CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/MF24193

MARINE & FRESHWATER RESEARCH

Murky waters running clearer? Monitoring, reporting and evaluation of the state of the Murray–Darling Basin after more than three decades of policy reform

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Handling Editor:
Max Finlayson

Received: 30 August 2024
Accepted: 25 October 2024
Published: 29 November 2024

Cite this: Colloff MJ *et al.* (2024) Murky waters running clearer? Monitoring, reporting and evaluation of the state of the Murray–Darling Basin after more than three decades of policy reform. *Marine and Freshwater Research* **75**, MF24193. doi:10.1071/MF24193

ABSTRACT

Context. Rigorous monitoring and reporting helps determine effectiveness of water reforms. We assess implementation of the Murray–Darling Basin Plan, intended to ensure that water resources are used sustainably. Many aspects of Basin Plan implementation are poorly monitored and reported, owing to fragmented and inadequate data collection across jurisdictions. **Aims.** To address this issue, we synthesised publicly available data for 27 indicators that provide insights into the State of the Basin since implementation of the Plan in 2012–2013. **Methods.** Indicators, in Indigenous, economic, environmental, social and compliance themes, were chosen to assess effects of policy interventions for water reform within the *Water Act* 2007 (Cth), the underpinning legislation for the Plan. **Key results.** Of the targets for the indicators, seven were met (26%), 10 were variable but showed no overall trend (37%) and 10 were not met (37%). **Conclusions.** Five of seven economic targets, relating to irrigated agriculture and capital value of land, showed improvement, whereas of 20 Indigenous, environmental, social and compliance indicator targets, only two environmental ones were met. **Implications.** We detail practical improvements, including building a more comprehensive, Basin-wide monitoring and reporting framework that could be implemented to aid assessment of progress on implementation of the Basin Plan.

Keywords: adaptive management, ecological character, evaluation and reporting, indicators, irrigated agriculture, monitoring, water policy, water reform, wetlands.

Introduction

Rivers, wetlands and water resources worldwide are vulnerable to growing threats from irrigation diversions, land-use change, pollution and global warming (Vörösmarty *et al.* 2010; Davidson *et al.* 2020) and their management has become increasingly urgent and challenging (Tickner *et al.* 2020). Mitigating these increased stresses on rivers and wetlands requires co-operation among multiple agencies and stakeholders and the design and implementation of reform programs to allocate water justly, sustainably, efficiently and effectively. Such an agenda, currently conducted in many river basins around the world, centres on the reform of governance arrangements based on the various modes of governance available (Pahl-Wostl 2019). Common global themes and challenges in water governance include the need for institutional reform for systems-based implementation that is integrated at trans-national, national, basin and catchment scales, and fairer, more flexible rules for water allocation and compliance and integration of water reform with adaptation to climate change (Bouckaert *et al.* 2022).

Any water-reform program requires structures and processes for monitoring, evaluating, synthesising and learning which policies and management interventions work and which ones do not, as a basis for transparent decision making and governance (Grafton *et al.* 2019). Effective monitoring and evaluation is fundamental to successful strategic adaptive management and organisational learning (Roux *et al.* 2022) and underpins the need for adjustment and re-design of policy instruments as circumstances change. For example, an assessment of the *European Union Biodiversity Strategy for 2020* found that policy instruments for aquatic ecosystems were effective in environmental target setting and reducing pressures but less effective in countering sectoral drivers of change and supporting sustainable development. These deficits require novel policy instruments to incentivise decoupling of economic growth and resource use (Rouillard *et al.* 2018). Monitoring and evaluation of water reform policies has helped to identify opportunities for improved stakeholder participation (Jager *et al.* 2016), identify pathways for improved governance (Bouckaert *et al.* 2022), identify constraints on the re-allocation of water from irrigation to the environment (Bender *et al.* 2023), show successes and failures of integrated water resources management strategies (Dirwai *et al.* 2021) and determine the policy 'dos and do nots' of water reform (Grafton 2019).

Scale-dependence is a major issue in assessing, interpreting and reporting environmental data. Spatial–temporal variation is a function of the scale at which observations on a particular process are made. Because patterns change across scales, high heterogeneity at the fine scale appears homogeneous at a larger scale. This phenomenon can either show or conceal any signal of change in variables, as assessed using monitoring data (Colloff *et al.* 2018). Accordingly, the scale at which environmental monitoring is undertaken needs to match the scale at which predictor variables and ecological responses are likely to occur. Ecological responses to environmental flows (managed releases of water intended to provide environmental benefits to rivers and wetlands) are highly scale-dependent, with major implications for the management of environmental water and the interpretation of environmental monitoring data (Colloff *et al.* 2018).

