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Principles for scientists working at the river science-policy interface

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Abstract

In the face of mounting environmental and political challenges in river management, accurate and timely scientific information is required to inform policy development and guide effective management of waterways. The Murray–Darling Basin is Australia's largest river system by area and is the subject of a heavily contested series of water reforms relying comprehensively on river science. River scientists have specialised knowledge that is an important input into evidence-based decision-making for the management of the Murray–Darling Basin, but despite extensive literature on

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the interface between science and policy, there is little guidance on achieving policy relevance for practicing scientists. Here, we provide a set of important discussion points for water scientists to consider when engaging with policy-makers and environmental water managers. We place our considerations in the context of a broader literature discussing the role of natural-resource scientists engaging with policy and management. We then discuss the different roles for river scientists when engaging in this space, and the advantages and pitfalls of each. We illustrate the breadth of modes of engagement at the science-policy-management interface using the Murray–Darling Basin as an example. We emphasise the need for effective governance arrangements and data practices to protect scientists from accusations of operating as advocates when working to inform management and policy.

KEYWORDS

administrative capture, environmental flows, river management, science integrity, science-informed policy, science-policy interface

1 | INTRODUCTION

As both environmental and political challenges facing global ecological systems intensify (e.g., Bradshaw et al., 2021), accurate and up-to-date scientific information is needed to enhance public policy and management. Such information has proven particularly important for river management where issues of water allocations between consumptive uses and environmental outcomes have often been antagonistic (e.g., Parsons, Thoms, Flotemersch, & Reid, 2016; Sommerwerk et al., 2010). Timely and impactful responses to natural-resource challenges, including water management, demand effective relationships between science and governance (van Kerkhoff & Lebel, 2015). While scientific advice to governments has never been in greater demand, there has also never been a time where it has been more contested and questioned (Colloff, Grafton, & Williams, 2021; Fenster et al., 2021; Gluckman & Wilsdon, 2016; Stewardson et al., 2021). Policy-makers increasingly require scientific evidence to underpin policies and decision-making, even as the nature of that evidence becomes more sophisticated and complex (Iyengar & Massey, 2019). Ideally, scientists with specialist knowledge are well placed to deliver their findings to inform policy or management (Lewandowsky, Risbey, & Oreskes, 2015), but the ideal is often thwarted. High-profile examples of the difficulties in achieving shared understanding among science, policy, and management in the environmental sciences include the bovine spongiform encephalopathy outbreak in the United Kingdom (Phillips, 2000), the COVID-19 pandemic (Fenster et al., 2021), and the allocation of water between consumptive and nonconsumptive users (Horne, 2017). In Australia, heavily contested water reform in the Murray–Darling Basin exemplifies the complex issues for river scientists working at the science-policy interface.

In this paper, we reflect as scientists who have engaged directly with government to inform water policy and management, specifically in the Murray–Darling Basin, Australia. We summarise the challenges and benefits of science-policy engagement and identify some of the key issue that arise at this interface. Seeking to provoke important discussion on these issues, we identify a set of principles that are informative for river scientists working at the science-policy interface.

2 | SCIENCE ENGAGEMENT WITH POLICY AND MANAGEMENT IN THE MURRAY–DARLING BASIN

The Murray–Darling Basin is Australia's largest river basin, with a catchment of greater than 1 million km^2. The basin's hydrology is highly variable and unpredictable exacerbated by the fact that Australia has the lowest continental run-off in the world (excluding Antarctica), with an average basin-wide runoff of 31,600 gigalitres (GL) year^{-1}, ranging from 6,700 GL year^{-1} in the driest years to 117,900 GL year^{1} in the wettest. This river system has been extensively developed since the late 19th Century for shipping passage, flood management, and irrigation (see Hart, 2016, and Hart, Bond, Byron, Pollino, & Stewardson, 2021 for reviews). From the 1930s to the 1990s, water diversion and use approximately tripled to almost 11,500 GL year^{-1}, and the average annual flow to the sea at the mouth of the river Murray dropped to 25% of natural flow, causing the mouth to close to the sea in some years (Bourman & Barnett, 1995). Because of these diversions, many environmental problems have emerged in the Murray–Darling Basin, including increased salinity and nutrients, lake acidification in the lower part of the system, declining condition of floodplain forests, and reduced populations of some native fish, invertebrates, waterbirds, and amphibians (e.g., Bond et al., 2020; Davies, Harris, Hillman, & Walker, 2010; Mac Nally, Cunningham, Baker, Horner, & Thomson, 2011; Mathwin et al., 2021; Walker & Thoms, 1993).

Several recent reviews have described the biophysical, social, and economic context that led to water reform in the Murray–Darling Basin (e.g., Doolan & Hart, 2017; Skinner & Langford, 2013). Here, we focus mainly on the biophysical issues, with which the authors are most familiar. In 1995, a regulatory cap stopped additional growth in water entitlements and allowed a water market to develop where participants could buy, sell, and transfer tradeable water rights. In 2007, after an extensive period of drought, the Australian Government launched a programme of legislative reform (Water Act, 2007; Skinner & Langford, 2013), changed institutional and governance arrangements (establishment of the Murray–Darling Basin Authority and the Commonwealth Environmental Water Holder), and new management arrangements with the States and Territories (Doolan & Hart, 2017).

