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Towards a systems approach for river basin management—Lessons from Australia's largest river

R.M. Thompson[1] | **N. Bond**[2] | **N.L. Poff**[1,3] | **N. Byron**[1]

[1] Institute for Applied Ecology, University of Canberra, Canberra, ACT, Australia

[2] The Murray–Darling Freshwater Research Centre, La Trobe University, Wodonga, VIC, Australia

[3] Department of Biology, Colorado State University, Fort Collins, Colorado, USA

Correspondence
R. M. Thompson, Institute for Applied Ecology, University of Canberra, Canberra, ACT 2617, Australia.
Email: ross.thompson@canberra.edu.au

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Abstract

Globally, large river systems have been extensively modified and are increasingly managed for a range of purposes including ecosystem services and ecological values. Key to managing rivers effectively are developing approaches that deal with uncertainty, are adaptive in nature, and can incorporate multiple stakeholders with dynamic feedbacks. Australia's largest river system, the Murray–Darling Basin (MDB), has been extensively developed for shipping passage, irrigation, hydroelectric development, and water supply. Water development in the MDB over the last century resulted in overallocation of water resources and large-scale environmental degradation throughout the Basin. Under the pressure of a significant drought, there was insufficient water to supply critical human, environmental, and agricultural needs. In response, a massive programme of water reform was enacted that resulted in considerable institutional, social, and economic change. The underlying policy was required to be enacted in an absence of certainty around the scientific basis, with an adaptive management focus to incorporate new knowledge. The resulting institutional arrangements were challenged by a need to generate new governance arrangements within the constraints of existing state and national structures. The ongoing reform and management of the MDB continues to challenge all parties to achieve optimization for multiple outcomes, and to communicate that effectively. As large-scale water reform gains pace globally, the MDB provides a window of insight into the types of systems that may emerge and the challenges in working within them. Most particularly, it illustrates the need for much more sophisticated systems thinking that runs counter to the much more linear approaches often adopted in government.

KEYWORDS

environmental water, river basin development, social–ecological systems, water markets, water policy

1 | INTRODUCTION

1.1 | Overview

The majority of large river systems globally are now heavily impacted by human activities, and both the magnitude and extent of these impacts will increase as demands for water for agriculture, consumption, and energy generation grow (Poff & Schmidt, 2016; Vörösmarty et al., 2010). In many regions, these pressures will be exacerbated by the effects of climate change (Hanjra & Qureshi, 2010) and will have consequences for human well-being and regional security (Jury & Vaux, 2007). It is currently estimated that 80% of the world's population is at threat from poor water security, and global demands for water are doubling every 20 years (Bhattacharya, 2016). As a consequence, the vast majority of large river basins have heavily modified flow regimes and/or are overallocated (Poff et al., 1997; Vörösmarty et al., 2010). Many of the unmodified river basins that remain are subject to proposals for large-scale development (Nilsson, Reidy, Dynesius, & Revenga, 2005; Poff & Schmidt, 2016).

There is an increasing awareness of the need to develop freshwater resources in a way which is sensitive to biodiversity and ecosystem function (Poff & Schmidt, 2016). In a number of parts of the world, there are large programmes underway that seek to restore degraded river systems in order to recover ecological values (e.g., Follstad Shah, Dahm, Gloss, & Bernhardt, 2007; Kneebone & Wilson, 2017; Schiemer, Baumgartner, & Tockner, 1999). These include dam removals (e.g., East

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et al., 2015), re-engineering of river channels (e.g., Koebel & Bousquin, 2014), reconnection to flood plains (e.g., Phelps, Tripp, Herzog, & Garvey, 2015), and restoring flow regimes (e.g., Dolédec et al., 2015). However, the success of these restoration activities is variable, and the investment required is very high (Lamouroux, Gore, Lepori, & Statzner, 2015; Wohl, Lane, & Wilcox, 2015). Most often, the pace of river basin development has outstripped the ability to impose limits and develop policy to manage these pressures. This has led to a need to retrospectively impose restrictions on water for consumptive uses and to create arrangements to manage river basins, which utilize existing institutions and governance. This is made even more complex by the need to carry out this reform against a complex backdrop of social, economic, and ecological systems that are often poorly understood and are rarely static.

