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To cite this article: Jamie Pittock, Samantha Corbett, Matthew J. Colloff, Paul Wyrwoll, Jason Alexandra, Sara Beavis, Kate Chipperfield, Barry Croke, Patrick Lane, Andrew Ross & John Williams (2023) A review of the risks to shared water resources in the Murray–Darling Basin, *Australasian Journal of Water Resources*, 27:1, 1-17, DOI: [10.1080/13241583.2023.2190493](https://doi.org/10.1080/13241583.2023.2190493)

To link to this article: <https://doi.org/10.1080/13241583.2023.2190493>



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A review of the risks to shared water resources in the Murray–Darling Basin

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ABSTRACT

Risks to shared water resources in the Murray–Darling Basin are reviewed after the report by CSIRO on the same topic in 2006. CSIRO outlined six major risks to shared water resources in the Basin. Herein, six groups of researchers have reviewed the risks of climate change, forest growth, groundwater, water infrastructure, water quality, and governance. These reviews bring an updated understanding of risk assessment and management that can contribute to the forthcoming reviews of the *Water Act* and Basin Plan in 2024–26. Drawing on these six papers, the authors synthesise knowledge of the risks to shared water resources and identify policy and management options and information gaps. We find that few risk factors have decreased in significance. Most risks remain and new risks are identified. Water managers must plan for a significant decrease in water availability and governments need to actively manage these risks under conditions of increasing uncertainty.

ARTICLE HISTORY

Received 22 December 2022
Accepted 9 March 2023

KEYWORDS

Climate change; forests;
governance; infrastructure;
risk; water

1. Introduction

Knowing the quantity and quality of available water is essential for river basin planning and management. Historically, surface water availability has been measured by river gauges, with the data used by managers to model water resources and support decisions about allocations. Historically, river flows were regarded as fluctuating around average values that could inform planning. However, with climate change, and other global change drivers, altering water availability, it is recognised that ‘stationarity is dead’ (Milly et al. 2008, 364). Accordingly, contemporary research focuses on predicting and projecting changes in water availability due to climate change. However, an important blind spot persists: how feedbacks or societal responses to climate change – for example, from irrigation efficiency programs, or storing more water in dams – contribute to compound risks (Pittock 2015).

With expanding populations and increased demand for water, greater proportions of the water resources in many river basins are diverted for consumptive use (Palmer et al. 2008). Several major river basins have become ‘closed’ due to high consumptive use (Falkenmark and Molden 2008). Closure, in this sense, refers to conditions by which *additional* water requirements for domestic, industrial and environmental uses

cannot be met during part or all of a year (*ibid.*). Increasing water scarcity leads to greater water insecurity and the likelihood that short-term management approaches will exacerbate risks, such as over-exploitation and depletion of groundwater resources, with adverse effects on groundwater-dependent ecosystems (Nelson 2022; Ross, Evans, and Nelson 2022).

Understanding the risks to water resources is essential for their management under conditions of increasing uncertainty, scarcity, contestation and over-exploitation, due to the combined effects of climate and land use change in catchments. Such conditions prevail in the Murray–Darling Basin in south-eastern Australia (hereafter, ‘the Basin’; Figure 1). The Basin is located in the mid-latitudes (24–37°S) where changes in precipitation and evapotranspiration are being driven by climate change and the rivers have undergone a marked reduction in inflows (MDBA 2020a). Basin water resources are over-allocated for irrigation, flow volumes have declined (CSIRO 2008) and the ecological condition of rivers and other wetlands is poor (Davies et al. 2010, 2012). Governments recognised the need to improve the management of risks to shared water in the Basin in 2004. Since then, multiple reforms have attempted to address

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This article has been republished with minor changes. These changes do not impact the academic content of the article.

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/13241583.2023.2190493>.

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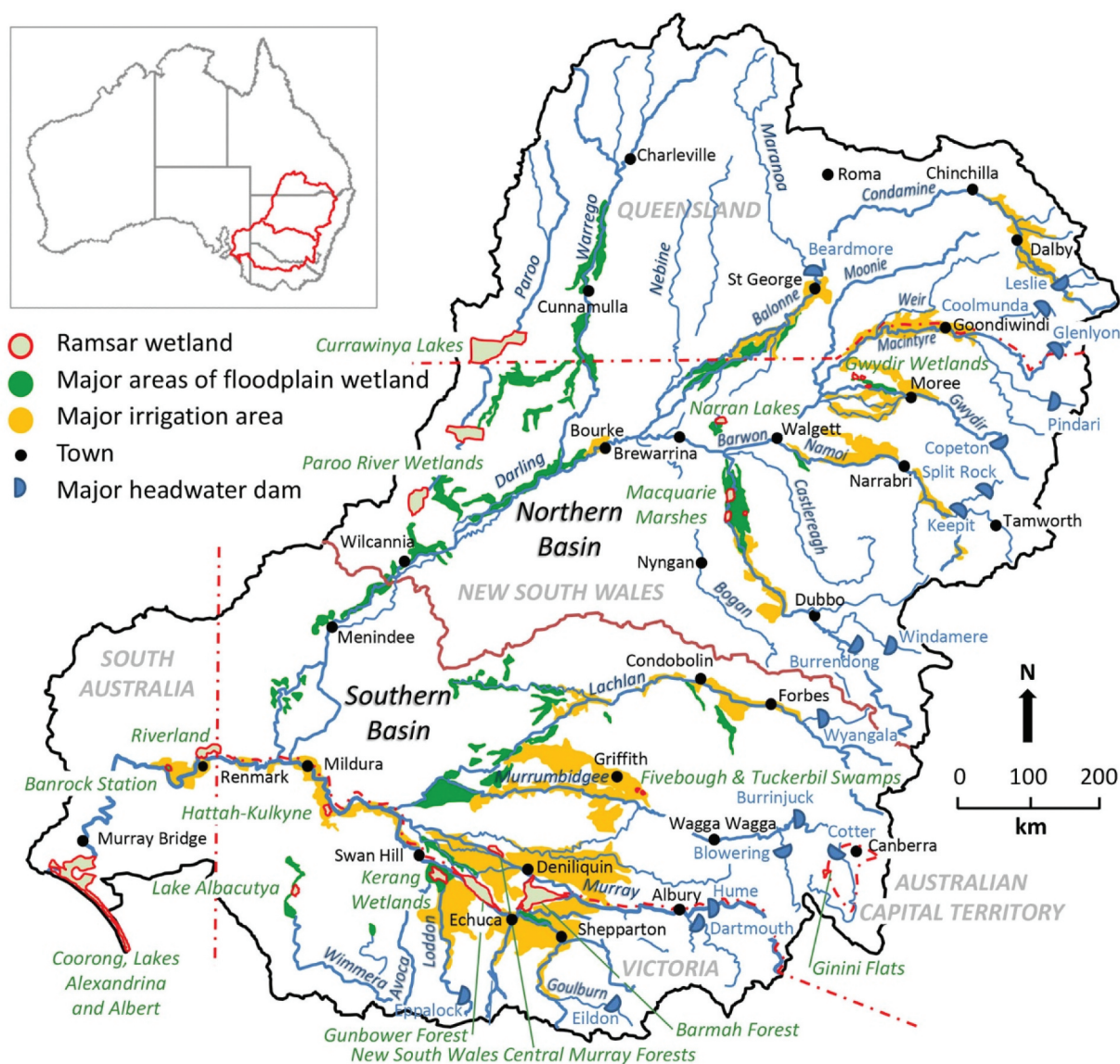