The Murray–Darling Basin Plan (2012; MDBA, 2016) was introduced to determine and implement a "sustainable diversion limit" for the Basin's catchments to balance the needs of the environment and irrigated agriculture. A central element to the Basin Plan was the recovery of an average of 2,750 GL year^{-1} for the environment from consumptive use ($\sim$ 20% reduction), achieved through an investment of AU$9 billion to modernise irrigation infrastructure and an AU$3 billion water-allocation purchase programme. The development of the Basin Plan was controversial and characterised by community concern and polarisation among stakeholders because, like many analogous policy decisions, it produced both winners and losers under the new regime (Horne, 2014).

A particular strength of the Murray–Darling Basin-reform process was engagement with scientists, including ecologists, geomorphologists, hydrologists, and environmental modellers (Overton, Colloff, Doody, Henderson, & Cuddy, 2009; Swirepik et al., 2016; Welsh et al., 2013). Funding provided by the Australian Government developed tools and frameworks for managing river flows (both environmental and consumptive) at a whole-of-basin scale. However, there was variable investment in social, economic, indigenous, and ecological research, as is typical for many large river basins worldwide (Nilsson, Reidy, Dynesius, & Revenga, 2005; Richter, Davis, Apse, & Konrad, 2012). Assessing environmental water needs in the Murray–Darling Basin was predicated on targeting flows to generate ecological responses at a few sites and a few ecological assets considered representative of the entire system (Swirepik et al., 2016).

In parallel with the process of water reform, there was a shift in the way science was engaged. Cullen et al. (2001) characterises science-policy engagement into three models: purchaser-provider, collaborative, and co-generative (Table 1). This typology shares many features with that of van Enst et al. (2014) who defines three types of engagement based on the role of the scientist (Table 1). In the middle of the 20th Century, science provision largely relied on government-employed scientists (e.g., in State science agencies and the Commonwealth Scientific and Industrial Research Organisation) under a collaborative/Type IIa model (Table 1). Independent scientists outside government were engaged mainly as providers of independent research or advice via a purchaser-provider/Type I model. To access non-governmental science capacity more effectively in the 1980s/1990s, government-supported research consortia focussed on management and policy issues (Tomlinson & Davis, 2010). These included partnerships between universities and government science

TABLE 1 Typology for models of engagement at the science-policy interface (adapted from [a]Cullen et al. (2001) and [b]van Enst, Driessen, and Runhaar (2014))

Model of engagement		Description
Purchaser provider[a]	Type I[b]	Scientists who are contributing to science generation for the purpose of informing policy or management who are reimbursed either individually or through their organisation for their services. The science programme and objectives are developed by the procurer.
Collaborative[a]	Type IIa[b]	Individual scientists or experts whose goal is to facilitate the creation, sharing, and use of knowledge acting as "honest brokers" (Pielke, 2007). Their strategy involves functioning as a bridge between science and policy through mediation in the development of research questions, explaining the visions, goals or ideas of both sides to each other.
Participatory knowledge development[b]	Type IIb[b]	Scientists participating as stakeholders through participatory knowledge development via processes such as stakeholder engagement. These processes aim at joint knowledge co-production but the scientist is a participant not the initiator and may or may not be remunerated.
Co-generative[a]	Type IIc[b]	Scientists work with policy or management to identify knowledge needs and generate or collate the information. The aim is joint knowledge co-production with the scientist as an equal partner with the procurer. The scientist is usually remunerated.
Boundary organisation[b]	Type III[b]	Scientists interacting via formal institutions, often having a legal basis, which serve as an institutional bridge between the worlds of science and policy, for example, IPCC (intergovernmental panel on climate change) and non-government organisations (NGOs).

agencies (e.g., Murray–Darling Freshwater Research Centre) and university consortia funded through competitive government-funding processes (e.g., Cooperative Research Centre programme). These were at "arm's length" from policy, and agencies were created to facilitate knowledge transfer into policy consistent with the Type III approach (Table 1) (Land and Water Australia, National Water Commission) (Alexandra, 2020).

In the early 21st Century, there was a deliberate attempt to increase the focus of research on management and policy issues through changes to the rules for the Cooperative Research Centre programme and funding of government science-led consortia (e.g., Commonwealth Scientific and Industrial Research Organisation Flagship Cluster for Environmental Flows). Closer links developed between science providers and policy agencies (Noble, Charles, & Keast, 2018), with scientists engaged to identify knowledge needs and servicing those needs, consistent with a co-generative/Type IIc model (Cullen et al., 2001) with participatory knowledge development/Type IIb (van Enst et al., 2014) approaches to engage more broadly with the scientific community (Table 1). This trend was accompanied by the closure of Federal agencies Land and Water Australia (2009), the National Water Commission (2014), and public-good Cooperative Research Centres (2015) (Alexandra, 2020). Increasingly in the late 2010s, research consortia were larger, more trans-disciplinary, and funded directly by industry and government without intermediaries, consistent with international trends (Brouwer, Büscher, & Hessels, 2018).