The Murray–Darling Basin in south-eastern Australia (hereafter 'the Basin') has been the focus of major water policy reforms at least since the 1990s (Connell and Grafton 2011). The Basin includes over 30,000 wetlands covering over 110,000 km^2 (Kingsford *et al.* 2004; Murray–Darling Basin Authority 2010*a*; Department of Agriculture, Water and the Environment 2021*a*) that support a diverse range of flow-dependent plant communities (Keith 2004), over 100 species of waterbirds (Kingsford *et al.* 2014) and 51 species of native freshwater fishes (Lintermans 2023). The Basin produces 40% of the value of irrigated agricultural production in Australia (Australian Bureau of Statistics 2019), provides domestic water supplies for 2.2 million people and its lands and waters cover the country of 46 Indigenous nations (Murray–Darling Basin Authority 2010*b*; Jackson *et al.* 2021).

The Murray–Darling Basin Plan (hereafter, 'the Basin Plan'; Commonwealth of Australia 2012) is one of the most ambitious water-reform programs ever attempted (Connell and Grafton 2011; Wheeler 2014). The main objective of the Basin Plan is to return water to the environment by reducing diversions by irrigators to redress the balance between consumptive use and the environment (Commonwealth of Australia 2012). The main water-recovery programs have been subsidising irrigation infrastructure and buybacks of water entitlements from willing sellers. The latter approach has been considered the most successful, achieving most of the water recovery to date, at least cost and with fewer negative externalities (Wheeler 2024).

The Basin Plan is a legislative instrument of the *Water Act* 2007 (Cth) that sets the legal framework for the water reforms undertaken in partnership between the Commonwealth and the four Basin States and the Australian Capital Territory. The environmental objectives of the *Water Act* involve restoring and protecting flow-dependent ecosystems against climate change and other threats (Commonwealth of Australia 2007, S21(2)(b) and S22.3) and include the setting of an environmentally sustainable level of take (ESLT) and a sustainable diversion limit (SDL), to be implemented through water resource plans for each catchment or region. Flows at 124 hydrological indicator sites across the Basin are assumed to represent the environmental water requirements of all rivers and wetlands (Murray–Darling Basin Authority 2012*a*).

The implementation of the Basin Plan requires rigorous, transparent, accountable systems for monitoring, evaluating and reporting on the effectiveness of policy instruments. The Murray–Darling Basin Authority (MDBA) has developed a monitoring and evaluation program through the 'framework for evaluating the Murray–Darling Basin Plan', first published in 2014, revised in 2019 (Murray–Darling Basin Authority 2019*a*) and again updated in 2022 (Murray–Darling Basin Authority 2022*a*), ahead of an evaluation due in 2025, together with its Monitoring Statement (Murray–Darling Basin Authority 2021*a*).

Over a decade on from when the Basin Plan received parliamentary assent in November 2012, there is still no rigorous, transparent, accountable system for monitoring, evaluating and reporting. Some indicators are monitored but assessment is not integrated within a systems framework. Although it is beyond our scope to provide a detailed critique of the current monitoring and evaluation processes, some of the main issues are outlined in the section on background and context below.

Concerns with the existing arrangements for monitoring, evaluation and reporting create the need for an independent assessment of the effectiveness of the Basin Plan. In this paper, we propose an independent State of the Basin reporting framework. We use a series of indicators, based on publicly available data, to assess outcomes of water reforms and the Basin Plan. We provide a rationale for the use of 27 indicators and assess changes since Basin Plan implementation in 2012.

Background and context of monitoring and reporting on water reforms

The Basin Plan builds on collaboration during the mid-1990s between Commonwealth and Basin State and Territory governments to address over-allocation of water resources, culminating in the National Water Initiative in 2004, which remains the primary policy framework for water reform in Australia (Marshall and Alexandra 2016) and is being updated in a new National Water Agreement. The over-allocation of water for irrigation and the poor ecological condition of rivers and wetlands (Davies *et al.* 2010, 2012) led to a Basin-wide cap on diversions in 1995 (Murray–Darling Basin Commission 1998). Impetus for reform grew during the Millennium Drought (2001–10), one of the longest and most severe droughts in recorded history (van Dijk *et al.* 2013).