Figure 1. Map of the Murray–Darling Basin, showing irrigation areas, major rivers, wetlands and regional centres.

these problems. These reforms include the National Water Initiative (CoAG 2004), the *Water Act* (Commonwealth of Australia 2007) and the Murray–Darling Basin Plan; hereafter ‘the Basin Plan’ (Commonwealth of Australia 2012), which provide the current policy framework. In particular, to address historical over-allocation of water to irrigation, in 2012 the state and federal governments decided to re-allocate $3,200 \text{ GL y}^{-1}$ to improve environmental outcomes by 2024 (Colloff and Pittock 2022).

In this special issue, six papers describe specific risks to the Basin’s water resources, and one addresses the overarching governance challenges. Our purpose is to provide an update of the risk assessment of van Dijk et al. (2006) and identify emerging and interacting risks. This synthesis is an important input to the review of the *Water Act* and Basin Plan scheduled from 2024 to 2026. In each of the papers, and in this

synthesis review, we describe: (1) our understanding of risks now compared with 2006 and 2012; (2) the policy options available to manage those risks; and (3) the knowledge needed to better quantify and respond to those risks and inform the revised Basin Plan. This synthesis is structured as follows. First, we summarise the history of Basin risk assessments. Second, we outline concepts of risk and uncertainty. Third, we provide a critique of the current risk framework for the water resources of the Basin. We then summarise how the scope, impact, magnitude and extent of risks have changed and, finally, address policy options for change.

2. A note on water justice, Indigenous peoples and risk

Australian society must urgently address the dispossession of water from Indigenous groups in the Basin.

Prior to British occupation, all water was managed by Indigenous peoples in line with Indigenous conceptions of water, rather than incongruent Western notions of property, and sovereignty was never ceded (Marshall 2017). Indigenous surface water holdings are under-represented and estimated to constitute no more than 0.17% of the equivalent permitted take across the entire Basin (Hartwig, Markham, and Jackson 2021). Despite various policy commitments by Australian governments, no substantial measures are planned to address this water injustice. The rights of Indigenous peoples are a necessary consideration in future governance and management of water resources in the Basin (Moggridge and Thompson 2021) and addressing water injustice can be seen as a vital step towards enhanced water governance (Chipperfield and Alexandra, 2022). As such, we do not see rectifying water injustice for Indigenous nations as a risk to shared water resources and have not assessed required measures in a risk context in this research. Reallocating water entitlements from existing water holders is not easy but there is public support for this (Jackson, Hatton McDonald, and Bark 2019). Further, eligibility criteria when granting new water extraction rights can, at a minimum, more equitably provide for Indigenous interests, which consistently align with environmental aims (Chipperfield and Alexandra, 2022). Changing the water holders does not necessarily change the water volume or quality in the rivers. There are many policy options to fast-track the return of water rights to Indigenous peoples to achieve economic, cultural and concurrent environmental benefits. Further, there are many small-scale examples in the Basin of Indigenous groups managing water to achieve cultural and environmental outcomes that have broader public benefits (Costanza-van den Belt et al. 2022). There is the potential to scale up nascent Indigenous river ranger programs and provide for greater Indigenous management of environmental water to significantly enhance cultural and environmental outcomes.

3. A brief history of Basin risk assessment

A 2003 report for the Murray – Darling Basin Commission (MDBC) – the precursor of the Murray–Darling Basin Authority (MDBA), the agency responsible for the implementation of the Basin Plan – contained a projected reduction of Basin inflows of 2,140 GL y^{-1} by 2023 under a ‘business as usual’ scenario. The factors expected to influence flow volumes were climate change, afforestation, extraction of groundwater, reduced return flows from irrigation, farm dams, vegetation regrowth after bushfires, industry changes and water trading. The reduced flows were expected to have a greater impact on the environment than on irrigation (Earth

Tech Engineering 2003; MDBC 2004). The abridged findings of this report were presented to the Murray–Darling Basin Ministerial Council in 2004 (MDBC 2004), which had the authority to address these risks under the *Murray–Darling Basin Agreement* (Commonwealth of Australia 2008).

In recognition of their potential severity, the MDBC developed a strategy to address risks to shared water resources (MDBC 2008). Governments agreed to report annually on their risk assessments and their policy and management responses to enable an independent audit. This only occurred once, in 2007, and was discontinued because, with the *Water Act* reforms, these risks were meant to be handled through the Basin Plan. As part of the risks strategy, the MDBC commissioned a detailed assessment of risks to shared water resources (van Dijk et al. 2006). At a time when average stream flow was understood to be 24,000 GL y^{-1} they reported a likely reduction in stream flow by 2026 of between 2,500 and 5,500 GL y^{-1} .

This assessment identified climate change as the most important risk factor, accounting for a reduction of up to 1,100 GL by 2026 and 3,300 GL by 2056. Reduced flows from groundwater pumping were estimated at 50% of the impacts of climate change, afforestation at 33% and bushfires and irrigation management changes smaller. Farm dams were estimated to account for a reduction of 1,900 GL. However, these impacts would depend on the efficacy of regulatory policies intended to restrict further development (van Dijk et al. 2006).

In preparation for the Basin Plan, the MDBA commissioned further reviews of risk factors and their interactions. These reports were peer reviewed and published by the MDBA on its website. However, many are no longer publicly available and their findings, particularly on climate change, were not incorporated into the final version of the Basin Plan (Alexandra 2021). In 2011, papers based on some of these assessments were published in a special section of *Water Resources Research*, entitled: ‘Water resources in the Murray–Darling Basin: past, present, and future’ (Roderick 2011). Schofield (2011, 90–92) detailed summaries of 17 MDBA-funded investigations on risks to shared water resources, including effects of climate change.

Prior to the publication of the Basin Plan, the *Sustainable Yields Audit* of Basin water resources estimated that 48% of available surface water was diverted for consumptive use (CSIRO 2008, 28). Under the final gazetted Basin Plan, the intent was to restore water to the environment by reducing the volume of surface water diversions by 2,750 GL y^{-1} , about 20% of the average Baseline Diversion Limit of 13,623 GL y^{-1} (the volume for irrigation and other consumptive uses). This reduction forms the basis for the Basin-wide Sustainable Diversion Limit (SDL) of 10,873

GL y^{-1} . However, in 2010 it was estimated that 3,000 to 7,600 GL y^{-1} would be needed to maintain wetlands and rivers (MDBA 2010, 110). Returning 2,750 GL y^{-1} to the environment would be insufficient to achieve the main environmental objectives of the Basin Plan (Prosser, Chew, and Stafford Smith 2021): to restore the ecological condition of rivers and wetlands and make them more resilient to climate change (Commonwealth of Australia 2012, S8.04).