Here, we briefly describe the history of development of Australia's largest river basin, the Murray–Darling Basin (MDB). Beginning with the recognition that the Basin was overallocated, we then provide an overview of the reform process and its scientific underpinnings. The intention is not to provide a detailed review of the reform process through any single disciplinary lens. This has already been done from the perspective of governance (e.g., Marshall & Alexandra, 2016; Marshall, Connell, & Taylor, 2013), policy reform (e.g., Cummins & Watson, 2012), and economics (e.g., Kirby, Connor, Ahmad, Gao, & Mainuddin, 2014). The emergence of water markets as a feature of water management in the MDB has been of particular significance and focus (e.g., Kiem, 2013; Grafton & Horne, 2014; Wheeler, Loch, Zuo, & Bjornlund, 2014; Grafton, Horne, & Wheeler, 2016). Numerous studies have described ecological knowledge needs and ecological responses to reform (e.g., Docker & Robinson, 2014; Reid, Colloff, Arthur, & McGinness, 2013; Thompson, King, Kingsford, Mac Nally, & Poff, 2017; Zampatti & Leigh, 2013). Most recently, the water reform experience in the MDB has been used to identify sets of general principles for river basin management (Parsons, Thoms, & Flotemersch, 2017). We adopt a “systems-level” perspective of water reform in the MDB. The need to manage competing demands for water for amenity, irrigation, energy, and environment, with imperfect knowledge and constraints of existing governance structure, necessitates a systems approach, challenging the more linear thinking that has often predominated in policy development and implementation. Systems thinking understands decisions as embedded in a network of nodes, with complex feedbacks and interactions that proliferate across the network in response to change (Checkland, 1999). In recent years, these approaches have been applied to a range of natural resource management challenges (see Cundill, Cumming, Biggs, & Fabricius, 2012, for a review). Here, a set of systems models from the MDB is used to illustrate the complex nature of these networks and their potential utility.

1.2 | The MDB

A number of narrative reviews have described the biophysical, social, and economic context that led to water reform in the MDB (e.g., Connell & Grafton, 2011; Doolan, 2016; Hart, 2016a, 2016b; Quiggin, Mallawaarachchi, & Chambers, 2012). Australia is the world's driest inhabited continent, with extreme temporal and spatial variation in rainfall and run-off (McMahon & Finlayson, 2003). The MDB in south-eastern Australia is Australia's largest river basin by area and the 15th largest globally. Average basin-wide run-off is modest (31,600 GL pa) but highly variable (6,700 to 117,900 GL). Beginning shortly after European colonization, the mainstem of the River Murray was modified for shipping passage, largely through the removal of woody debris, particularly in the late 19th century (Erskine & Webb, 2003). A second major period of development between 1920 and 1950 saw the construction of a series of locks and impoundments for flood management and diversions for irrigation and passage of shipping (Bren, 1988). By the mid-1990s, the MDB was the most important agricultural region in Australia, producing approximately 40% of all agricultural commodities, a third from irrigated agriculture, consuming on average in excess of 13,000 GL pa (1997–2007; Australian Bureau of Statistics, 2013).

From the 1930s to the 1990s, water use approximately tripled to almost 11,500 GL, and the average annual flow to the sea at the Murray mouth dropped to 25% of what it would have been under natural conditions. In dry years, the proportion of water supporting the environment dropped even further and the Murray mouth (where the river enters the sea on Australia's southern coast) closed a number of times (Bourman & Barnett, 1995). Extensive modelling of the river under abstracted and preabstracted levels showed that development had reduced the seasonality of flows, greatly reduced the frequency of mid-sized floods, and significantly increased the duration of low flows (Maheshwari, Walker, & McMahon, 1995). The consequences of these changes led to a range of environmental issues including increased salinity, acidification of lakes in the lower part of the system, declines in the condition of floodplain forests, and reductions in populations of native fish and waterbirds (e.g., Gell, Tibby, Little, Baldwin, & Hancock, 2007; Leslie, 2001; Mac Nally, Cunningham, Baker, Horner, & Thomson, 2011; Walker & Thoms, 1993). In 1995, an audit of water use in the MDB showed increasing diversions and widespread decline in river health (Davies, Harris, Hillman, & Walker, 2010).