Chapter 13 of the Basin Plan describes the legislated program for monitoring and evaluation as, the 'effectiveness of the Basin Plan is to be evaluated against the objectives and outcomes set out in Chapters 5, 8 and 9, and by reference to the matters in Schedule 12' (s13.01(3)), with 5-yearly reporting for the Basin Plan as a whole, the environmental watering plan, achievement of environmental outcomes, water quality and salinity targets, water-trading rules and water-resource planning (first undertaken in 2020). It delineates principles for monitoring and evaluation processes, defines roles of agencies (MDBA, Commonwealth Environmental Water Holder, CEWH, Basin States and Territory governments and agencies) and specifies reporting requirements. Principles 1 and 2 name the MDBA as responsible for leading monitoring and evaluation at the Basin scale, in partnership with other actors.

The MDBA is required to evaluate the effectiveness of the Basin Plan; a situation described as 'marking its own homework' (Productivity Commission 2018, p. 351). This conflict of interest 'compromises the MDBA's ability to be an impartial regulator', whereas its compliance role undermines its ability to work openly with the States and Territory (Productivity Commission 2018, p. 28). To address this issue, the Office of the Inspector-General for Water Compliance was established in 2021, but the evaluation of the Basin Plan is still within the remit of the MDBA. There has been no independent assessment of whether objectives of the Basin Plan and the *Water Act* are being achieved. Prior to the Basin Plan, the Sustainable Rivers Audit (SRA), an environmental monitoring program overseen by an independent panel of ecologists and hydrologists, produced a clear, objective assessment of the ecological condition of the river valleys during and after the Millennium Drought (Davies *et al.* 2010, 2012). These assessments were terminated in 2012, although re-instatement of some version of the SRA is intended to inform the 2026 review of the Basin Plan (Department of Climate Change, Energy, Environment and Water 2023*a*). Halting the SRA caused an 11-year hiatus in environmental monitoring that has not adequately been filled with other monitoring activities.

Responsibilities for monitoring and reporting on the Basin Plan are held by the MDBA, the Commonwealth Environmental Water Office (CEWO), the Commonwealth Department of Climate Change, Energy, the Environment and Water and the State and Territory government agencies responsible for water. The reality is that monitoring and evaluation is mostly contracted out and data are collected and held by catchment management authorities, non-governmental organisations (NGOs), researchers, consultants and government agencies. These agents hold a diverse range of environmental, social and economic data, often site- or catchment-specific, including long-term ecological time series for many wetlands (Colloff *et al.* 2015). These arrangements make the task of compilation of such fragmented data and reporting of it at the appropriate scale (e.g. catchment, Basin or sub-Basin) particularly challenging.

The MDBA receives environmental monitoring data from CEWO, State government agencies and researchers. Data from the CEWO Long-Term Intervention Monitoring (LTIM) program (intended to measure the ecological benefits of Commonwealth environmental water releases), from water years 2013–14 to 2018–19, formed the basis for ecological evaluation and reporting for the Basin Plan (Hale *et al.* 2020), along with its successor, the Flow Monitoring, Evaluation and Research (Flow-MER) program (Commonwealth Environmental Water Office 2021). Data on river flows are collected by State government agencies and collated and made available by them, the MDBA and the Bureau of Meteorology. The Bureau is also responsible for Australian Water Resources Information System and the National Water Account (see http://www.bom.gov.au/water/, accessed 15 August 2024).

Another major constraint is the lack of practical structures and procedures for co-ordination and publication of data. Although the MDBA is responsible for monitoring the effectiveness of the Basin Plan, including collecting information and providing open access to data (Commonwealth of Australia 2012, S13.03), in practice, the collection, curation, analysis and synthesis of environmental monitoring data are not centralised, remain incomplete and much of the data are not available publicly (Chen *et al.* 2021; Ryan *et al.* 2021). Chapter 13 of the Basin Plan is effectively silent about such responsibilities. Shortfalls in environmental monitoring and reporting are compounded by the lack of an integrated framework for reporting social, economic and environmental outcomes, although such a system, the MDBA Outlook program, is being developed (Murray–Darling Basin Authority 2023*a*). The *Water Amendment* (*Restoring Our Rivers*) *Act* 2023 (Cth) requires the Secretary of the Commonwealth Department of Climate Change, Energy, the Environment and Water to provide annual reports on social and economic impacts of water recovery as part of the process of Ministerial decision making about water purchases by the Commonwealth (S85AB), as well as annual reports on how Indigenous values and uses are considered regarding environmental watering (Commonwealth of Australia 2023, S85E,F), but there is nothing in the Act about improved accountability of reporting on environmental data.