The water budget of the Basin provides some indication of the sensitivity of water resources to risks caused by climate change and other factors (Figure 2): mean annual runoff is only 6% of mean annual rainfall (Potter, Chiew, and Frost 2010, Figure 2 therein). Despite commissioning reports on the risks from climate change in the lead-up to the Basin Plan (Chiew, Cai, and Smith 2009; Kiem and Verdon-Kidd 2009), the MDBA failed to explicitly manage for climate change in the final Basin Plan (Alexandra 2017, 2021; Pittock, Williams, and Grafton 2015). The MDBA used historical climate and flows for Basin Plan modelling and the setting of ecologically sustainable limits of take (ESLTs) and SDLs (Alexandra 2020; Commonwealth of Australia 2012; MDBA 2020a), despite express advice to use recent climate conditions as the predictor of likely scenario of flows (Chiew, Cai, and Smith 2009, 3).

Risks to water availability from farm dams, plantation forestry, floodplain harvesting and groundwater extraction were also recognised under the National Water Initiative (NWI): a national policy framework in which all governments committed to policies on monitoring and regulating interception activities

outside of the water entitlement system (CoAG 2004). A report to the National Water Commission documented major interception activities, their estimated water usage and the likelihood of expansion (Sinclair Knight Merz, CSIRO and Bureau of Rural Sciences 2010). Some predictions proved inaccurate: for example, floodplain harvesting was deemed unlikely to expand due to regulations restricting the construction of new storages. However, floodplain harvesting has increased markedly since 2010, with the extent and volume of water taken increasing significantly more than predicted (Williams et al. 2022; Figures 6 and 7 therein).

Since gazetting the Basin Plan in 2012, relatively little research has focused on refining knowledge of risks to shared water resources. While the MDBA chose to ignore advice on climate change for political reasons (Alexandra 2017; Walker 2019), Section 6 of the Plan acknowledges climate change as a major risk, central to future revisions, that requires up-to-date assessments (Commonwealth of Australia 2012, S6.06). This section has been interpreted by some to mean the MDBA is not required to revise climate change impacts until the first revision of the Basin Plan (Vertessy et al. 2019, 14). By this time, two decades will have elapsed since the Murray–Darling Basin Ministerial Council (MDBMC) formally recognised climate change risks (MDBC 2005). Opportunities for climate change adaptation were largely ignored during this period.

New and interacting risks have emerged over the 16 years since the report by van Dijk et al. (2006), which require assessments and robust policy

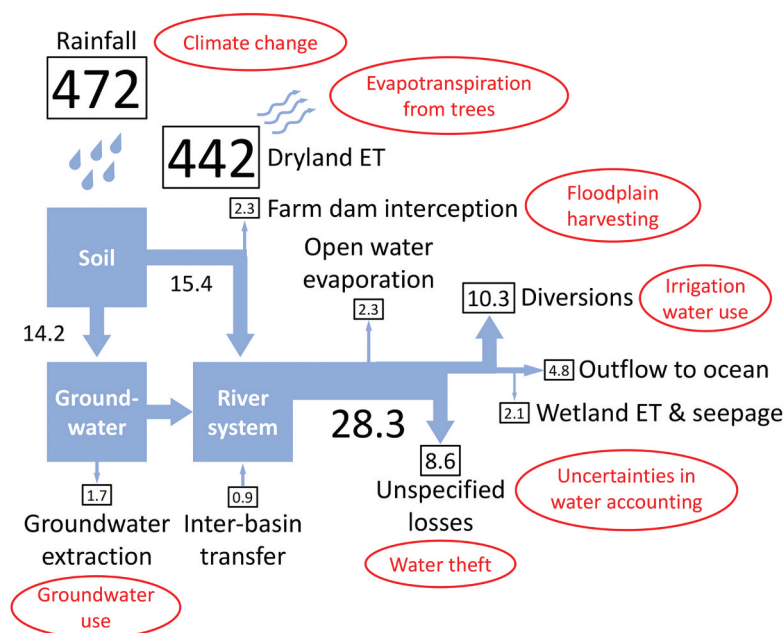


Figure 2. The approximate water budget of the Murray–Darling Basin (mm y^{-1}) under a scenario of current water resource development and historical climate. Potential losses and uncertainties due to risks to shared water resources are in red. Based on Leblanc et al. (2011, Figure 2 therein).

responses. These risks include water theft (Baird, Walters, and White 2021; Wheeler et al. 2020), the growth in floodplain harvesting in the northern Basin and its effects on the communities and flow-dependent ecosystems of the Baaka/Darling River (Brown et al. 2022), groundwater and surface water interactions, the politicisation of water reforms and consequent failures of governance (Colloff and Pittock 2022; Grafton and Williams 2020). It has become apparent that risks to water resources interact in complex ways so that their total impact is synergistic: greater than the sum of the parts (van Dijk et al. 2006). The combined impacts of climate change and irrigation diversions are reflected in recent assessments of river flows. MDBA (2020a, 21) reported that Basin inflows have declined by 39%: from 11,234 GL y⁻¹ between 1895–2000 to 6,841 GL y⁻¹ between 2000–2020. The Wentworth Group of Concerned Scientists (2020a) estimated that observed river flows were an average of 22% lower at the South Australian border than expected from Basin Plan modelling, adjusted for the effects of climatic variability. Accordingly, an update of how different risks interact is overdue. More importantly, these figures demonstrate the need to better account for the cumulative impact of risk factors in how Basin water resources are planned and managed.

4. Concepts of risk and uncertainty

The previous section summarised the history of Basin risk assessments. This section sets out to clarify concepts of risk and uncertainty. One definition of risk is the possibility of real or perceived adverse or unknown consequences from exposure to hazards (Aven 2012). The definition used by MDBC (MDBC 2008, 2), and the Australian/NZ risk management standard, is ‘the chance of something happening that will have an impact on objectives’, based on the probability of occurrence and the consequences thereof. From an epistemological perspective, risk assessment involves the application of knowledge to the unknown and how risks are defined and framed establishes an approach to decision making under uncertainty (Althaus 2005). It follows that the ways in which risk is defined and perceived in a particular context affect risk assessment and management (Quiggin 2005).

Often conflated with risk is the concept of uncertainty (Aven 2012; Bark et al. 2013; Mallawaarachchi et al. 2020). If risk is concerned with possible consequences from exposure to hazards, then uncertainty is the state of something not being definitely known or knowable. Risk-based approaches attempt to identify and manage uncertainty, by characterising or reducing uncertainty so as to reduce undesired outcomes (Aven

2012). Risks in the Basin are large scale, dynamic and systemic, embedding multiple uncertainties that interact between social, economic, political and ecological systems (Alexandra 2017; Mallawaarachchi et al. 2020). We argue that lack of knowledge should not be used as a reason not to take risks into account.