Recognition during the 1990s that the ecological functioning of the MDB had been significantly compromised led to a number of initiatives (see Doolan, 2016, for a review). In 1995, the MDB Cap stopped further growth in diversions and allowed a water market to develop where participants could buy, sell, and transfer tradeable water rights. The Living Murray programme was established to return 500 GL of water to the environment at a cost of $AUD 700 million (Murray–Darling Basin Authority, 2011). A number of other state-level programmes were initiated to restore river environments. However, these actions were insufficient to halt environmental decline, which dramatically worsened through the Millennium Drought (1995–2007). In 2004, state and federal governments agreed to the principle of achieving sustainable water use (National Water Initiative; Council of Australian Governments, 2004). This led to several major programmes to secure water specifically for the environment.

In 2007, the Commonwealth Government launched a programme of legislative reform (the Water Act, 2007), changes in institutional arrangements (the Murray–Darling Basin Authority and the Commonwealth Environmental Water Holder), and new management arrangements with the states and territories (Doolan, 2016). The Murray–

Darling Basin Plan (2012) was introduced to set a new sustainable diversion limit for the Basin and its catchments seeking to deliver a "healthy working basin" with healthy and resilient ecosystems, vibrant and strong regional communities, and productive and sustainable water-dependent industries. The $13B National Water Reform Water Recovery Program (Department of the Environment, 2014) was implemented to recover an average of 2,750 GL per year from consumptive use (20% reduction) for increased environmental flows through a $AUD 9 billion investment in modernization of irrigation infrastructure to save water and a $3B water purchase programme to buy water entitlements for the environment from willing sellers. Intergovernmental agreements with the States were established covering funding for water recovery projects, implementation of the Basin Plan, and their relative roles and responsibilities.

The development of the MDB Plan was highly controversial and took over 5 years to be finally agreed. The period of the Plan's development was characterized by high investor uncertainty and significant community concern and polarization (Horne, 2014). Despite an extensive biophysical knowledge base, integrating this into a defensible set of water management guidelines was extremely difficult. The resulting Basin Plan established the MDB as one of the most highly regulated and highly managed river basins in the world. This incurred significant ongoing cost; at the present roughly, recurrent costs include at a minimum, ~$5,670M pa to run the river (Murray–Darling Basin Authority, 2013) and ~$140M pa to cover the charges associated with environmental entitlements (Commonwealth Environmental Water Holder, 2013).

The development of the MDB Plan has particularly informative because of the large spatial scale of the development (1 million km^2) and the resulting cross-jurisdictional challenges that this generates. General principles (e.g., Parsons et al., 2017) from the MDB are therefore relevant to many river basins globally that are currently experiencing rapid development (e.g., the Mekong River Basin and the Amazon Basin). The MDB is also subject to high flow variability and an underlying drying trend, making insights particularly relevant to developments in semiarid parts of Africa and Asia and in the Mediterranean.

2 | THREE RIVER BASIN MANAGEMENT CHALLENGES

Three major challenges emerge in river basin management, and they are all illustrated clearly in the MDB. The recognition of these challenges is not new (Parsons et al., 2017; Richter, Warner, Meyer, & Lutz, 2006; Rogers, 2006), nor are they specific to river basin management (e.g., Biggs et al., 2012; Lindenmayer & Cunningham, 2013). Nonetheless, summarizing and illustrating those issues here provide an important foundation to our call for a stronger emphasis on systems approaches that incorporate both complex direct and indirect effects of management and feedbacks.

2.1 | Dealing with uncertainty of knowledge

The basic information required to support sustainable water resource management includes a good understanding of the hydrology of the systems to be developed and managed (e.g., Richter, Davis, Apse, & Konrad, 2012; Ryder, Tomlinson, Gawne, & Likens, 2010). This includes understanding surface water flows, groundwater levels, their connectedness, and their behaviour under the climate variability experienced by the region (both across years and decades). Understanding how the system behaves in drought is particularly important. It also requires a knowledge of environmental assets and their water requirements including any dependent downstream assets (e.g., fisheries). Collection of baseline hydrologic data provides a key baseline for future management. However, in many other river basins, these data are lacking, despite the clear need for this as a fundamental basis for river management (Acreman & Dunbar, 2004; Richter et al., 2012).