The 2020 Basin Plan Evaluation (Murray–Darling Basin Authority 2020*a*) reports on procedural outputs and processes (e.g. progress in setting SDLs, acquisition of environmental water and accreditation of State water-resource plans), but is less clear on progress towards objectives for the environment, society and economy. The bulk of environmental reporting is on hydrology, including observed and modelled expected flows. Grafton *et al.* (2022) found that climate change had resulted in a 20–30% reduction in flows of rivers in the northern Basin. The MDBA acknowledges that climate change has resulted in reduced inflows in the 20 years between 1998–99 and 2018–19, particularly in the southern Basin (Murray–Darling Basin Authority 2020*a*, pp. 20–22). Despite such findings, climate change is not factored into the hydrological models, nor are issues with return flows or losses of water from unlicenced diversions and theft (Wheeler *et al.* 2020). The Wentworth Group (2020) reported substantial deficits between observed and expected flows for water returned to rivers under the Basin Plan (average 20% less than expected) after accounting for climate variability. Environmental water requirements (the frequency, magnitude, duration, and timing of flows required to achieve environmental outcomes) were not met at 65% of river gauge sites assessed (Sheldon *et al.* 2024). These findings underpin the important need for independent assessment of Basin Plan outcomes.

The 2020 Basin Plan Evaluation highlights various ecological benefits from environmental flows (Murray–Darling Basin Authority 2020*a*), but these claims are often anecdotal or contradicted by other reports. For example, in the Evaluation snapshot report: 'Populations of waterbirds [in the southern Basin] have been maintained since implementation of the Basin Plan, despite continued dry conditions' (Murray–Darling Basin Authority 2020*b*, p. 3), yet this assertion is in stark contrast to findings from the Eastern Australian Waterbird Survey (Kingsford *et al.* 2017; Porter *et al.* 2024) and is not supported by any evidence in the main report or the southern Basin evidence report (Murray–Darling Basin Authority 2020*c*). The main report mentions waterbird outcomes only for the Coorong and Lower Lakes, but without supporting evidence. In contrast to the evaluation snapshot report, the MDBA Lower Lakes Coorong and Murray Mouth report card graded waterbird populations between 2015–16 and 2019–20 as 'D', indicating few objectives were met (Murray–Darling Basin Authority 2021*b*).

Socio-economic objectives of the Basin Plan remain vague. They are described as 'wide ranging and work towards optimising social, economic and environmental outcomes' and include a series of aspects of the Basin Plan that are likely to affect socio-economic outcomes, rather than objectives as such' (Murray–Darling Basin Authority 2020*a*, p. 73). Socio-economic reporting in the 2020 Basin Plan Evaluation relied on data from the Australian Bureau of Statistics (ABS), Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), researchers and consultants and drew heavily on the assessment of social and economic conditions in the Basin (Sefton *et al.* 2020). This assessment is not part of an ongoing monitoring program and contains little in the way of quantitative data. The Australia-wide Regional Wellbeing Survey, commenced in 2013, has 6000–8000 respondents from within the Basin annually, but this number is insufficient to produce data for each Basin Local Government Area (Schirmer *et al.* 2021). By supplementing data from this survey with other sources, Schirmer and Mylek (2020) assessed whether Basin communities experienced poorer or better than average socio-economic conditions and any changes over time. Regarding socioeconomic outcomes, the 2020 Basin Plan evaluation report states such an assessment is complex: 'the Basin Plan lacks an appropriate adaptive management framework that would include quantifiable objectives or targets and an associated monitoring program' (Murray–Darling Basin Authority 2020*a*, p. 73). Indeed, Wheeler *et al.* (2024) provided a critical review of all the socio-economic research conducted on water recovery in the Basin, finding that much of the work funded by the MDBA was classified as of low quality. The authors emphasised the need for longitudinal, causal identification and rigorous socio-economic impact analysis.

Murray–Darling Basin Authority (2020*a*) acknowledges:

> a combination of issues – including fragmented results and findings, variability in monitoring methods, and disconnection across State boundaries – have reduced the value of information available to the evaluation … [and] influenced the ability to fully evaluate against baseline conditions and to understand how conditions have changed over time [p. 131].