Reducing some specific uncertainties does not necessarily reduce uncertainty overall (Bark et al. 2013) or alter risk probabilities. Uncertainty can increase where conflicting perceptions of risk arise at the science-policy interface (Alexandra 2021). For example, the MDBA considered predictions of the effects of climate change on water availability in the Sustainable Yields Audit (CSIRO 2008) were too variable to be used in the Basin Plan (Alexandra 2020), despite having commissioned extensive, independent reviews of climate risks (Alexandra 2021). While uncertainty can be managed and mitigated, it cannot be eliminated (Quiggin 2005) and some uncertainty is manufactured (Quiggin 2008). Management outcomes are not achieved simply by attempting to reduce uncertainty, or by more accurately quantifying risks probabilities and impacts. Rather, effective risk management must enable decision making even under conditions of high uncertainty (Aven 2012; Bark et al. 2013). Irrigators, environmental water managers and other water users need to make decisions on water use under highly uncertain sets of variables, including how much water will be available to them from year-to-year. The state-contingent approach (Adamson, Quiggin, and Mallawaarachchi 2005) or contingent-planning decision model provides a framework suited to making policy decisions under conditions of deep uncertainty (Alexandra 2022a). Overall, it is important that risk assessments and management efforts do not conflate risk and uncertainty or use the complex nature of uncertainty to avoid making decisions on managing risks. Where matters of serious environmental threats are concerned, legislation may require decisions despite the lack of full scientific certainty, such as the precautionary principle as espoused in s 391(2), EPBC Act and the limited reference to this principle in the Basin Plan, 8.38.

5. Synergistic, complex or compound risks

Traditional risk assessment tends to treat risk factors separately, according to sectorial, jurisdictional, legislative or managerial relevance. Such an approach fails to address the fact that drivers of change in complex, adaptive, social-ecological systems, such as the Basin, interact in ways that are novel, non-linear and unpredictable (Williams 2017). Accordingly, assessing or managing risks separately ignores the reality that a policy intervention to manage a particular risk is likely

to result in a response from water users that will lead to unpredictable changes in the overall state of the water system.

Synergistic risks, also referred to as complex or compound risks, result from the combined, cumulative effects of risk factors that interact to increase the likelihood of a risk eventuating. The challenges of interconnected, compound, interacting, and cascading risks (Pescaroli and Alexander 2018), are manifest in the Basin. An example is where climate change causes prolonged and severe drought (Zscheischler et al. 2018). This results in synergistic risks with severe environmental, social and economic consequences. For example, these consequences can occur from the combined effects of: 1) lower flows and higher water temperatures caused by drought; 2) increased erosion, sediment and nutrient transport in runoff to rivers from areas denuded of vegetation; 3) declines in water quality caused by increased concentrations of dissolved organic matter, nitrogen and phosphorus; 4) cyanobacterial blooms and blackwater events leading to oxygen depletion, 5) major fish kills and 6) water supply shortages, declining water quality and water security in communities where water is no longer fit for use. These events occurred during the 2017–2020 drought. Fish kills at Menindee on the lower Baaka/Darling River were caused by oxygen depletion following cyanobacterial (blue-green algal) blooms brought on by drought and upstream irrigation diversions (Australian Academy of Science 2019; Vertessy et al. 2019). Elsewhere in the Basin major erosion, sedimentation, carbon and nutrient pollution of waterways followed catastrophic bushfires (Alexandra and Finlayson 2020; Biswas et al. 2021) contaminating domestic water supplies (Khan 2020; Pickrall 2020).

6. Complex risks , resilience thinking and risk

Recognition of complex risks has led to new assessment frameworks, particularly for climate change, including for understanding cross-border and cross-sector risks (Carter et al. 2021; Challinor et al. 2018), compound weather and climate events (Zscheischler et al. 2020), connections between physical and social drivers (Keys et al. 2019), and climate risks (Simpson et al. 2021). Beyond climate change, decision-making processes have been developed for governance of systemic risks (Florin and Nursimulu 2018; Renn 2016, 2021) within food-energy-environment-water systems (Food Energy Environment Water Network 2019; Seidou et al. 2021; Wyrwoll et al. 2018) and for social and economic resilience (Grafton et al. 2019; Linkov et al. 2018). Systemic approaches to addressing complex global risks recommended by the World Economic Forum (2022), and in the Sendai Framework for Disaster Risk Reduction (UNDRR 2019), are widely used in healthcare and epidemiology.

Resilience is the capacity of a system to absorb disturbance yet persist and reorganise while undergoing change so as to retain essentially the same functions, structures, identity and feedbacks (Holling 1973; Park et al. 2013). Park et al. (2013) suggest resilience can be understood as the outcome of a recursive process that includes sensing, anticipation, learning and adaptation. Resilience thinking includes consideration of incompleteness, with strategies directed at the ability to enable a system to anticipate and adapt to potential disturbances (Woods and Hollnagel 2017). Accordingly, aspects of resilience thinking can be applied to risk management and adaptive governance, while acknowledging that resilience means different things to different people, and the concept and its attributes, need to be clearly defined and consistently used in order to avoid misuse and misunderstanding (Walker 2020). For example, attempts to maximise efficiency and minimise uncertainty can create rigid structures that constrain adaptability and reduce resilience (Park et al. 2013).

7. A critique of the risk framework for the Murray–Darling Basin

This section provides a critique of the risk framework used in the Basin, focusing on three stages (1) risk classification; (2) risk allocation and (3) risk assessment and management.

Risk classification is important in determining the risk management focus and potential policy options. For example, van Dijk et al. (2006, 7) identified factors that could reduce flows, impacting the role of the MDBMC in co-ordinating policies to improve sustainability of the Basin. The *Water Act* requires the MDBA to develop a Basin Plan that identifies risks to the condition and availability of water resources, including water for the environment, water quality and ecological condition of flow-dependent ecosystems (Commonwealth of Australia 2012). Section 22(3) of the *Water Act* requires ‘An identification of the risks to the condition, or continued availability, of the Basin water resources’ including the risks that ‘arise from the following: (a) the taking and use of water (including through interception activities); (b) the effects of climate change; (c) changes to land use; and (d) the limitations on the state of knowledge on the basis of which estimates about matters relating to Basin water resources are made’. But the only strategy identified in Section 4.03 of the Basin Plan to manage these risks is to improve knowledge of their impact. As a result, risk management is delegated to the Water Resource Plans (WRPs), implemented by the Basin states, which must detail methods and strategies to assess and manage risks. The ‘level of risk’, according to the Basin Plan

(Section 10.40) is defined by the ISO 31000 risk standard (Standards Australia and Standards New Zealand 2009). This Basin Plan wording is of limited value since the ISO 31000 risk standard does not provide advice on setting acceptable levels of risk.