Recognising the uncertainty underlying the available evidence, the revised Water Act and Basin Plan sought explicitly to include principles of adaptive management. Adaptive management (sensu Walters, 1986) provides the opportunity to "learn by doing", allowing refinement of management approaches through time as experience and evidence improves (Parsons, Thoms, & Flotemersch, 2017). However, there are challenges in implementing adaptive management in large, complex ecosystems (e.g., Westgate, Likens, & Lindenmayer, 2013). Developing robust monitoring and assessment programmes that formalise and share results from management interventions are essential (Webb, Watts, Allan, & Warner, 2017). In the Murray–Darling Basin, three programmes were established to monitor the effectiveness of environmental flows for achieving environmental outcomes. The AU$32 million Commonwealth Environmental Water Office's Long Term Intervention Monitoring project was initially established over five years (2014–2019) to deliver monitoring and evaluation outcomes of environmental water to support adaptive management, good governance, and reporting. During that time, an additional AU$10 million was invested via the Environmental Water Knowledge and Research programme to do targeted research and improve the science available to support environmental water management in the Murray–Darling Basin. These two programmes were independently reviewed upon completion (Butcher et al., 2021) and were extended into the Environmental Flows Monitoring Evaluation and Research (Flow-MER) programme to create an integrated, Basin-scale programme.

The scale of these science and monitoring programmes, and the wide range of disciplines required, meant that many Australian water scientists have been engaged with one or more of the Murray–Darling Basin programmes (collectively, there have been greater than 30 research consortia and more than 200 researchers involved). The model of the science-policy interface employed is that of co-generative and participatory knowledge development (Table 1), with joint fact-finding and knowledge co-production among scientists, policy, management, and other stakeholders (van Enst et al., 2014). This model is considered most appropriate for environmental management situations where there are many stakeholders working at broad scales and across jurisdictions (Pütz & Brassel, 2021). The approach generates a large, cross-disciplinary consortium that seeks to achieve common understanding and knowledge using participatory approaches to test alternative scenarios. The continual exchange of ideas and knowledge produces a common understanding of policy and management problems, allowing the scientific data to be more closely focussed on addressing the knowledge needs (Briggs, 2006; van Buuren & Edelenbos, 2004).

3 | LESSONS FROM THE MURRAY–DARLING BASIN FOR RIVER SCIENTISTS AT THE SCIENCE-POLICY INTERFACE

3.1 | Models for engagement at the science-policy interface

Sarkki et al. (2015; p506) characterised science-policy interfaces as the "… social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision-making and/or research". Our experience as working scientists in the Murray–Darling Basin has identified a series of fundamental issues at the science-policy interface that should be considered by river scientists engaging with river management and policy. Increasingly, these issues have been highlighted by public critiques of scientists' roles in water policy and management (e.g., Colloff et al., 2021; Stewardson et al., 2021). For scientists and policy-makers, effective science-policy interfaces are often dogged by a lack of a reciprocal understanding of each other's paradigms and imperatives (e.g., Choi et al., 2005; Cullen, 2006; Fenster et al., 2021; Parsons et al., 2017; Sarkki et al., 2015). Differences in operating environments across the interface are reflected through timeliness, cultural differences, and access to and need for diverse information types (Lacey, Howden, Cvitanovic, & Colvin, 2018; Parsons et al., 2017). The process of knowledge-exchange is often limited by poor matching between knowledge needs and the nature of knowledge provision, and is further exacerbated by the increase in large, complex, and multidisciplinary projects. These challenges, combined with a growing recognition of the value of the knowledge-exchange process, have increased the focus on different types of knowledge-exchange processes and the means of evaluating their effectiveness. Examples include the "credibility, relevance and legitimacy" framework (Cash et al., 2003), which was later extended to include "iterativity" by Sarkki et al. (2015).

Engaging scientists in co-generative or participatory knowledge development (sensu Cullen et al., 2001; van Enst et al., 2014; Table 1) is increasingly common and is today considered best practice (Lacey et al., 2018). Policy is often reactive and rapid, outstripping the availability of suitable scientific information (Briggs, 2006). The pace of current policy cycles means that scientists are often required to provide expert *advice* directly, rather than *evidence* emerging from policy reviews of the peer-reviewed literature (Sarkki et al., 2015). Policy-makers and managers frequently make integrated, large-scale decisions that require data and knowledge syntheses from many disciplines, challenging scientists to work more collaboratively and in larger multidisciplinary teams, and often to adopt the role of integrator across disciplines and scales. These new roles can compel individual scientists to engage in science-policy interaction in ways that make them uncomfortable, such as providing advice with incomplete data or based on uncertain trends only.

3.2 | Understanding the roles of river scientists at the science-policy interface

Pielke (2007) defined a set of roles for scientists to engage with policy (Table 2) that are differentiated mainly by how much the scientists are engaged with and tailor their research to policy or management needs. These roles are different from the models of engagement (Table 1), which emphasise the governance arrangements around the engagement, rather than the motivations and behaviours of the individual scientist. Pielke's (2007) classification is a simplification because it creates labels suggesting that scientists occupy a single, well-defined, and constant role on an issue, which we contend is rarely the case—scientists often operate in different 'roles' depending on need. This classification system also casts policy-makers and managers as passive partners in the interaction, when the interface with scientists is instead generally an active conversation about knowledge needs, research limitations, and interpretations. The concept of "science-informed policy" tends to focus on the supply of appropriate data, with an assumption that good science and careful analysis will be received and acted upon (Dicks et al., 2014). The reality is much more complex (Head, 2016; van Enst et al., 2014). However, Pielke's (2007) roles are useful abstractions to illustrate points along a continuum of science-management-policy interactions.