A particular strength of the MDB reform process was early success in integrating across hydrological models to provide a single tool and shared understanding of the major hydrological drivers (Welsh et al., 2013). Provision of central government funding over a sustained period led to the development of the Source Integrated Modelling System as a well-supported common framework for managing flows at a whole-of-basin scale. A disadvantage of this success was a very strong focus on complex physical modelling, with insufficient attention paid to social, economic, and ecological models of equivalent sophistication. Despite decades of research into the MDB and review of several thousand scientific studies in the area, there was a lack of data at the appropriate temporal and spatial scales, in key areas, and relating management interventions to ecological outcomes. This is typical of many large river basins worldwide (Campbell, 2007; Nilsson et al., 2005; Richter et al., 2012).

Although there is a broad literature that expresses flow–ecology relationships in conceptual terms and numerous site-specific studies of biota responses to flow drivers, there are few studies that express general relationships, which could be applied at basin scales (Richter, Mathews, Harrison, & Wigington, 2003), and almost none that have included a social component. Aquatic ecological studies are typically at small (kilometre) scales and over short periods (1–3 years), making addressing large-scale management issues using these data particularly difficult (Likens et al., 2009). Development of flow guidelines in the MDB was developed based around targeting flows to generate key ecological responses at a number of "umbrella sites," which were representative of other parts of the system (Swirepik et al., 2016). This used data-rich areas as the basis for making decisions, due to the uneven knowledge across the MDB. Detailed knowledge from some sites is critical, particularly when that data can be placed in the context of results of meta-analyses of published flow–ecology papers (Poff & Zimmerman, 2010).

Although incomplete knowledge and uncertainty are features of river basin management, by no means are these challenges unique to this sector. There have been rapid advances in analytical approaches to dealing with uncertainty in natural resource management, particularly through the application of Bayesian approaches (e.g., McCann, Marcot, & Ellis, 2006; Mendoza & Martins, 2006). There are also increasingly well-accepted approaches to dealing with large numbers of conflicting scientific studies (e.g., Eco Evidence; Webb et al., 2012). Formalizing these approaches into knowledge frameworks (e.g., Alavi & Leidner, 2001; Plummer & Fitzgibbon, 2004) can organize and conceptualize complex interactions between methods and information.

This is becoming realistic based on the insights from large numbers of natural resource management reform programmes globally, including water reform in the MDB (Bjornlund & McKay, 2002).

2.2 | The challenge of adaptive management

Given that knowledge is most often imperfect, management systems need to be flexible and open to new knowledge and refining existing knowledge. Trade-offs between the urgent need to implement clear guidelines and the need to refine the knowledge base are inevitable. In the MDB, this led to the explicit inclusion of principles of adaptive management in policy from the outset. Adaptive management *sensu* Walters (1986) provides the opportunity to "learn by doing" allowing refinement of management approaches through time. However, the need to work across five states and territories within the MDB required a complex set of arrangements and responsibilities around altering parts of the Plan in response to new information. Ways of assessing and incorporating new knowledge are a key element in adaptive management frameworks but can be difficult to build into policy, which can be prescriptive in nature.

One way to achieve an adaptive management system is to provide markets as a mechanism for enabling adaptive behaviour of individual users (Pahl-Wostl, 2007). The potential for water markets to provide a flexible mechanism for water management has been widely discussed in an international context and with respect to learnings from the MDB (e.g., Bjornlund & McKay, 2002; Garrick, Siebentritt, Aylward, Bauer, & Purkey, 2009; Grafton et al., 2013). This approach to the allocation of water was chosen early in the MDB reform process and relied on an early separation of land and water rights and a progressive introduction of water trading under a "cap and trade" approach (Crase, Pagan, & Dollery, 2004; Turral et al., 2005). The MDB water markets have developed in the context of a relatively arid system, with high interannual and intraannual variation in rainfall and large within-system storages to buffer against that variability. These climatic conditions have generated a range of agricultural users, ranging from winter farmers of wheat, who can choose to not plant crops in a given year, to horticulturists who require regular access to water to maintain trees and vines. This provides the flexibility for water trading as a means of diversifying income for some farmers in dry years. Recent reviews of the adoption of water markets in the MDB have suggested that the general principles of the market have proven a sound mechanism for reallocation of water between users across the Basin (Carr, 2015; Wheeler et al., 2014) and to recover water for the environment (Docker & Robinson, 2014).