Risk allocation is about who bears the risk. Under the NWI (CoAG 2004) risk is allocated, or shared, according to existing water rights, congruent with protecting water access entitlements as a central objective of the Murray–Darling Basin risks strategy (MDBC 2008, 4). Under future reductions in water availability, water access entitlement holders bear the risk if reductions in water availability are caused by climate change and droughts. Risks arising from changes to water plans after 2014 are shared between entitlement holders, state and territory governments and the Commonwealth, while governments bear the risk of any reduction arising from changes in policy. How the allocation of risks will be borne in practical and legal terms by governments is both unclear and untested legally (Alexandra 2022a). The NWI framework for risk allocation assumes the clear separation of risks but does not account for how stakeholders may manage certain risks differently, or manage overlapping risks (Chambers and Quiggin 2004).

Risk assessment and management: in the lead-up to the Basin Plan, the MDBC conducted a Basin-scale risk assessment (MDBA 2010, 75–88; MDBC 2008). A framework was developed (though never fully implemented) for managing risks (MDBC 2008, Figure 1 therein). Risk analysis tools such as a Bayesian network, were used to investigate linkages between different risks (Pollino et al. 2010; Pollino and Glendining 2010). Categories of risk identified (and their likelihood of occurrence) were: insufficient water for the environment (moderate: 40–80%); water quality unsuitable for use (high: >80%) and poor health of flow-dependent ecosystems (moderate 40–80%). Additional factors considered (but not ranked) were: policies that have unintended adverse impacts, knowledge gaps and lack of compliance. The accompanying risk management strategy prioritises actions into four

categories, with ‘highest’, for immediate action, to address: lack of knowledge of wetlands; ecosystem functions and water availability; lack of compliance with the Basin Plan; improved flow management and environmental watering; improved inventories and mapping of wetlands and to implement WRPs (MDBA 2010, Table 3.1 therein). The *Water Act* assigns responsibilities for risk management to the MDBA (Commonwealth of Australia 2007), with approaches to risk management outlined in the Basin Plan (Commonwealth of Australia 2012; Chapter 4). Implementation of risk management, like risk assessment, is effectively devolved to WRPs. What is outlined in the Basin Plan with regard to implementing risk management is *ad hoc*, based on a miscellany of policy mechanisms that are unlikely to prove adequate to address the magnitude and extent of predicted changes (Alexandra 2020).

8. The changing risks to shared water resources in the Murray–Darling Basin

The conceptualisation, impact, magnitude and extent of the risks identified in 2006 have changed markedly in the past 16 years (Table 1). For example, the perspective on risks for groundwater has changed from a specific concern about risks to surface water from groundwater pumping to a much broader range of risks including the availability and quality of groundwater and groundwater dependent ecosystems. New risks have arisen, such as the increased floodplain harvesting that threatens downstream wetlands and communities. Interactions that create complex risks have climate change as a major factor and are not managed under current arrangements, as is apparent from evidence of declining water quality and reduced flows (cf. Supplementary Material, Tables S1 and S2). Further, conversations about the risks posed by water governance crises have evolved over the past 16 years to highlight that the lack of best practice water governance itself is one of the most significant risks to shared water (Chipperfield and Alexandra, 2022).

Table 1. The state of risks to shared water resources in the Murray–Darling Basin since 2006. ↑ = increased risk; ↓ = decreased risk; and new = where an existing risk has been compounded by a new risk. For example, increase in the volume of take from floodplain harvesting in the New South Wales northern Basin, which poses a substantial risk to inflows to the Barwon–Darling River and its tributaries, has been possible because of an increase in the construction of farm dams.

Risk	Trend increasing, decreasing since 2006	Significance of risk in 2022	Confidence in data
Climate change	↑	High	High
Trees and forests	↓	Low	Medium
Bushfires and forest regrowth	↓	Low	Medium
Groundwater–surface water interactions	↑	Medium	Low
Irrigation water management	↑	High	Low
Farm dam expansion	↑	High	High
Floodplain harvesting	↑	High	High
Water quality	↑	Medium	Medium
Insufficient modelling capabilities	New	TBA	TBA
Governance and regulation	New	High	Medium
Projected reductions in streamflow	↑	High	High

↑ = increased risk; ↓ = decreased risk; and new ...

8.1. Groundwater

Definitions of risk relating to groundwater have changed since 2006. Ross, Evans, and Nelson (2022) detail risks to surface water from groundwater use and several risks that have emerged or increased (Table S1). There are uncertainties about sustainable groundwater extraction limits in a dry climate scenario. The implementation of WRPs may not offer effective treatment of groundwater-surface water connectivity or sufficient protection of groundwater-dependent ecosystems. There are significant risks due to a lack of monitoring and assessment and insufficient research on the connectivity of groundwater and surface water resources and the impacts of extractions. There is limited knowledge and monitoring of groundwater quality. New risks to groundwater resources include coal seam gas extraction and coal mining. Greater integration of groundwater and surface water management is required to better address risks to groundwater.

8.2. Water infrastructure

Irrigation diversions are a major risk, particularly due to a marked increase since 2006 of the impacts of irrigation efficiency programs on return flows, streamflow and water quality (Williams et al. 2022). The expansion of farm dams was recognised as a risk in 2006, but the magnitude and extent of floodplain harvesting in the northern New South Wales Basin have only recently been quantified (Brown et al. 2022). The mean annual take, estimated at 778 GL, is just under half the mean annual volume of held environmental water returned to wetlands under the Basin Plan (Chen et al. 2021). Growth in storage capacity and density of farm dams is now a major risk to shared water resources. The take from floodplain harvesting not only has major negative impacts on downstream users but also breaches the 1994 Murray–Darling cap on diversions as well as catchment SDLs (Slattery and Johnson 2021).

8.3. Water quality

Risks of water quality considered in 2006 included salinity and cyanobacterial blooms. Beavis et al. (2023) reframe water quality as integral to risks to shared water resources rather than as an incidental risk. This perspective accords with the example given above of synergistic risks to water resources, whereby water quality was a central element to compounded risks that resulted in the catastrophic fish kills at Menindee in 2018–19.

New risks to environmental condition since 2006 include the increased frequency of hypoxic blackwater events, stratification events, dispersal of

cyanobacterial blooms over weirs and dams, water quality impacts from bushfires due to mobilisation of sediment, carbon and nutrients, acid sulfate soils and acidification of the water column. Major drivers of these risks include climate change and irrigation diversions. The Basin Plan provides a framework for water quality and salinity management. However, so far, management has not prevented the continuing decline in water quality and salinity management remains dependent on salt interception schemes which cannot be seen as sustainable into the longer term. The use of green infrastructure and soft infrastructure to manage streamflow to dilute salt inflows and to transport salts safely to the oceans has not been given the attention it requires under the current MDB plan (Williams et al. 2022). Improvements are needed in quantification of, and responses to, water quality risks.