The *pure scientist* (Pielke, 2007) generates scientific content without any specific policy use in mind, and while they might engage with policy by providing knowledge and testing hypotheses, they do not take a direct interest in modifying the communication style of the output or in how the science is applied in policy. As such, scientists in these roles have little risk of being accused of advocating any position (Table 2). *Science arbiters* provide a focussed, content-based response to policy questions without indicating a preferred policy outcome. While science arbiters communicate specifically to meet policy needs, they do not take responsibility for the policy interpretation of the science. Somewhat intermediate between these two is the idea of "use-inspired basic research" that allows wide-ranging generation of scientific content within the broad bounds of a set of intended policy outcomes.

Other roles for scientists can be more focussed on policy outcomes. Pielke (2007) defined the *issue advocate* as a content expert who communicates to support a particular policy outcome, and advocates for a particular policy position. While Pielke (2007) considered this a valid role, he warned against "stealth issue advocates", who present themselves as "science arbiters", but have an undeclared bias for a particular policy outcome. Pielke (2007) also warned of the risk that scientists become perceived as "just another interest group" whose agenda is political rather than genuinely seeking to inform a good policy outcome based on scientific evidence. Adopting an advocacy position can present an ethical risk of potential overemphasis or over-interpretation of data. It can also polarise scientific debate or be used deliberately to obfuscate the consensus scientific position (Mooney, 2007). Gluckman (2014) stated that trust can be maintained only if the science adviser were to act as a broker of knowledge, rather than an advocate. However, we contend that scientists can be advocates, providing they make clear that their values have played a part in their advice and that their advice does not run counter to the scientific evidence (Grundmann, 2013; Likens, 1992).

The final role that Pielke (2007) defined is the *honest broker*—a scientist who provides a comprehensive overview of all content with

TABLE 2 Potential roles for scientists in engaging with policy. Roles marked with a[a] are from Pielke (2007), others are from this article. For more details see text

Role	Level of engagement with policy-makers	Ethical risk	Responsibility for communicating research in policy-relevant way	Responsibility for valid application of the research in policy
Pure scientist[a]	Low	Low	None	None
Science arbiter[a]	Moderate	Low	Moderate	Low
Issue advocate[a]	Moderate	High	High	High
Honest broker[a]	High	Moderate	High	Moderate
Provocateur	Moderate	Moderate	Moderate	Moderate
Disruptor	Low	High	Moderate	Low

an interpretation of policy options, but without clearly indicating a preferred option. Pielke (2007) considered that the honest broker has two defining qualities: they consider multiple policy options, and they seek to clarify the evidence associated with all options. Knowledge brokerage is a much-used path to link the policy and the science communities, and knowledge brokers can act at the interface between researchers or experts and decision-makers to present evidence in a way that informs policy options but does not determine policy development (Gluckman, Bardsley, & Kaiser, 2021). The importance of *trusted advisers* has been emphasised in several studies of policy-makers (Cullen, 2006; Sarkki et al., 2015). However, while honest broker[s] of policy alternatives are needed, they are rare in practice. It is difficult and perhaps impossible for a researcher to be completely dispassionate or non-opinionated when assessing policy options because all individuals are subject to both conscious and unconscious biases arising from their social, cultural, and intellectual background. Scientists are influenced by politics in terms of what science they choose to do and to what policy options they gravitate towards (e.g., Jasanoff, 1996). From the policy perspective, the genuine assessment of alternate policy options is often achieved by diverse working groups and in some cases by public debate (Pielke, 2007). Policy-makers are, therefore, challenged to determine the quality of advice from any one individual, and it is difficult for scientists to ensure that they remain within the realms of technical advice and do not stray into advocacy unsupported by evidence.

While Pielke (2007) focussed on generally positive or neutral modes of engagement with policy, we also characterise two other types of science-policy engagement. These are the *provocateur* and the *disruptor* (Table 2). Provocateurs have a good understanding of the policy context but challenge the *status quo* because they believe that the debate itself produces better policy outcomes. Provided there is full understanding of the policy arena, provocateurs can provide a valuable safeguard against groupthink within the science-policy relationship (Janis, 1973) and can be used to provide external reviews of funded science. In contrast, the disruptor believes that disruption of policy from outside of established processes is important as it leads to a more diverse, and potentially innovative, set of policy options being considered. Disrupters can have genuine scientific concerns over the basis of a policy, and therefore, attempt to disrupt it. Alternatively, this perspective can come from an ideological opposition to established policy or governance; with such ideological-based disruptors having a poor understanding of how policy is operationalised or might have an inadequate understanding of the scientific evidence (Rogers, 2006). Cullen (2006) describes in some detail the way in which scientists can 'disrupt' the constructive science-policy interface with what he refers to as junk science and denigration strategies.