If key outcomes of the Basin Plan are poorly monitored, evaluated and not transparently and rigorously reported (Wentworth Group 2017) and trends are not analysed, then it remains unclear which objectives are being met and which are not.

The lack of an integrated system for reporting on outcomes of the Basin Plan parallels the Australian State of the Environment report (Department of Agriculture, Water and the Environment 2021*b*). The authors of each 5-yearly report since inception in 1999 have stressed the lack of data on changes over time and urged for improvements in monitoring. Partly to address this deficit of useful time-series data, but also to make spatial environmental data more accessible, in 2015 the Centre for Water and Landscape Dynamics (CWLD) at the Australian National University commenced the integration of satellite observations, field data and model outputs to monitor the changing condition of the Australian environment and produce an annual report (van Dijk and Rahman 2019; Centre for Water and Landscape Dynamics 2020; van Dijk *et al.* 2021). The framework herein follows the principles of the CWLD model.

Methods

A framework for State of the Basin reporting

The State of the Basin reporting framework herein covers indicators for Indigenous, economic, environmental, social and compliance themes. We use the objects of the *Water Act* (Section 3) for the development of the Basin Plan (Section 21) and its content (Section 22) as the most legitimate expression of desired and desirable outcomes. These outcomes were reflected in bipartisan and near-unanimous votes in favour of the *Water Act* by the Australian Parliament in the House of Representatives and the Senate. Section 3(b) gives primacy to environmental outcomes, namely to 'give effect to relevant international agreements', and specifically 'to protect, restore and provide for the ecological values and ecosystem services of the Murray–Darling Basin (taking into account, in particular, the impact that the taking of water has on the watercourses, lakes, wetlands, ground water and water-dependent ecosystems that are part of the Basin water resources and on associated biodiversity)' (S3(d)(ii)). The *Water Act* then specifies the secondary economic need 'to maximise the net economic returns to the Australian community from the use and management of the Basin water resources' (S3(d)(iii)) and the social need 'to improve water security for all uses of Basin water resources' (S3(e)). Interpretation of the *Water Act* as an environmental law remains contested on the basis of a view that its object requires the so-called 'triple-bottom-line' approach for optimising the social, economic and environmental impacts of reform (Commonwealth of Australia 2010; Senate Legal and Constitutional Affairs References Committee 2011). The 'triple-bottom-line' interpretation was apparently backed by an opinion from the Australian Government Solicitor (AGS). In the report of the Murray–Darling Basin Royal Commission, established by the South Australian Government, the triple-bottom-line interpretation was comprehensively dismantled as legally incorrect and unworkable in logic and practice, with the AGS shifting from an environmental interpretation to a triple-bottom-line perspective after the furious public reaction over cuts in irrigation water entitlements proposed in the *Guide to the Basin Plan*, released on 8 October 2010 (Walker 2019, pp. 20–26).

This argument over the interpretation of the *Water Act* affects monitoring and reporting on the State of the Basin. If the environmental interpretation is correct, the volume of water recovered under the Plan must be sufficient to meet the requirements of environmental assets and ecosystem functions. If the triple-bottom-line view is correct, a justification can be made for recovery of a volume less than that required for the environment on the basis of economic and social arguments. Regarding environmental water requirements, the MDBA has been clear that economic and social factors underpin the ESLT, resulting in less water being recovered for the environment (Murray–Darling Basin Authority 2011, pp. 2–3; Senate Legal and Constitutional Affairs References Committee 2011, p. 70; Walker 2019, pp. 201–204).

The *Water Act* has been criticised for failing to set objectives to address the claims of Indigenous peoples to access or manage water (O'Bryan 2018; Godden *et al*. 2020). We include an Indigenous theme in this analysis because the need to increase access to lands and waters is part of the National Agreement on Closing the Gap as Socio-economic Outcome number 15: 'Aboriginal and Torres Strait Islander people maintain a distinctive cultural, spiritual, physical and economic relationship with their land and waters' (Commonwealth of Australia 2020, p. 40). Additionally, the framework in the National Water Initiative (NWI) recognises the following: 'Indigenous needs in relation to water access and management' (Council of Australian Governments 2004, point 25ix, p. 5) and the Basin Plan must have regard to the NWI.