As in many other natural resource management issues (e.g., Arvai et al., 2006; Voß & Bornemann, 2011), there are significant challenges in implementing adaptive management in freshwater ecosystems. In particular, developing robust knowledge networks that formalize and share learnings from management interventions is critical (Raymond et al., 2010). In the MDB, a set of institutions were responsible for sharing knowledge and best practice across the Basin. Two of those organizations (Land and Water Australia and the National Water Commission) have subsequently been disestablished, providing some challenges in applying adaptive management within the MDB. There are also considerable challenges in embracing an adaptive management perspective in the policy domain, where command and control and top-down thinking continue to predominate (Voß & Bornemann, 2011). From the scientific perspective, developing knowledge frameworks that are open to information from managers, and interfacing these with social networks have been a significant challenge in terms of both culture and data management (Ison, Röling, & Watson, 2007).

2.3 | Integrating across systems

Management of large river basins in contemporary society most often involves balancing social, economic, and environmental needs (Rogers, 2006). Each of these components, and the underlying physical and climatic processes, represents complex systems of interactions. The MDB water reform process required a readjustment of the benefits of water from the "social" and "economic" spheres to the "environment" component. Key to this was achieving detailed knowledge of movement of the one "currency" that reached across all of these components—water. This drove an emphasis on achieving a whole-of-basin understanding of surface water yields, patterns of flow and inundation, and factors underlying transfer efficiencies and constraints on river flow (Doolan, 2016). However, obtaining an equivalent knowledge of the ecological, economic, and social systems of the MDB was highly problematic.

Developing robust models of community perceptions and social and economic drivers is an important component of sustainable basin development (Hall, 2015; Lukasiewicz & Baldwin, 2014). The failure to fully quantify these components early enough in water reform in the MDB generated challenges in clearly articulating "triple bottom line" outcomes, although, more recently, detailed social surveys within the MDB have provided important information detailing social attitudes and consequences of water reform (Schirmer, Yabsley, Mylek, & Peel, 2016). Indigenous engagement has been a challenge in the MDB and continues to require the development of a dialogue around provision of cultural flows and recognition of indigenous concerns. In all river basins, but particularly those in the developing world, issues of indigenous engagement will be critical to achieving the outcome of a water system, which is sustainably managed with an engaged and empowered local community benefitting from development. In the MDB reform process, this has proven to be a particular challenge, although there are emerging examples of indigenous issues being integrated into water planning (e.g., Bark et al., 2015; Maclean, Robinson, & Natcher, 2015). Similarly, despite decades of research on the MDB, there remains a lack of a system-wide understanding of ecological patterns and processes (e.g., Ballinger & Mac Nally, 2006; Kingsford, Bino, & Porter, 2017), although this is now being attempted (Rolls et al., 2017).

Compounding the challenge of describing these separate components of the MDB system was the need to then effectively optimize water delivery across all components. This raises a traditional problem with "triple bottom line" approaches: determining a common "currency" for optimizing social, economic, and ecological outcomes (Milne & Gray, 2013; Williams, 2017). Ultimately, water diversion limits in the MDB were generated by a political process of compromise that was informed by social, economic, and hydrological considerations, but not by any formal optimization across the three components (Hart, 2016b; Kneebone & Wilson, 2017). The resulting process therefore combined components that were underpinned by sophisticated quantitative modelling with a high degree of certainty, others that were quantitative but characterized by high levels of uncertainty, and some components that were poorly articulated.

3 | MOVING TOWARDS A SYSTEMS APPROACH TO THE MDB

The reality of natural resource management systems at large spatial scales is that they need to incorporate a range of complex, interacting social, economic, and ecological networks. The MDB reform process illustrates the potential for economic systems to be applied to achieving ecological outcomes but by no means was an effective integration into a robust social–economic and environmental network achieved. The concept of social–ecological systems (SES) analysis provides an approach to achieving this integration. An SES consists of a biophysical–geophysical unit and its associated social actors and institutions. SES are complex and adaptive and delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context (Walker, Holling, Carpenter, & Kinzig, 2004). Central to achieving understanding of SES is to proceed by seeking to describe the complex interactions between all actors in the system, rather than trying to simplify networks into linear chains of cause and effect. The value of more sophisticated approaches to measuring outcomes has been well illustrated in recent studies, which contrast outcomes from management for single metrics versus multiple outcomes (Bark et al., 2013).