The roles of scientists are diverse, placing constraints on how they engage with policy and management. Scientists within government agencies can be constrained in the degree to which they can comment publicly on policy and management outcomes. Driscoll et al. (2021) recently found that >30% of scientists employed within government and industry had experienced undue interference by employers in communicating science. Scientists who work for organisations outside of government, but are directly contracted by government, can also be constrained by the nature of the contracted relationship and clauses therein around public comment and public release of data. However, Driscoll et al. (2021) suggested that fewer (5%) university scientists had experienced interference in publication. Nonetheless, interference does still occur as evidenced by a recent case where a politically sensitive paper discussing funding for conservation (Wintle et al., 2019) was allegedly subject to an attempt to supress publication (Cox, 2021). Scientists who are outside of contracted relationships can be relatively unconstrained in the role they adopt. All these roles are bound by scientific integrity and scientists should not be making commentary that runs counter to scientific evidence. Deliberately misrepresenting scientific evidence can erode trust for both individuals, institutions, and science-policy/management relationships (Kretser et al., 2019).

The nature of interactions among scientists, managers, and policy-makers within the Murray–Darling Basin is diverse. Many researchers work with water managers in planning, delivering, and monitoring the effects of individual flow events, and provide management recommendations to inform future flow actions; however, they usually remain distant from policy development. Scientists in this role function to some extent as pure scientists or science arbiters (Table 1) collecting data and reporting outcomes to support adaptive management of future flow events (Allan & Watts, 2017; Watts et al., 2020). Because of the uncertainty and the need for timely advice, these scientists also provide advice based on previous experience, and therefore, can occupy the roles of trusted adviser and knowledge broker in a management context. These real-world interactions between scientists and managers are essentially policy- or management-driven (i.e., focussed on delivering objectives established in policy), but they are policy-blind with respect to the scientific outcomes—the data either achieve the policy-mandated objective or they do not. There are several examples of technical reports with clear statements about which of the policy-derived flow objectives has been met or not (e.g., environment.gov.au/water/cewo/monitoring). The scientists are also contractually obliged to make the data publicly available, enabling future interrogation of the data from any party.

Finally, there is explicit reporting against the policy objectives. Here, a group of scientists work with policy-makers to assess whether the policy objectives are being met (e.g., the objectives of the Basin Plan for the Murray–Darling Basin). This process does not require scientists to advise on policy development or reporting; it addresses the questions arising from policy-makers through analysis and reporting of the scientific data and analysis. These processes are robust and can involve scientists assuming provocateur or disruptor roles to ensure that the scientific narrative is robust, has integrity, and that the best scientific models are supported. This process is assisted further by independent external review, and ultimately via exposure through public release of documents, peer review of manuscripts, scientific publications, and evaluation by scientists from outside the research teams.

We propose that the specific role a scientist chooses to take when engaging with policy and management is immaterial, but whatever the role it must be an active decision, be made clear to policy partners, be constantly subject to critical self-reflection, and avoid moral compromise on being able to provide reliable data and interpretation. Science-trained advocates are valuable components of policy debate, but such people are often obliged to extend beyond the available scientific evidence. Pielke (2007) contends that scientists must actively choose which of these roles they are seeking to fill and represent themselves genuinely in providing advice. Because trust forms such an essential part of relationships between policy-makers and scientists, it is difficult to transition seamlessly from one role to another. The perceived value of scientific advice can be eroded when the proponent is revealed as an undeclared advocate or has been publicly established as the critic of a policy position (Figure 1). In such cases, it can be difficult to re-establish trust with policy-makers (Briggs, 2006). However, trust is contextual, bounded, subjective, and dynamic (Lacey, Howden, Cvitanovic, & Colvin, 2018), and it also brings a personal element to scientific integrity.

3.3 | Scientific independence

Public debates on issues such as climate change, vaccines, and water management often suffer from narratives seeking to devalue perspectives of those scientists who are actively engaged with and funded by government agencies, within a broader social narrative challenging scientific credibility (Fenster et al., 2021). Concerns over loss of scientific integrity because of funding relationships are not a new phenomenon (e.g., Barr, 2007)—infamous examples include conflicts of interest and scientific misconduct revealed in research funded by the tobacco and pharmaceutical industries (e.g., Yach & Bialous, 2001; Muggli, Hurt, & Blanke, 2003; Grüning, Gilmore, & McKee, 2006;). Many responses have ensued to protect scientific independence, including individual training, increased institutional oversight, a focus on independent external reviews (e.g., Drenth, 2010; Farrell, 2016; Rowe et al., 2009), and full disclosure of all funding sources (Carroll et al., 2017).

Scientists, funders, and scientific institutions are acutely aware of the importance of scientific integrity (e.g., Carroll et al., 2017; Kretser et al., 2019; Merchant & Asch, 2018; NASEM, 2017). Consequently, structures and processes have been established to ensure scientific independence is maintained (Kretser et al., 2019). Fundamental to these processes are the detailed contractual arrangements between the funder and the research institution. For example, it is common for contracts to require that scientists submit papers to the funder for review, but uncommon for the funder to have the right to prevent publication (commercial-publication in-confidence information notwithstanding). In addition, most scientific journals today mandate that data, computer code for analysis, and documents describing more fully the methods, analyses, and results are made freely available to promote transparency and repeatability (e.g., Cox, 2021; Driscoll

