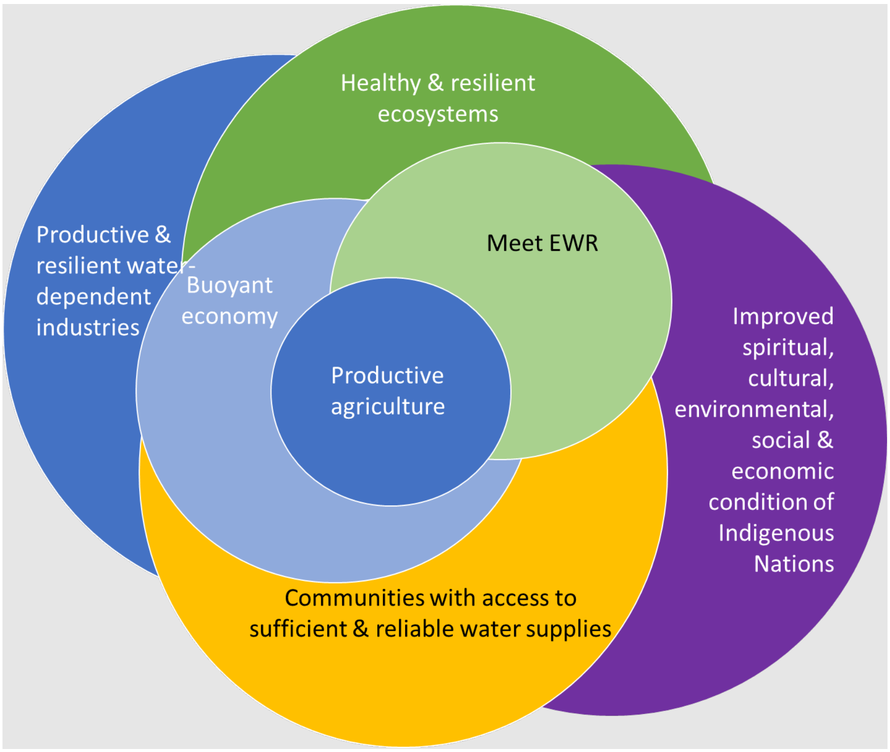

Figure 1. Conceptual representation of the overlapping and concentric nature of the values of the Basin with examples drawn from those relating to productive and resilient water-dependent industries.

For the purposes of maintaining those values within the Basin, the next step is to understand which are likely to be vulnerable under changing future climates and to what extent. Vulnerability can be conceptualised as the intersection between sensitivity to change (i.e. here a changing climate) and the adaptive capacity of the value (i.e. the set of resources available for adaptation which may include social, economic, environmental or cultural resources, among others) (Wahid et al., 2022). These vulnerabilities have been well captured in the rapid assessment undertaken by (Wahid et al., 2022). In understanding the vulnerabilities of multiple values, it is important to note that systemic vulnerability will exist for some values, and that there will be tensions and trade-offs among values. These tensions and trade-offs were outside the scope of the rapid assessment (Wahid et al., 2022), but remain a key knowledge gap. Vulnerability may exist across scales and may be cumulative under multiple stressors. Finally, understanding and prioritising which values can or should be protected and endure in the face of projected change is necessary and requires input from communities and stakeholders. For the Basin, we focus on vulnerability to climate change, but there will be other drivers of change that may also need to be considered.

To provide a demonstration of how such trade-offs and synergies could be considered, the multiple values of the Basin can be represented as a circle, with colours representing different related values (Figure 2). The concentric rings from Figure 1 can be simplified to be represented a single circle, with arrows illustrating the multiple values. For each of the values in given location, a desired future state (e.g. aligning with Basin Plan objectives) can be represented (orange line). Current state (blue line) can be overlaid, illustrating any gaps between the current state and the desired future state. Finally, future states can also be represented. These may be based on modelling, for example, and could represent plausible future states without adaptation (dashed red line) or accounting for an adaptation (solid red line). Such a representation may be possible at a catchment scale, for example but it may be unlikely that it would be feasible or desirable to simplify the future condition of values at larger scales such as at a Basin scale.