8.4. Trees and forests

In 2006, reduced streamflow due to regrowth of trees following bushfires was identified as a risk. However, with improved understanding of rates of water use and evapotranspiration in forests of mixed resprouter eucalypt species, these risks are now considered overestimates (Lane et al. 2023). There remains some risk to streamflow in obligate seeder forests of mountain ash and alpine ash that are regenerating post-fire, but these constitute a very small proportion of the forested area of the Basin. Growth in plantation forestry no longer seems to be a major risk to water availability, with the current extent of new plantations much lower than expected in 2006. Future revegetation for carbon sequestration, ecological restoration and ecosystem services may result in increased water use and evapotranspiration. However, the interacting dynamics of rising temperatures, decreasing rainfall and the assumed increased water use efficiency with rising CO₂ concentrations remain unclear (Lane et al. 2023). Complex system feedbacks – like interactions between changed fire regimes, extreme climate forcings and vegetation responses (e.g. increased flammability from more open forests) – are not yet well understood.

8.5. Climate change

In 2006, climate change was understood as the largest future risk to shared water resources due to rising temperatures, declining rainfall and the increasing potential for evapotranspiration (van Dijk et al. 2006). These risks could expose significant complex social and environmental vulnerabilities across the Basin due to reductions in stream flows. Yet despite warnings, focus within the MDBA remained on historical data and the uncertainty of such climate

projections. The Sustainable Yields Audit (CSIRO 2008) and the Victorian Department of Environment, Land Water and Planning (DELWP, 2020; DELWP et al., 2021) have confirmed the warming and drying trends, punctuated by wet periods, predicted in 2006. The current impacts of climate change present a reality that significantly threatens conservation of flow-dependent ecosystems, regional irrigation communities, water yields of catchments and confidence in governments to deliver effective water policy reforms (Alexandra 2022b). Therefore, acting on climate risk assessments must become central to Basin planning. New contingent planning methods are needed that can aid responses to emerging changes in climate and their effects on shared water resources.

8.6. Measurement and modelling of risk

Effective management of water resources requires adequate information regarding the spatio-temporal distribution of the quantity and quality of the water resource being managed. This information is obtained through measurements and modelling of storages and fluxes across the river network as well as monitoring of extractions by water users. Often, management institutions have focussed on averages and median projections, rather than considering how to manage dry and wet extremes, as illustrated by the Federal Government's focus on the median scenario from the CSIRO Sustainable Yields Audit (Pittock, Williams, and Grafton 2015). Despite the acquisition since 2008 of nearly 2,100 GL y^{-1} long term average annual yield in surface water entitlements from consumptive users by the Federal Government to sustain flow-dependent ecosystems, the Wentworth Group found observed River Murray flows were more than a fifth lower than projected under the Basin Plan (WGCS 2020a). These figures illustrate both the potential magnitude and the limited progress since 2006 in improving an understanding of the uncertainty of water availability and hence the risks to shared water resources.

All measurements and model predictions have an associated uncertainty. Observations of water fluxes (e.g. rainfall, evaporation, streamflow) can have considerable uncertainty (Steiner et al. 1999; Tomkins 2014). Model predictions also have uncertainty due to the observations and parameter values used, as well as how well the model represents the system. These uncertainties need to be properly considered to understand the confidence in values that are obtained. A better understanding of the confidence in the values leads to more informed decision making.

There have been developments in modelling of water resources generally since 2006, for example,

the Australian Water Resources Audit (AWRA) model (Hafeez et al. 2015; Vaze et al. 2013) and the adoption of a National Hydrologic Modelling Strategy (Blackmore and Prosser 2008) by the Council of Australian Governments. However, these developments have not necessarily resulted in improvements in water resource management due to the time lag between creation and implementation, as well as inherent limitations.

The quality of water modelling being applied by governments has been questioned. Basin Plan modelling has not been updated since before 2012 and does not include changes to river operating rules ('pre-requisite policy measures'), such as those made unilaterally by the NSW Government in the Barwon-Darling rivers in 2012 (Australian Academy of Science 2019; WGCS 2010). Further, at least one state government has been reported as manipulating confidential Basin water modelling to favour economic interests (Hannam 2021). The Wentworth Group has criticised the governments for measuring only point-source water extractions ('single entry accounting') rather than also comparing extractions to water remaining in the rivers and against model projections (WGCS 2020a). Adoption of 'double entry accounting' would facilitate quantification of inflow changes and theft, and support efforts to refine hydrological models. For the Basin, the Federal Government elected in 2022 committed to 'updating the science' and making the Authority's 'modelling and data available to the public wherever possible', and committed to continue the Basin water model 'uplift' program (ALP 2020).

8.7. Governance and the regulation of risks

Deficiencies in water governance can have extensive adverse consequences for river systems and the equitable sharing of water such that those deficiencies can amount to crises (Chipperfield and Alexandra 2022b). In the MDB, there are many opportunities to better align with best practice water governance, which can potentially positively impact the collective variables and risks affected by regulation and governance (Chipperfield and Alexandra 2022). In the context of implementation failures of the law (such as lower than predicted flows despite a federal *Water Act* with the purpose of 'additionality') and the Basin Plan, enhanced compliance and enforcement is required, notwithstanding the challenges apparent with effectively implementing the current law (Chipperfield and Alexandra, 2022). Many have called for enhanced transparency and accountability and more consistent compliance and enforcement. These aims form part of

Table 2. Risk interactions relating to shared water resources of the MurrayDarling Basin. Magnitude and extent of interaction: red = high; amber = medium; blue = low. x indicates interaction exists but evidence of magnitude and extent is limited.

	Groundwater extraction	Climate change	Forest vegetation change	Farm dams	Floodplain harvesting	Irrigation infrastructure efficiency	Adverse water quality events	Bushfires	Drought	Floods
Groundwater extraction			Blue			Amber	Blue			x
Climate change	Amber		Red		Amber	Red	Red	Red	Red	Red
Forest vegetation change			x				Amber		x	x
Farm dams	Amber				Red	Amber				
Floodplain harvesting				Red		Red				
Irrigation infrastructure efficiency	Red			Red			Amber			x
Adverse water quality events	Amber						x	Red		
Bushfires			x	Amber			Amber	Red	Red	
Drought	Red		Amber		Red			Amber		
Floods					Red	Amber	Red			

the broader principles of good water governance, which can be grouped by themes of trust and engagement, efficiency and effectiveness (OECD 2015). These water governance principles, analogous to the ways ‘risk’ can be conceptualised, are synergistic and interacting. Comprehensive review of existing law and opportunities to enshrine requirements to better align with, and continually plan for, good water governance in the MDB is recommended. Failure to take current opportunities to do so is itself a significant risk to the shared water resources of the Basin.

8.8. Risk interactions and assessment of complex risk

There is a need to address the risks that arise from non-linear, emergent, unpredictable interactions within complex social-ecological systems like the Basin. Interactions between risks identified in this special issue remain incompletely known (Table 2). This knowledge deficit reinforces the need to understand risk beyond just identification and management of individual risks, as exemplified by the complex risk arising from the interactions between climate change, irrigation diversions and water quality outcomes. The frequency of events that cause low water quality is likely to increase with climate change and resultant extreme droughts and floods. Risks to water availability and quality result from multiple drivers of

change and have multiple, cascading consequences (Figure 3). Drivers and impacts can reinforce each other and the influence of drivers on responses may vary in space and time. Risks are thus inherently dynamic, interactive and must be considered holistically in risk management decision making. The introduction of a three-infrastructure framework (Williams et al. 2022) is one management approach that may address this matter.