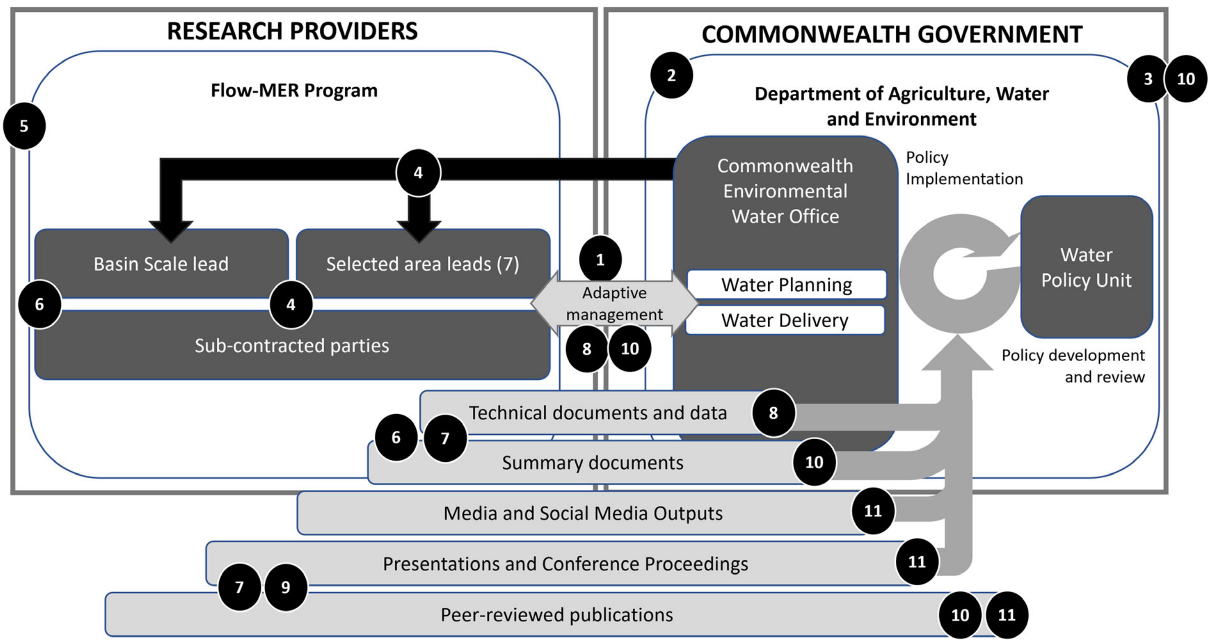

FIGURE 1 Review processes within the structure of the Flow-Monitoring Evaluation and Research project funded by the Commonwealth Environmental Water Office. Dark grey boxes indicate agencies and institutions, with black arrows indicating contractual arrangement and outputs. Mid-grey arrows indicate information flows into policy development, implementation, and review. Numbers in black circles indicate the nature of reviews; 1. Regular science-management interactions enabling adaptive management. 2. Commonwealth oversight of procurement and contracting. 3. Political oversight of government spending (Senate Estimates Committee). 4. Contractual terms regarding authorship, integrity, and intellectual property. 5. Institutional oversight of scientific integrity. 6. Independent external scientific review. 7. Within-project review across teams. 8. Interactions/review with outside parties, including state agencies. 9. External peer review. 10. Public availability of data for reanalysis and interpretation. 11. Public release of reports and analysis [Color figure can be viewed at wileyonlinelibrary.com]

et al., 2021). Open-source data requirements are now standard in almost all environmental and ecological scientific journals and are increasingly a feature of data used to generate government reports (see example below).

Arrangements around data integrity and management are important for ensuring defensibility of scientific outcomes. To illustrate how protections for scientific independence and integrity can function, we show in Figure 1 the review processes built into the Murray–Darling Basin Flow-Monitoring Evaluation and Research programme funded by the Commonwealth Department of Agriculture, Water and the Environment. These protections are consistent with those recognised as best-practice in this space (Kretser et al., 2019). Within the Department, an operational separation exists between staff tasked with monitoring and those developing policy. It is unusual for scientists engaging in monitoring and evaluation to engage with policy development staff (although there can be value gained from doing so). Interactions between scientists and water managers within the Department occur frequently but inform the process of adaptive management rather than policy issues (Figure 1; Point 1). Because the investment in science is often large, these funds are governed by oversight mechanisms, including public oversight through open political processes such as the Senate Estimates Committee (Figure 1; Point 2,3). Contractual arrangements between funders and providers are also subject to oversight from the provider organisations, which include assessments of risk to independence and scientific integrity (Figure 1; Point 4, 5). These are formalised into contractual statements regarding publication and use of intellectual property. Scientific review is generally done through internal peer review, use of external panels, review by outside agencies, and ultimately, via peer review of scientific outputs in the academic literature (Figure 1; Point 6, 7, 8 and 9). Datasets and research reports are made publicly available, together with metadata that aid accessibility and interpretation of these data (Figure 1; Point 10, 11) (environment.gov.au/water/cewo/monitoring; flow-mer.org.au).