Indicators

Indicators are simple surrogate measures that track status and trends within complex social-ecological systems, where not everything can be measured effectively or meaningfully (Smeets and Wetterings 1999). Accordingly, indicators are useful only if they are designed and interpreted with caution (Bradbury 1996). Carefully designed indicators can be used to assess condition (social, economic, environmental) at a point in time or monitor changes over time to assess performance of policy and management interventions (Dale and Beyeler 2001). Indicators used to assess changes in response to a policy intervention need to be relevant to policy objectives and applicable at the appropriate spatial and temporal scales (Cairns *et al*. 1993).

For this assessment, we chose 27 indicators that are likely to reflect responses to policy and management interventions over time. New indicators can be added or existing ones adapted and improved as and when this assessment is repeated in the future. The choice of indicators is a trade-off between comprehensiveness and accessible communication. Indicators were selected to meet the following criteria. They (1) are directly related to objects of the *Water Act* or the Basin Plan; (2) provide evidence of the extent of progress towards desired outcomes; (3) are linked to Indigenous, economic, environmental, social and compliance variables, policy interventions and responses; (4) are based on objective (i.e. falsifiable), quantitative information; (5) effectively track changes over time; indicators that just showed increases, or were capable of increases only to a particular limit (e.g. numbers of fishways constructed) were not included; (6) are based only on data that are publicly available; (7) are based on data that are collected and updated regularly; and (8) include a target for each indicator that can be set on the basis of legislation or national standards. We used data that were available up to and including 31 March 2024.

We constructed a systems diagram of the links among drivers of change, policy instruments and their response variables relevant to each indicator (Fig. 1). Details of methods used to derive the indicators and references to the sources of data are provided in the Supplementary material. Justifications for each indicator and details of targets are provided in the following section. In our assessment of trend, we used the term in its general usage (i.e. tending to increase or decrease over time), rather than its formal statistical meaning (i.e. showing a statistically significant change). For no trend, an indicator time series showed no clear tendency to increase or decrease and remained largely unchanged, although variable.

Results and discussion

Indigenous theme

Indicator 1. Indigenous water holdings

Target. The volume of water owned or controlled by Aboriginal organisations is increasing.

Objective in the *Water Act*. The *Act* states that the Basin Plan must have regard to 'social, cultural, Indigenous and other public benefit issues' (S21(4)(c)(v)) and include a description of the Basin water resources and the uses to which the Basin water resources are put (including by Indigenous peoples) (S22.1(b)). Water-resource plans must include requirements in relation to social, spiritual and cultural matters relevant to Indigenous people (S22(3)(ca)) and the MDBA must engage with the Indigenous community on the use and management of Basin water resources (S172(1)(ia)). The *Water Amendment (Restoring Our Rivers) Act* 2023 (Cth) states that the Basin Plan must ensure that the use and management of Basin water resources take into account spiritual, cultural, environmental, social and economic matters relevant to Indigenous peoples, including in relation to their knowledge, values, uses, traditions and customs (Commonwealth of Australia 2023, S3fa) and the MDBA must review and report on:

> the extent to which the Basin Plan, including requirements relating to water resource plans, recognises and protects the interests of Indigenous people . . . opportunities for Indigenous people to participate in determining and developing priorities and strategies for the development or use of Basin water resources [S14B].

Justification of indicator and target. For over two decades, Indigenous peoples have sought to advance their objectives in water governance through Basin programs and policies (Godden *et al.* 2020; Hartwig *et al.* 2020). A central tenet of Indigenous 'cultural flows' is to increase access to and control of water through rights and entitlements (Moggridge and Thompson 2021). We consider the volume of water that Aboriginal organisations hold represents a suitable provisional indicator, noting refinement of such an indicator is a matter for Indigenous peoples to agree (Hartwig *et al.* 2021).

Findings. The volume of Indigenous water holdings in the New South Wales part of the Basin is very small and declined