The call for systems approaches to natural resource management is not a new one (see, e.g., Armitage et al., 2009; Berkes & Folke, 1998; Walker et al., 2004). This has included in freshwater systems (Baron et al., 2002; Rogers, 2006). Most recently, one of eight principles identified by Parsons et al. (2017) was the recognition that rivers are SES where science is one of many inputs. A more explicit SES approach to management of the MDB has been called for in recent years, with intention of more effective integration of multiple values. A number of authors have illustrated both the need for, and the utility of, SES models for integrating social perspectives (Kandasamy et al., 2014). More complex systems models have been developed for the MDB, integrating indigenous values (Bark et al., 2015) and physical models with economic and social models (Kandasamy et al., 2014; Qureshi, Whitten, Mainuddin, Marvanek, & Elmahdi, 2013; Van Emmerik et al., 2014). Food web frameworks for combining trophic networks with hydrologic metrics have also been developed (Robson et al., 2017).

To date, the challenge has been that recognizing the potential importance of SES and actually applying it are two very different endeavours. Recent reviews by Bodin, Sandström, and Crona (2016)

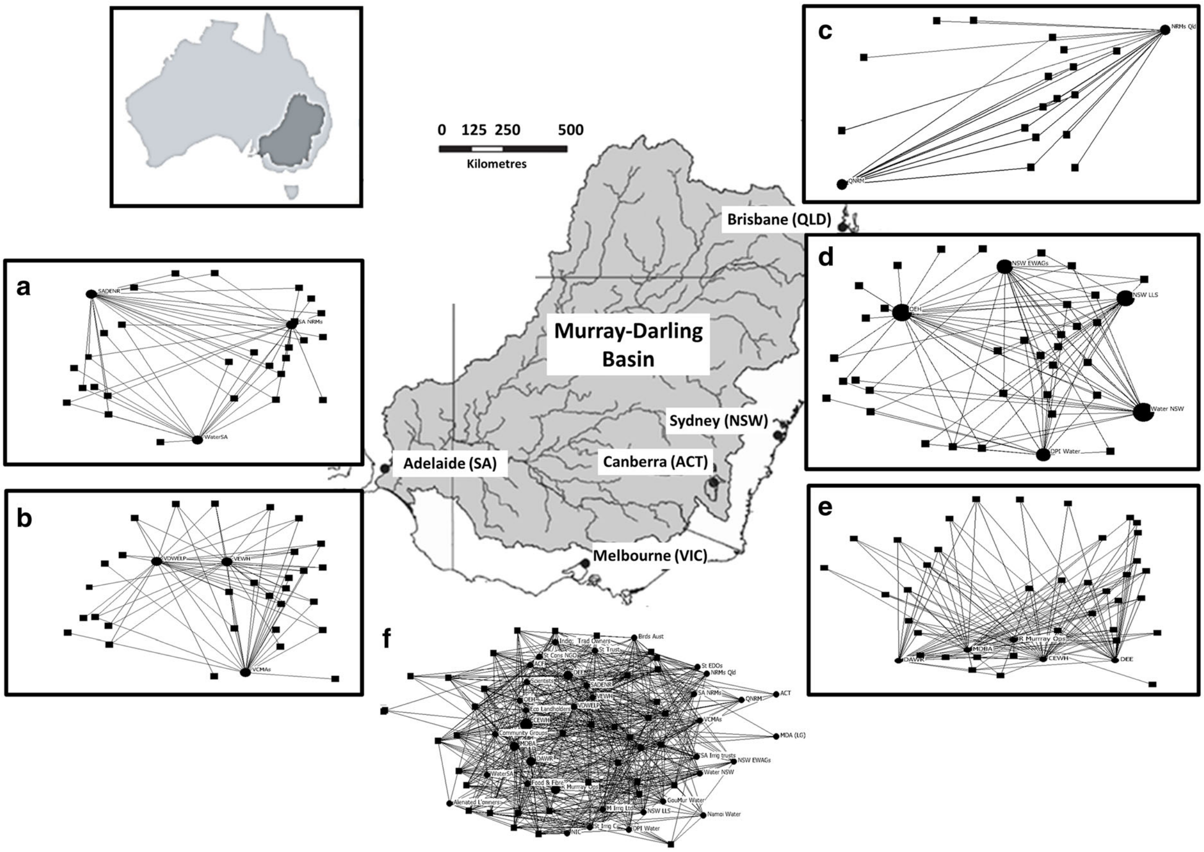

FIGURE 1 Networks of information flow between governmental and non-governmental institutions for environmental flow management. Networks are shown for (a) the state of South Australia (SA), (b) the state of Victoria (VIC), (c) the state of Queensland (QLD), (d) the state of New South Wales (NSW), (e) the federal government, and (f) a combined national network (all states plus the federal government). Capital cities of each state are shown. Network figures prepared in Ucinet©