An essential element in ensuring scientific integrity is the process of peer review, where other scientists can independently appraise the strength of evidence underlying specific conclusions, limitations, and any alternative interpretations. However, the relatively slow process from submission to publication in academic journals often conflicts with the more rapid requirements of policy reform (Briggs, 2006; Cullen, 2006; Sarkki et al., 2015). Furthermore, the peer review process often requires a higher assessment rigour than is typically required before research can be considered useful for management or policy. Fortunately, the ability to share data and results before publication has been enabled by a range of web-based tools, including preprint servers. The prompt and open release of publicly funded data (and their interpretation) is an essential part of transparency at the science-policy interface and allows another form of peer review. In academia, the peer-reviewed process is the "gold standard"; however, many policy-makers either do not have direct access to paywalled journals, and/or do not possess the necessary expertise to understand and appraise the material. Policy-makers often consider government reports to be the most accessible and authoritative sources of information because they emphasise consensus views tailored to policy needs (Sarkki et al., 2015). Therefore, drawing on substantively different knowledge sources can create conflict between scientists, policy-embedded researchers, and policy-makers (see Briggs, 2006; Cullen, 2006 for discussion).

There is a perceived trade-off between the independence of scientists and effective deployment of science resources under this model. Several features were designed into both the Long Term Intervention Monitoring, Environmental Water Knowledge and Research, and Flow-Monitoring Evaluation and Research programmes to manage this perception of independence. To attract the highest-quality researchers, funding was allocated on a competitive basis and with oversight from independent national and international peers. Similar scrutiny was used for the planning and outputs of the projects as they progressed. Presentation of research outputs at conferences through the peer-reviewed literature and a final, independent review (Butcher et al., 2021) provided additional rigour to the research and monitoring outcomes. That review in turn was subject to international review. Each funding programme has also been reviewed by independent scientists who are separately funded and not employed by research providers. We stress that allowing perspectives from all scientists, regardless of their role at the policy-science interface, is necessary to ensure robust development, implementation, and review of policy. Scientists outside of funding relationships have an important role in ensuring robust debate over the veracity of data and their interpretation. However, funding relationships in isolation should never negate the rights of scientists who either agree with or dispute policy positions either publicly or privately. Where there is suggestion of political interference in publication, this needs to be investigated rigorously (Cox, 2021). However, care needs to be taken that the commentary of scientists is not being denigrated (Cullen, 2006) simply because it is funded by government agencies.

Working with policy-makers directly does not imply that a scientist cannot be critical of policy or management. However, the fora available for revealing criticism are often highly structured and rarely public. For scientists, uncertainty and robust debate are necessary aspects of scientific endeavour and knowledge advance (Cullen, 2006). But a lack of consensus is difficult to manage in policy, which must forecast the risks of choosing the wrong scientific perspective on which a policy is based. This risk is compounded by a lack of guidance to policy-makers on how to appraise the reliability and robustness of research (Sarkki et al., 2015). Unresolved scientific debate, particularly when it is being played out in public fora, can lead policy-makers to ignore or dilute scientific input, allowing economic and political perspectives to prevail instead (Rayner, 2006; Sarewitz, 2004). Instead, where discussions are structured using consultative processes and internal reviews, evidence-based critiques can be effective in assisting policy formulation. Scientists who are not engaged with policy-makers might also interpret the lack of public critique or debate from policy-engaged scientists as evidence of "administrative capture of science" (Colloff et al., 2021; Grafton & Williams, 2020) However, administrative capture implies that scientists forego their scientific independence and potentially their scientific integrity to support a particular policy without presentation of scientific evidence or adequate consideration of all science supporting policy options.

4 | THE MODERN ROLE OF RIVER SCIENTISTS IN PUBLIC POLICY AND WATER GOVERNANCE

Modern river scientists who engage with policy, management, and industry not only offer technical knowledge that extends beyond most others involved in policy reform, they also often possess a deeper understanding of the relevant societal issues because of their involvement and experience in the sector. In fact, this combination of knowledge and experience can even result in conservative viewpoints, giving a deeper understanding of the limitations of existing evidence. In contrast, scientists observing from outside of these relationships are relatively unconstrained and can freely offer perspectives potentially without supporting evidence. For the most part, modern scientific endeavour has evolved from the "ivory tower" model where researchers critique from the sidelines, now to engage actively in generating solutions. One of the reasons the ivory-tower model has become obsolete is that it is unrealistic for major applied scientific endeavours. Global issues such as climate change, natural-resource management, and vaccine development directly engage scientists with relevent expertise. Thus, these experts will all have some degree of engagement with industry or agencies, including via funding arrangements. Excluding these experts from policy debate risks reducing the public debate to a content-free discussion of policy alternatives.

Scientific output is most effective when it is delivered in a co-generative partnership with industry and/or government (Cullen et al., 2001; Fenster et al., 2021; Sarkki et al., 2015). This partnership allows scientists to have a clear understanding of the problems and the consequent challenges around solutions and their implementation; and also allows policy-makers greater understanding of limitations, transferability, and confidence in the science. The impact of scientists working closely with partners via rigorous, contemporary discussion allows for rapid implementation and development of understanding and trust (Butcher et al., 2021). While this can challenge scientists asked to advise prior to a detailed peer review of their results, or before definitive data are available. The anachronistic view that scientists should do research in complete isolation from funding agencies, and that relevant policy insights will emerge organically, is not supported by evidence (e.g., Holmes & Savgard, 2008; Innvaer, Vist, Trommald, & Oxman, 2002; Sarkki et al., 2015). Modern systems of peer review and governance underpin the monitoring of accountability of those across the science-policy-management interface to minimise or negate potential conflicts of interest or "capture" (Lacey et al., 2018). Likewise, knowledge brokerage is a mechanism that should be further fostered to overcome inherent bias and maintain optimal trust (Lacey et al., 2018).