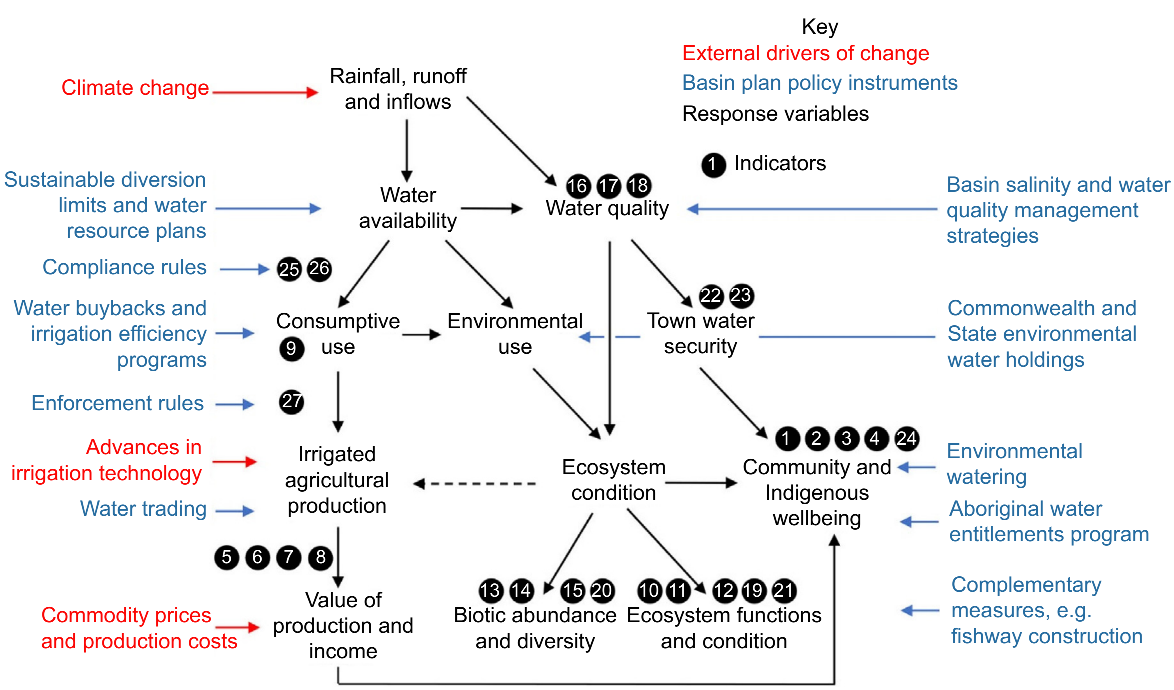

Fig. 1. Diagram showing drivers of change, policy instruments and response variables and the respective Indigenous, economic, environmental social and compliance indicators used to assess changes in the Murray–Darling Basin since the commencement of the Basin Plan. Numbers refer to indicators for each variable (see text and Table 1 for details).

from 14.7 GL year^{-1} in 2008–09 (66 entitlements held by 27 Aboriginal organisations; 0.17% of total non-environmental entitlements) to 12.1 GL year^{-1} in 2018–19 (55 entitlements, 25 organisations and 12 GL year^{-1} in 2020–21; 0.1% of total non-environmental entitlements for both 2018–19 and 2020–21) (Fig. 2*a*; Hartwig *et al.* 2020, 2021). We consider that the target for this indicator has not been met.

Indicator 2. Volume of environmental water released to wetlands within areas represented by Indigenous organisations

Target. The volume of water released by the CEWH and State agency partners as flooding flows to wetlands in areas under the jurisdiction of Indigenous organisations is steady or increasing. These areas include those under Native Title claims, Aboriginal Land Councils in New South Wales, Registered Aboriginal Parties in Victoria and Cultural Heritage Bodies in Queensland (Costanza-van den Belt *et al.* 2022, fig. 1 therein).

Objective in the *Water Act*. As for Indicator 1, implementation of the Basin Plan must have regard to the uses to which the Basin water resources are put, including by Indigenous peoples (S22.1(b)). The MDBA must engage with the Indigenous community on the use and management of Basin water resources (S172(1)(ia)).

Justification of indicator and target. We used flooding flows as an indicator because they represent a closer expression of Indigenous cultural relations with water than do in-channel flows (Moggridge and Thompson 2021). Ensuring that managed flow releases provide benefits to Indigenous peoples is required under the Basin Plan but has not yet been realised (Costanza-van den Belt *et al.* 2022). The MDBA stated a 'clear and committed pathway for First Nations social and economic outcomes' is necessary (Murray–Darling Basin Authority 2020*a*, p. 125). CEWO stated that they 'value the ongoing contribution that First Nations people make to the planning and delivery of water for the environment' (Commonwealth Environmental Water Holder 2024), although they do not report on the nature and extent of this engagement (Department of Climate Change, Energy, Environment and Water 2023*b*). Meaningful engagement would involve Indigenous peoples in cultural water planning (Murray–Darling Basin Authority 2020*d*, p. 3; Woods *et al.* 2022), including recognition of Indigenous watering objectives (Department of Climate Change, Energy, Environment and Water 2024*a*). The Monitoring, Evaluation and Research program (MER 2.0), run by CEWH, has committed to providing a minimum of 10% of catchment budgets for engagement with Aboriginal partners.