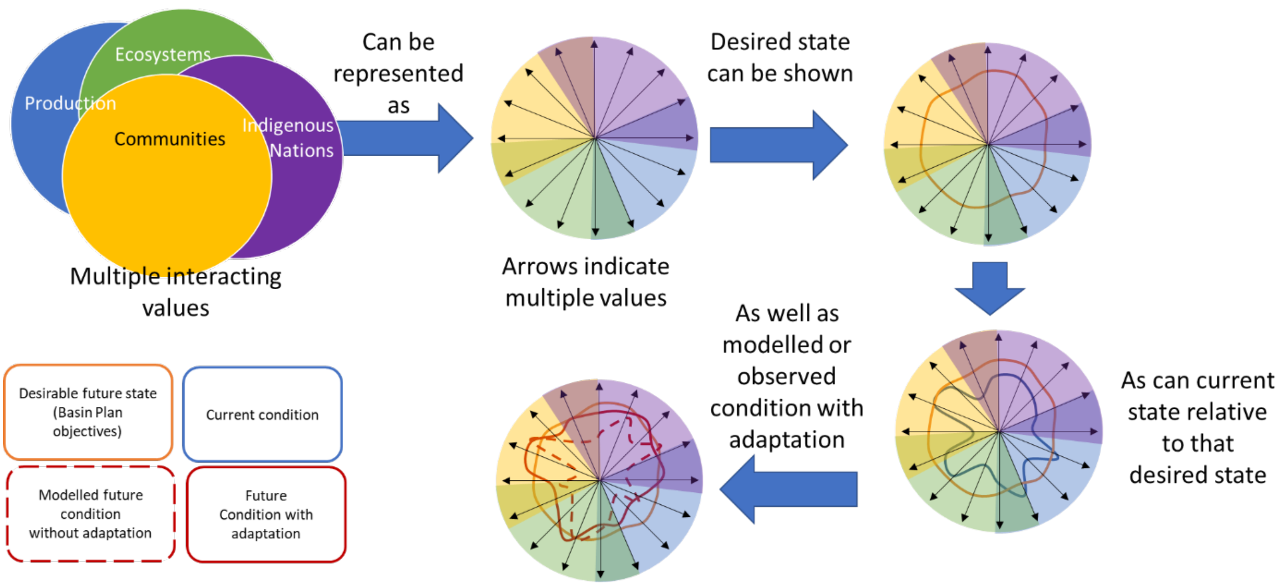

Figure 2. Conceptual representation of multiple values, potentially varying across the Basin, and how desired states, current condition and plausible future states (both with and without adaptation) can be illustrated

Adaptation to future climates

One of the key challenges to fulfilling the objectives of the Basin Plan, and to maintaining the values within the Basin, is to enable adaptation to future climates (Wahid et al., 2022). For the Murray–Darling Basin, a hotter, drier and more variable climate is the most likely projection for the future (although hotter and wetter is also possible). Either will pose significant risks to values (Wahid et al., 2022). Adaptation will be necessary, and it may not be possible to maintain all values (e.g. species extinctions; Moore and Schindler, 2022). Many types of adaptations will be possible, some by water managers, using levers under their control, but others by other government entities, stakeholder groups, communities and individuals, as they seek to shift and adapt their way of life in the face of a changing climate (along with any other stressors) (Lyle, 2015). Some of these adaptations are likely to be more effective than others. They will certainly interact and affect the condition of values (Lyle, 2015) – potentially beyond the target value that they were designed to protect or enhance. Understanding what these possible adaptation options are, who might be responsible for them (e.g. are they under MDBA control or not) and how effective each may be would significantly enhance the likely impact of future adaptation by enabling informed decision making around which adaptation options should be implemented, in what combinations, where, when and by whom.

A recent rapid assessment of the values and vulnerabilities of the MDB identified that the southern Basin was more vulnerable to flow change in terms of economic values than the northern Basin, regardless of whether the future was warmer and drier or warmer and wetter (Wahid et al., 2022). In contrast, social values were more vulnerable to future change in the northern Basin than the southern Basin (excluding the Lachlan region) (Wahid et al., 2022). This assessment was based on existing data and the authors identify a need to undertake a participatory process, particularly regarding First Nations values and vulnerabilities, to enhance the outcomes (Wahid et al., 2022).

Beyond rapid assessments such as that undertaken by Wahid et al. (2022), modelling can be used to illuminate plausible future states (Figure 3). Desired future states, along with current condition can be used as a starting point. Based on future climates and landscape context, plausible future conditions can be modelled (e.g. DPIE, 2020). Assessing many such scenarios could be used to implement a robust decision making framework, if sufficiently diverse scenarios were investigated. Landscape context can include a range of drivers such as stressors that exist, specific bioregions, the degree of certainty or uncertainty around condition or response and other factors that may modify the response of a value (land use or acid sulfate soils, for example). Adaptation options can then be modelled, including those that are within the control of MDBA and others, to identify the likely impact of those adaptations on the values in question. The outcomes of modelling such as that illustrated here can then be used to inform decisions about possible future actions including the implementation (or not) of specific adaptation options, or the review of the Basin Plan, for example.