9. Discussion

9.1. Risks to shared water resources have changed

Since 2006, the understanding of the impacts and types of risks has improved. Some risks were over-estimated, such as the expansion of plantation forestry. Other risks have proven much greater than projected, such as floodplain harvesting, reduced return flows and the increasing number of extreme events leading to poor water quality. Water availability is now clearly diminished by climate change and compounding risk interactions highlight the need for integrated risk assessments (Alexandra 2022b). Groundwater is recognised as constituting a major part of the shared water resources of the Basin (Ross, Evans, and Nelson 2022). Effective policy levers for managing groundwater are different but complementary to those for managing surface water. Water quality also needs to be

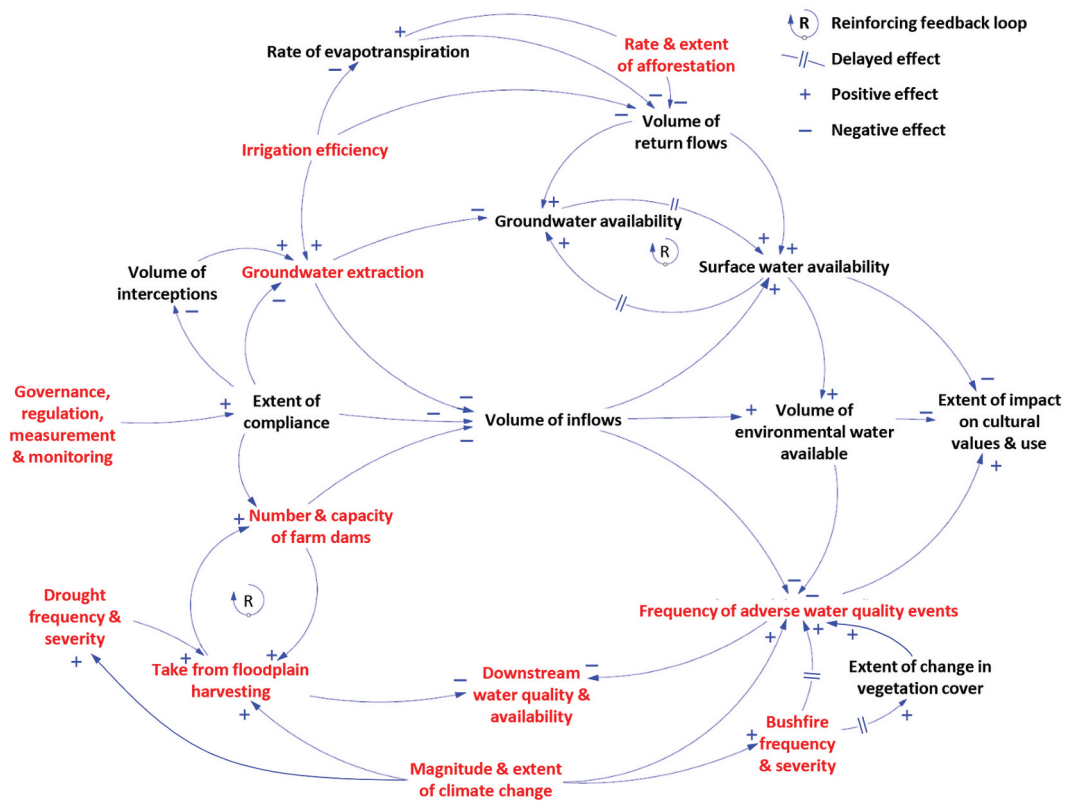


Figure 3. Causal loop diagram showing major interactions of risks to shared water resources in the Murray–Darling Basin and their effects. Risks are in red, effects in black.

considered integral to water resources management (Beavis et al. 2023) needing adoption of effective policies. A deficient governance framework, including a lack of capacity or willingness, to manage these risks, as noted above, is itself a risk. Below we outline other issues of concern.

9.2. Measurement and modelling are inadequate

Currently, measurement and modelling are inadequate to identify risks for determining the efficacy of risk management. Inadequate modelling and measurement of risks is itself a risk and uncertainty over the effectiveness of management is part of the problem. Monitoring impacts of extractions in connected groundwater and surface water resources and monitoring of floodplain harvesting are two examples where measurement and modelling are deficient. Basin-scale water audits, the use of remote sensing for enforcement and a better network of flow gauges in the northern Basin are needed to improve measurement (Williams et al. 2022). Improved monitoring of the impacts of extractions is a prerequisite for understanding whether sustainable diversion limits need to be adjusted when the Basin Plan is reviewed by 2026. There are also insufficient tools to model water quality risks, with effective biogeochemical models for water quality prediction yet to be developed (Beavis et al. 2023).

Barriers to integrating modelling and measurement across the Basin are driven, in part, by the complexity of cross-border management (Chipperfield and Alexandra 2022). Limited assessment and monitoring capacity lead to poor understanding and management of local risks. For example, inadequate groundwater monitoring and modelling by state agencies means risks to groundwater-dependent ecosystems from surface water–groundwater interactions are not adequately addressed in the implementation of WRPs (Ross, Evans, and Nelson 2022). (Chipperfield and Alexandra 2022) identify technical and legal problems of modelling and measurement that underpin effective regulation and compliance. Overcoming these deficiencies is central to managing risks.

The magnitude of many risks needs to be better understood due to measurement and modelling limitations, poorly understood feedbacks and the dynamic impacts of climate change. While there have been shortfalls in expected river flows (WGCS 2020a) the drivers of these shortfalls cannot be easily partitioned and quantified, though recent progress in identifying the relative contribution of the effects of climate change and irrigation diversions is promising (Grafton et al. 2022). Compounding risk interactions received little attention in 2006 and greater understanding is needed (Beavis et al. 2023). Where risk factors were well documented in 2006, the slow implementation of public policy responses to

effectively address them is a systemic risk (Chipperfield and Alexandra, 2022). In other cases, knowledge gaps remain, including: 1) the interactions between vegetation, climate, fire and the effect of these variables on water availability and quality (Lane et al. 2023); 2) climate change impacts on declining water quality and recovery (Beavis et al. 2023); 3) and cross-scale impacts of ground-water and surface water use and storage on the total consumptive pool (Ross, Evans, and Nelson 2022).

9.3. Inadequate governance and management of risks

The inadequate management by governments of the threats identified in 2006 is hard to understand and represents a major opportunity cost to the implementation of water reform. Some risks have greatly increased, such as increased density and size of farm dams used for floodplain harvesting (Williams et al. 2022). The Basin cap on diversion and subsequent rules had no effect in reducing this impact (Williams et al. 2022). Further, policy differences across states have constrained effective regulation of licenced and unlicensed farm dams. In our view, the adoption of a Three-Infrastructures Framework (Williams et al. 2022) in the future reform and revision of the Basin Plan represents a significant opportunity for Australia to avoid past failures and mitigate the multiple risks to water availability, quality, accessibility, and security.