and Dee et al. (2016) have advanced this somewhat, through identifying the small number of effective cases where SES has been applied in management settings. Dee et al. (2016) identify a continuum of approaches to applying SES methods to natural resource management. At one extreme, simple conceptualizations of connections may be useful to communicate complexity and to indicate broad scale responsibilities. Quantitative description of networks can be used to generate measures of vulnerability to the loss of nodes or the criticality of particular nodes (institutions/individuals/species) to the functioning of the remainder of the network. At the most sophisticated extreme, it is becoming tractable to create networks of models that can be used in dynamic optimization (Dee et al., 2016). There is considerable opportunity to learn from marine fisheries management in adopting systems approaches to large river basin development (see Pollnac et al., 2010, for a review).

We use two case studies from the MDB to illustrate the potential for SES approaches. In the first case study, we developed networks of the information flow between major governmental and non-governmental institutions involved in environmental flow management, at the state and federal levels. Connections between institutions were determined based on the expert knowledge of the authors. The resulting networks (Figure 1) clearly illustrate a number of factors. First, different state jurisdictions have widely varying institutional arrangements around environmental water management. Second, the resulting networks vary considerably in structure and complexity. Third, the combined network at a basin scale (Figure 1f) is extremely complex, with a very large number of nodes in the network. When considered conceptually, the networks are a highly effective way of communicating the complexities and interdependencies of institutional arrangements around water. There is clearly abundant opportunity to analyse these networks to identify which nodes are critical to overall performance in delivering water. The variability between states also allows comparisons between states in terms of efficiency of decision making and how this may relate to network structure. An overall assessment of the networks in terms of knowledge transfer suggests that there is relatively small opportunity for knowledge flow between states and that which is possible is moderated by a very small number of federal institutions. This is suggestive of a potential barrier to effective adaptive management (Rubenstein-Montano et al., 2001).

The second case study shows three existing networks from the MDB (Figure 2). The socio-political network (see above) describes movement of information between institutions. The infrastructure