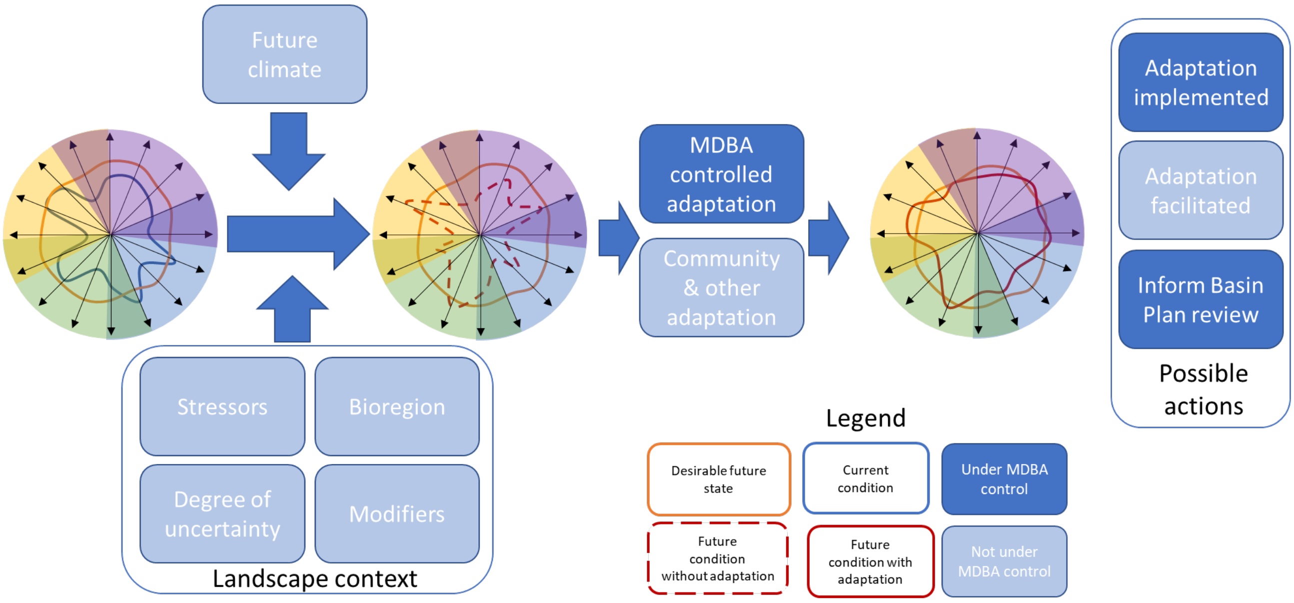

Figure 3. Conceptual representation of a pathway to modelling the impact of adaptation options on the condition of values and vulnerabilities in the Basin. Note: modifiers indicate other stressors or conditions that will alter the response of one or more values. Land use is an example, as is the presence of acid sulfate soils, as these may alter the efficacy of an adaptation.

While Figure 3 illustrates a largely linear process, in reality, decisions about possible adaptation options, and even any modelling to inform those decisions, will be multifaceted with feedback loops, iterations and trade-offs (Lyle, 2015). Multiple adaptation options may be under consideration. Different adaptation options may affect different sets of values, or act in different locations or at different rates. Adaptation may be occurring already, and so may not be subject to a specific management decision. Decision making in this space will be complex and this needs to be acknowledged and represented as best as possible in tools to assist.

Causal networks

The challenge associated with identifying the impact of future climates along with complex sets of interacting adaptations has analogies to the challenge associated with developing environmental impact assessments to identify any negative impacts of proposed human developments on the environment, its biota and ecological processes (Peeters et al., 2022). There, challenges exist in assessing causal pathways, limited spatial and temporal assessments and often a lack of transparency regarding how risks are evaluated (Peeters et al., 2022).

In response to these challenges, Peeters et al. (2022) developed the causal network concept. This approach aims to create a network representation of cause-and-effect relationships to illustrate likely relationships between activities (here, adaptation options and climate change) and environmental impacts (or responses) (Peeters et al., 2022). Their approach uses as systematic evaluation of the likelihood, consequences and mitigating action associated with each casual pathway, potentially across multiple human activities for multiple valued assets (Peeters et al., 2022). A particular focus is the identification of the confidence in each evaluation, identification of knowledge gaps and how they constrain assessment of risk (Peeters et al., 2022).