Scientists engaging with policy should be aware of the different mechanisms for engagement. Scientists often engage as members of public or technical committees, as reviewers of other research, or for technical input to a specific problem—and these roles can be remunerated or not. In some cases, third parties engage scientists to assess science-based policy. Scientists can also provide research applied in a context or to a problem unrelated to the reason the work was originally done. These roles play out across a policy landscape that can include public or private consultation, structured review processes, and politically influenced demands for review or critique. In some circumstance, participation in public debate can serve an important role in driving consideration of science in policy development.

For many scientists, engaging with policy and management can be challenging. Science arises from a paradigm where alternative hypotheses are clearly stated, and data have primacy. This leads to the naïve expectation that there is a linear flow from scientific evidence to policy and management outcomes (Owens, Petts, & Bulkeley, 2006; Sarewitz, 2004). However, in social-ecological systems, management decisions also need to incorporate social, cultural, and economic factors in addition to scientific evidence. Policy formulation is a product of compromise and trade-offs of these factors, and scientific evidence therein is considered only one of many threads that lead to a policy or management outcome (Choi et al., 2005; Cullen, 2006; Sarewitz, 2004). Science can have a greater or lesser role in these outcomes and can be partly determined by the mode of information sharing (cf. Parsons et al., 2017); but policy and management are almost inevitably "evidence-aware" rather than "evidence-based" (Nutley (2003), and scientists should be cautious about expecting their inputs to have primacy.

Several recent reviews and empirical studies have demonstrated the importance of sustained engagement among scientists, policy-makers, and managers through the entire policy cycle (e.g., Holmes & Savgard, 2008; Innvaer et al., 2002; Sarkki et al., 2015). However, a consequence of this closer cooperation is that it challenges perceptions of scientific independence. Such challenges are magnified where the policy or management agency is the predominant source of funding, as is common for natural-resource management, including water management. However, there are well-established techniques for protecting the integrity of the scientific process and the results it generates within funding arrangements, and these are embedded both institutionally and culturally in the arrangements around publicly funded applied science (Carroll et al., 2017; de Kerckhove, Rennie, & Cormier, 2015). An important component of such arrangements is that other scientists can scrutinise the integrity and legitimacy of the expert's providing advice, by having access to all data and reporting on public policy monitoring or objectives.

As scientists who have engaged directly with government to inform water policy and management, we reflect in this paper on the challenges and benefits that this engagement brings. In making these reflections, we note that we are primarily university- and research agency-based, and thus subject to different constraints than consultants from the private sector or scientists directly employed by government agencies. From our collective experience, we have developed a set of principles that are explained in this paper and which we have summarised in Table 3. These principles represent important considerations for scientists who are choosing to engage at the science-policy interface. We also believe that they are informative for policy-makers

TABLE 3 Important principles to consider as river scientists engaging at the science-policy interface

Principle	Explanation
1. Promotion of open and transparent collaborative agreements between science, management, and policy partners.	• Acceptance that policy development is a complex product of compromise, trade-offs, weighing of scientific evidence, political imperatives, timing, individual agendas, and socio-economic factors. • Science can either be consistent with policy objectives or challenge them and has a role in identifying data that is critical or supportive of policy.
2. Establish an agreed set of engagement criteria that governs the collaborative working relationship.	• Open declaration of funding sources, links to organised advocacy groups, and other potential sources of conflicts of interest whether actual or perceived. • Funding agreements must include structures that protect scientific integrity through external peer review, the right to publish, and explicitly recognise processes that deal with differences in the interpretation of data. • Recognising the role of scientists and others outside of funded relationships through informed critique and independent analysis of data, interpretations, and policy.
3. Commit to the publication of data and information in reputable journals.	• Committing to publishing in the peer-reviewed literature. • Data availability in a timely manner to facilitate re-analyses and re-interpretation of data to ensure transparency.
4. Support the inclusion of multiple lines of evidence.	• Being open to all results and opinions from a full range of scientists, including those directly employed by industry or government, consultants, indigenous and cultural knowledge holders, those doing contractual research, and those not engaged in any such way. • Assume scientists behave with integrity, unless that assumption is proved incorrect in the light of how data are collected, analysed, and interpreted.

and managers in order to understand the risks and challenges those scientists face when engaging in this way. These principles point to an important role for institutions in crafting governance and contractual arrangements that are transparent and defensible (Principle 1). These arrangements need to explicitly recognise the nature of the engagement criteria and state the ways in which that will be reflected in the operations of the project (Principle 2). These include commitments to making data publicly accessible and committing to the principle of the right to publish (Principle 3). Finally, we emphasise the importance of a diversity of scientific roles and opinions in ensuring that policy is robustly informed by the best scientific knowledge (Principle 4). In reflecting on our engagement with water policy and management we are emphasising the challenges of being working river scientists at the science-policy interface, in the hope of stimulating discussion among other scientists on the nature of interactions in this fascinating and important space.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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