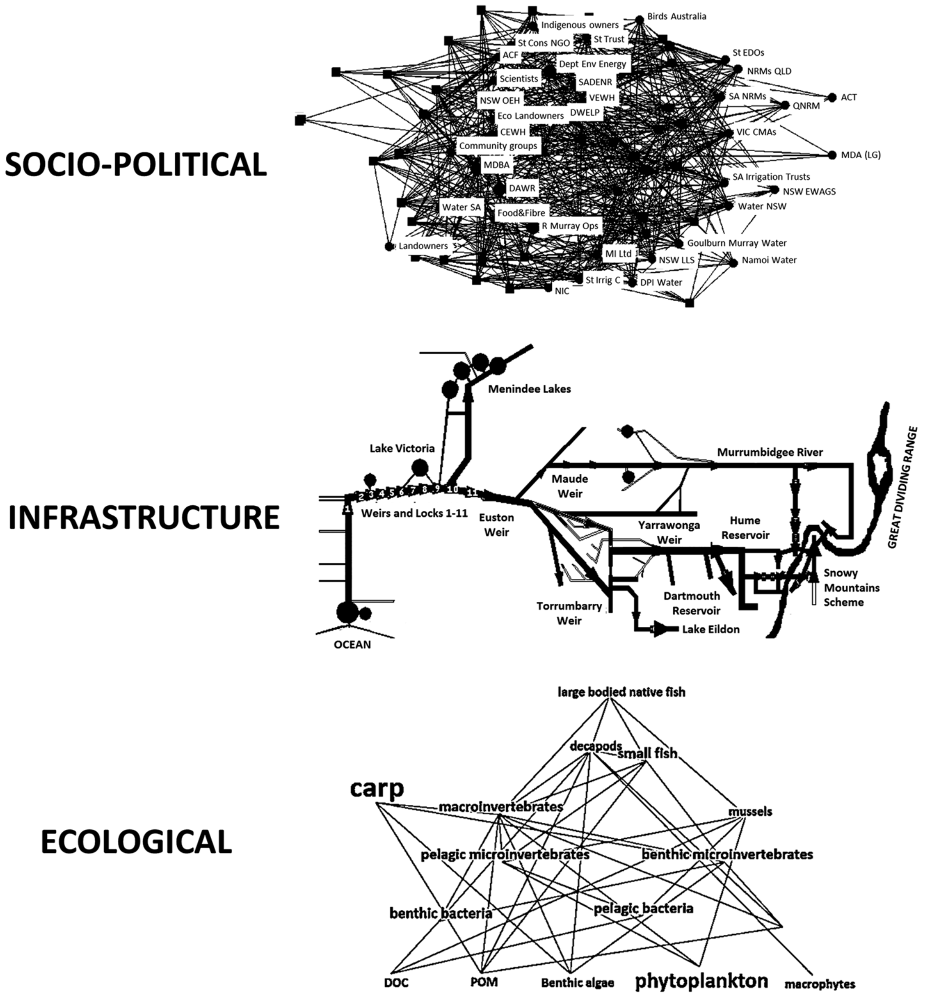

FIGURE 2 Examples of existing networks for the Murray–Darling Basin: socio-political, illustrating flows of information between institutions (see Figure 1f), infrastructure and illustrating major diversions and impoundments on the Murray River (www.murraydarlingbasinhiphop.wikispaces.com), and ecological, showing movements of energy through the food web of the main channel (Bond et al., unpublished)

network shows a part of the physical infrastructure around water delivery and flow management in the Murray River. The ecological network (Bond, unpublished) describes energy flow through major compartments in the food web of the main channel. There are substantive challenges in describing any of these networks adequately, and these have most recently been addressed in developing frameworks for generating food web understanding of the effects of environmental flows (Robson et al., 2017; Rolls et al., 2017). The challenges in integrating across these networks are clear. Although water is a driver of all three networks in some regard, the network structures are very different and share very few nodes. Further, the "currency" of the connections between nodes is very different. Understanding the relationships between these networks and how they influence each is a key challenge for next generation management of the MDB (Kandasamy et al., 2014).

4 | CONCLUSIONS

Many reviews of outcomes of water reform in the MDB have assessed success either through a single disciplinary lens (ecological, e.g., Kingsford et al., 2017, or economic outcomes, e.g., Wittwer & Dixon, 2013), using simplified metrics (Grafton, 2017) or providing critique without providing clear alternative approaches (e.g., Capon & Capon, 2017). While useful academic endeavours, these reviews have failed to recognize the inherent nature of outcomes in complex SES systems. First, knowledge is incomplete at the start of any reform process, and solutions developed at the beginning will often be imperfect in the light of later understanding. This requires reform to be adaptive in nature, but this is challenging in the constraints of classical policy thinking. Second, reform does not occur in a vacuum but needs to integrate across multiple existing systems in governance and knowledge management. Third, assessing reform success using any single outcome or metric will be compromised by the need to manage for multiple outcomes across complex systems.

There are clear opportunities for taking a SES approach to management of the MDB.

1. The initial emphasis in the MDB was on flow as a "master driver" of ecological improvement in the Basin. Although this was a key to achieving political buy-in around a key management issue, it led to a failure to fully assess and acknowledge potential impacts of other drivers, such as climate change and broader scale social and economic trends. In the MDB, emphasis on a few intervention points in management terms (provision of environmental water and physical infrastructure to manage flows) has come at the cost of a broader set of management options, which include other "complementary works" such as pest control, grazing management, and riparian restoration. Managing in concert using these other tools would likely allow greater ecological returns from investments in environmental water.
2. The failure to recognize the systems nature of decision making and the need for information sharing in the MDB has led to a fragmentation of effort and a failure to take advantage of local adaptive management learnings across the Basin.
3. The lack of a clear narrative and conceptualization of the complex nature of the system being managed has led to poor public understanding of why decisions are being made and where responsibility lies at a whole-of-basin scale.

The scale of water reform within the MDB over the last decade has been considerable and has had far reaching social, economic, and environmental impacts. The approaches taken were pragmatic in utilizing pre-existing institutional arrangements and relatively simple metrics for outcomes. Looking forward however, there is a need to become more sophisticated in ensuring that water management is carried out in a way that truly balances the system-wide needs of people and the environment.

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ORCID

R.M. Thompson http://orcid.org/0000-0002-5287-2455

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