Ross, Evans, and Nelson (2022) identified that WRPs are inadequate to respond to the conjunctive management of groundwater, specifically because water scarcity and climate change are interacting with groundwater-dependent ecosystems. At the time of writing, only two of 20 New South Wales groundwater and surface water WRPs due for completion in 2019, were adequately prepared by the NSW Government and have been accredited by the Federal Government. As another example, MDBA assessments of the risks to water resources from forest expansion in the Northern Victoria, Goulburn–Murray and Victorian Murray WRPs all use the same text (e.g. in MDBA 2020b) to argue that the risk is low because the plantation area did not expand from 2009 to 2016 and thus additional regulation is not required. These plans do not consider the risks arising from forest area expansion due to carbon sequestration plantings.

Beavis et al. (2023) identify that water quality risks are not adequately addressed in the implementation of the Basin Plan. In several cases, this has led to catastrophic ecological and social consequences from extremely poor water quality.

Inadequacies in the governance and management of risk are now themselves significant risks (Chipperfield and Alexandra, 2022). These

inadequacies result in systemic vulnerabilities which limit the capacity of agencies to deal with known and emerging risks. This situation erodes public confidence and trust in the credibility and legitimacy of governments and their agencies in managing shared water resources. Chipperfield and Alexandra (2022), after analysing features of governance insufficiencies in the MDB based on a principled good water governance framework, identify that enhanced water governance and regulation are possible.

10. Policy options for change

Although lack of knowledge should not delay decision making, there is an urgent need for governments to invest in improving knowledge of the nature, extent and magnitude of risks and identifying effective policy options to manage them. These endeavours should be central to the revision of the Basin Plan by 2026. The needs include improving the capacity for measurement and modelling to identify the magnitude and extent of risks. Options for improvement raised in this special issue focus on better data collection, comprehensive water accounting, public accessibility of data and integrated Basin-wide modelling (Table S3). This will require governments to agree how to commit to develop, store and share very large data sets. Where new risks have been identified, robust risk analysis is needed to identify effective management actions that avoid those risks becoming complex and cumulative. Integrated risk assessments must be developed to address such complex risks and iterative assessments put in place to track changes in magnitude and extent of risks (Challinor et al. 2018).

Improving transparency and availability of data and models, as well as providing explicit detail on the nature of risks and their consequences, will help build confidence and restore trust in the agencies responsible for implementation of the Basin Plan. Trust in the MDBA and state government agencies by Indigenous peoples and other stakeholders, and residents of regions suffering from environmental degradation (such as the lower Baaka/Darling River), has been damaged. The top-down technocratic approach to water reform undertaken has resulted in a lack of opportunity for stakeholders to equitably engage and contribute in meaningful ways to Basin Plan outcomes (Colloff and Pittock 2019). Renn (2016) argues that active stakeholder participation is critical for assessing systemic risks and options for managing them.

Systematic modelling of the ecological condition of flow-dependent ecosystems, as well as a prioritisation framework for biodiversity conservation, must be established to ensure effective risk assessment and to realise the environmental objectives of the Basin Plan (WGCS 2020b). Improving how uncertainty is

assessed, managed and communicated is a central issue for governance reform (Alexandra 2021; Mallawaarachchi et al. 2020). Under future climate change and increasing water scarcity, water entitlements may need to be adjusted automatically to reflect multi-decadal trends in water availability and environmental water requirements (WGCS 2020b). Such a system would require a comprehensive water accounting framework and a robust, reproducible Basin-wide environmental monitoring system linked to an effective strategic adaptive management system (Roux and Foxcroft 2011). These fundamental tools are lacking ten years into the implementation of the Basin Plan.

A move away from business-as-usual governance can help ensure effective management of risk, including upholding best practice principles, transparency, accountability and participation (Alexandra 2019; Chipperfield and Alexandra, 2022; Williams et al. 2022). Achieving best practise governance of risks requires major reforms to address the structure and adverse cultural impacts of the agencies tasked with managing water resources in the public interest. In particular, the integrated management of groundwater and surface water is required (Ross 2018). There is an irrefutable need to prepare and adapt to increasing scarcity of water resources caused by climate change (Alexandra 2022b; Keys et al. 2019). However, the authors of papers in this special edition identify the policy responses to risk continue to fall short of what is required.

Reforms required include the development and implementation of a systemic approach to adaptation planning, including use of adaptation pathways to conserve flow-dependent ecosystems and biodiversity (WGCS 2020b) and address options for new livelihoods and wellbeing of Basin communities (Colloff and Pittock 2022). Without such approaches, it will become increasingly difficult to address how water can be credibly and legitimately allocated between consumptive uses and the environment under a changing climate (WGCS 2020b). Such approaches require policy and management shifts to find equitable and adaptive solutions and the triaging needs of users and the environment.

11. Conclusions

Two decades have elapsed since the MDBMC formally recognised the significance of multiple risk factors that could diminish flows outside the formal water allocation frameworks (MDBC 2004). This special edition outlines how these risks, including climate change, are documented in various risk assessments over these decades and why proactive policy development should be a priority for Basin governments. The papers also demonstrate that in subsequent decades the policy responses have been inadequate and that opportunities for developing co-

ordinated and effective approaches to risk management and climate adaptation were wasted. As a result, there remains a pressing need for improved policies to manage the imminent risks of there being significantly less water available in the Basin. The first Basin Plan did little to indicate the severity of combined impacts of the known risk factors, and their social and environmental consequences. For example, there is an adaptation deficiency in the Basin: communities are not adequately supported in developing their responses to increasing climate impacts. Basin governments need to develop effective approaches to risk mitigation policies and adaptation strategies. The failure to do so, when given multiple opportunities, demonstrate the governance risk outlined by Chipperfield and Alexandra (2022), and why reinvigorating Basin risk assessments is critical (Williams et al. 2022). Reinstating the MDB Risk Audit, in which all states report on their efforts to quantify and respond to the recognised risks, would be one mechanism that would improve transparency and coordination in developing effective policy across the Basin.

Government managers have an opportunity to move past erroneously delaying risk management decisions by awaiting quantitative precision on likely water losses. The major challenge is to make better water governance decisions now on an adaptation pathway under constant uncertainty. These endeavours should be central to the revision of the *Water Act* and Basin Plan by 2026.

Acknowledgements

We thank Prof. Katherine Daniell, editor, *Australasian Journal of Water Resources* for supporting our proposal for this special issue and to all authors who have contributed to it. We appreciate the insightful advice from two anonymous reviewers that has enhanced this paper.

Disclosure statement

Jamie Pittock is a member, and Matthew Colloff and associate, of the Wentworth Group of Concerned Scientists. No other potential conflict of interest was reported by the authors.

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