The approach can be adapted in the context of basin-wide management of a large river system to enable the identification and characterisation of the causal links from climate to values and vulnerabilities. Capturing a network of those causal links (see Figure 4 for an example) can turn any assessment of the likely impact of future climate or the efficacy of an adaptation option from a 'black box' to a transparent assessment of specific processes. This assessment therefore identifies the links between climate to outcomes for valued assets in the Basin. It also provides a transparent framework for characterising how local-scale outcomes can lead to large-scale outcomes or be synthesised with other groups of outcomes to provide holistic assessments.

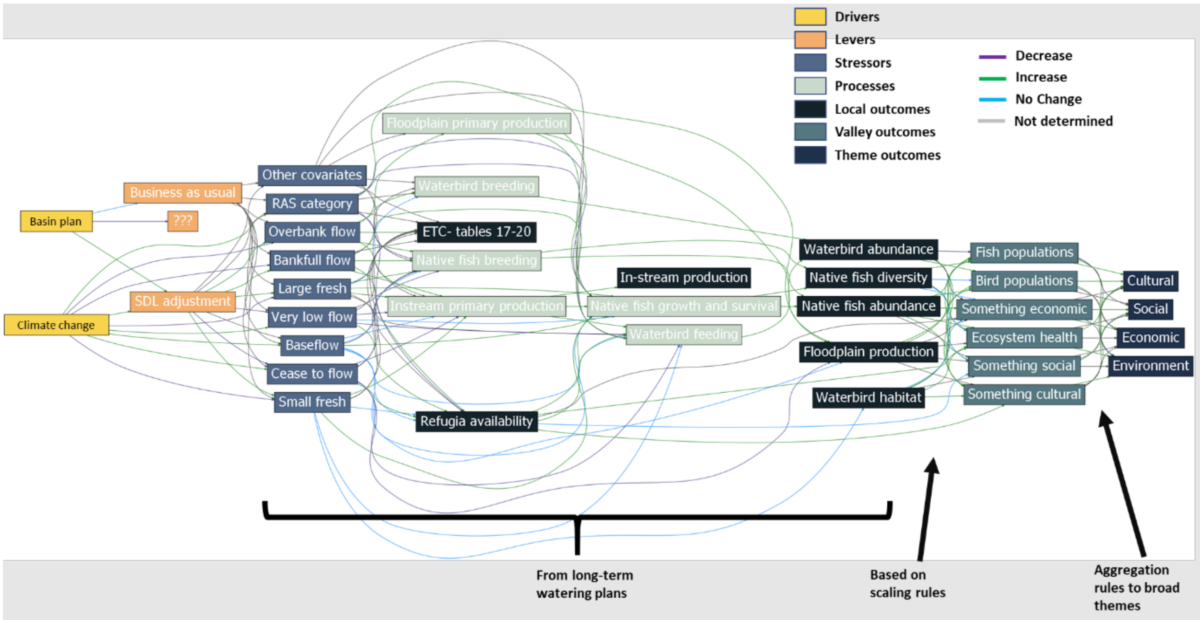

Figure 4. Example causal network capturing links from climate drivers (yellow) and MDBA responses (orange) to hydrology (indigo) to ecological processes (sage) to local objectives for the outcomes of those processes (black) to valley-scale aggregations (blue-green) and finally theme-scale outcomes. Link colours indicate directionality, but are only illustrative at the moment. This example built from a small subset of the NSW Long Term Watering Plans (environment.nsw.gov.au/topics/water/water-for-the-environment/planning-and-reporting/long-term-water-plans).

One of the major benefits for using such an approach is that managers will be able to identify and define links between outcomes and value types. Another major benefit of this approach is its inherently visual nature. This visual nature explicitly captures causality and so will be of significant value for both internal and external communication and engagement. Internally, among managers, the conceptualisation tool assists to define model components, for example. Externally, it can be used as a tool to develop trust in the process assessing the impact of future climates or adaptations, and for engagement purposes.

6. INVESTMENT IN CAPACITY

Adding to the current strengths in management in the Murray–Darling Basin is ongoing investment in the capability to address challenges and knowledge gaps and continue to improve the science available to inform decision making at all scales within the Basin. Identified MDBA science needs include a climate adaptation framework, review of existing methodologies to assess the environmentally sustainable level of take and the sustainable diversion limit, along with a better understanding of how the Basin Plan has contributed to changes in the environmental, social, cultural and economic conditions of the Basin, and improved connections between First Nations knowledge and Basin water management, among others.

Investment in capacity is occurring via the MD-WERP program in:

1. Defining values and assessing their vulnerability under a future climate
2. Understanding plausible adaptation options
3. Better ability to model hydrology at very low flows and during flooding
4. Better ability to model response of values and vulnerabilities to plausible future climates and changes in that response as a result of adaptation options
5. Better understanding of the low-flow requirements of environmental assets and prioritisation of those assets
6. Better understanding of the impact of future climates on social, economic and cultural values and vulnerabilities in the Basin.

Investment in modelling capacity that will occur via the Integrated River Modelling Uplift includes:

1. Better integration of individual models to enable basin-wide hydrologic modelling and faster integration of new knowledge.
2. Better ways to share water data and modelling information. Transparency in the models and how these are used in decision making is key to building trust.

Other programs are also contributing to build capacity and knowledge, including the CSIRO Ecosystem Functions project, and the Commonwealth Environmental Water Office Flow-MER and Short-term intervention monitoring programs. One Basin CRC will deliver policy, technical and financial solutions to reduce threats in the Basin, as it becomes established.

Identified gaps

Despite the scale of the investment, including in programs such as MD-WERP, gaps in capacity will remain at the conclusion of those programs.

Some of the key gaps that are likely to remain, and could be the focus of additional resources, include:

1. Development of additional tools for capturing responses in social, economic and cultural values
2. Development of integrative tools, capable of simultaneously assessing values and vulnerabilities across disciplinary boundaries (e.g. social and economic or cultural and environment), to draw out explicit trade-offs and synergies
3. Development of approaches to reduce the number of indicators of values and vulnerabilities that need to be considered in decision making

4. Development of communications strategy, including tools and techniques, to more effectively communicate the basis for decisions i.e. decision dashboards to enable interactive exploration of trade-offs
5. Application and adaptation of frameworks designed to enable decision making under deep uncertainty, to recognise the reality of management under a changing climate, with complex adaptation decisions being taken by many and varied stakeholders.

7. CONTINUOUS EVOLUTION

Management of the Murray–Darling Basin will continue to evolve, in response to a changing climate, a growing understanding of the processes and drivers affecting the social, cultural, economic and environmental values in the Basin and as communities and ecosystems adapt.

At the time of writing, in 2022, 80 % of Australia's population believe that climate change is occurring in Australia (statista.com/statistics). Recent years have brought widespread catastrophic fires (2019), floods (2022) and pandemic (2019-2022) to Australia, creating a greater awareness of the uncertainty that we face regarding the future. This awareness of uncertainty has shifted the conversation to one that recognises that the future will not look like the past, in many cases, and that we must change and adapt. The same years have demonstrated the ability of communities and ecosystems to adapt to new realities, recognising the difficulties associated with that change for many. There is great uncertainty associated with what the future will bring, but an opportunity to deepen the conversation with communities about that future and how best to respond and adapt.

Adaptive management has long been a by-word in natural resource management, but its implementation has varied in efficacy. Adaptive management seeks to link policy and implementation (Stankey, 2005). It is frequently conceptualised as a cycle, with steps to plan management, act, monitor and evaluate (Stankey, 2005). In the past, the links between monitoring, evaluation and revision of plans have, at times, been less explicit, or less timely, than ideal. Clear links between monitoring and evaluation and changes to policy are essential (Stankey, 2005). Frameworks for management under deep uncertainty are entirely congruent with this approach with some, such as dynamic adaptive planning for example (Walker et al., 2001), explicitly based on similar principles – that decisions need to be made without perfect knowledge but that the opportunity to learn from our experience exists. Significant investment is made in Basin Plan Monitoring and Evaluation, to underpin and evaluate the implementation of the Basin Plan. This monitoring and evaluation will be critical to assess the impacts of changing future climates and enable adaptation – of policy, communities and ecosystems.

There will be challenges associated with the management of the Murray–Darling Basin under a changing future climate. Difficult decisions will be needed regarding values that may not be able to be supported under that future and how best to deal with those people, industries and ecosystems that may be displaced as a result. But the same change will also bring new opportunities for different, more effective and more holistic ways of living and creating livelihoods in the Basin. Australia's First Nations have thrived and adapted over more than 70,000 years in our variable and unpredictable climate and there are many lessons to be learned from their example. Renewable energy will be centred in the regions, bringing the prospect of more diverse industries to our Basin that are less vulnerable to water availability. The pandemic has shown that employees can work effectively from anywhere, creating new opportunities to diversify our ways of living and working. Effective management of the Basin will need to be based on new science, better integration of the range of values for which we manage and better recognition of uncertainty in our approach to management. But, in the end, success will require open, respectful and effective communication with the community, as they decide what they would like the future of the Basin to be.

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