Findings. The volume of environmental water released by CEWO, in partnership with State agencies, as flooding flows to wetlands that are under the jurisdiction of Indigenous organisations varied between 102 and 721 GL year^{-1} between 2012–13 and 2022–23, representing an annual average of 18% of the total volume of environmental water being released. Most of this water was accounted for at major wetlands such as Macquarie Marshes, Gwydir Wetlands and those of the central and lower Murray and lower Murrumbidgee. The time-series indicates a variable and fluctuating pattern, with no discernible trend (Fig. 2*b*).

Economic theme

Indicators 3 and 4. Personal community income by Basin Local Government Area

Targets. The targets are (3) mean personal community income is increasing in real terms and (4) disparity between lowest and highest incomes is stable or declining.

Objective in the *Water Act*. The objective is to optimise economic outcomes within the Basin (S20d).

Justification of indicator and target. Commonwealth government water-market reforms and water-efficiency projects have

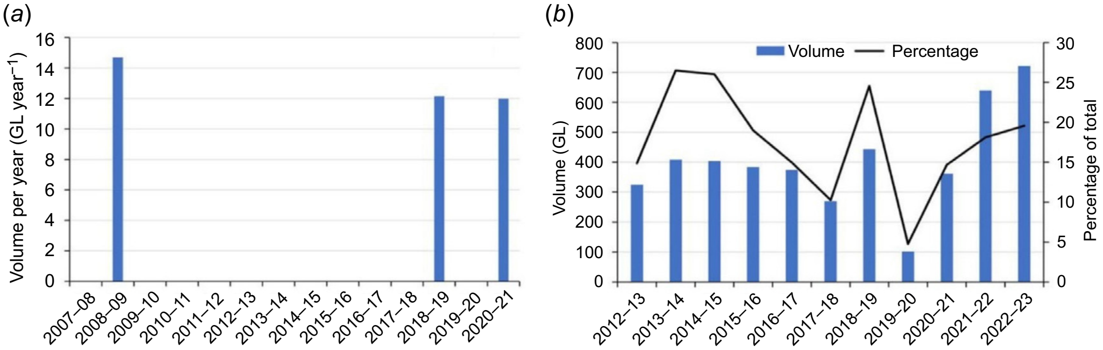

Fig. 2. Indicators, Indigenous theme. (*a*) Water holdings by Indigenous organisations in the New South Wales Basin. (*b*) Volume of Commonwealth environmental water released to wetlands as flooding flows in areas represented by Indigenous organisations. Data sources are provided in the sections for Indicators 1 and 2 the Supplementary material.

been implemented with the intent of generating economic benefits for irrigators under conditions whereby less water is available. Basin governments and their agencies have recognised that changes in water policy and management could have negative effects on the livelihoods of irrigation communities. Such impacts have been widely reported (Sefton *et al.* 2020; Schirmer *et al.* 2021). Accordingly, it is important to measure the economic outcomes for Basin communities. Nominal personal income of communities (not adjusted for inflation) is reported at Local Government Area (LGA) scale (Australian Bureau of Statistics 2021). We included all LGAs that had most of their area located within the Basin and calculated the mean of annual personal incomes, adjusted to real (current) values, with 2011–2012 as the reference year, and compared LGAs containing irrigation districts with non-irrigation LGAs, as well as the difference between LGAs with highest and lowest incomes within each group as a measure of income disparity. Increase in income inequality in Australia since the 1980s has prompted a range of public policies to address economic disadvantage and its consequences (Senate Community Affairs References Committee 2014). Inequality in wages and wages growth is only one of several measures of income inequality and is less comprehensive than the more commonly used Gini coefficient (Fletcher and Guttmann 2013). We use change in wages disparity herein because data are publicly available at the LGA scale and can be scaled up to whole-of-Basin scale and partitioned into LGAs within and outside irrigation districts.

Findings. Between 2011–12 and 2020–21 there was little difference in income between LGAs in irrigation districts and non-irrigation LGAs in the northern and southern Basin. The grand mean for northern Basin irrigation LGAs was A\$48,613 person^{-1} year^{-1}, for northern Basin non-irrigation LGAs, it was A\$46,839, for southern Basin irrigation LGAs, it was A\$47,871, and for southern Basin non-irrigation LGAs, the grand mean was A\$49,850. Income increased by between A\$515 person^{-1} year^{-1} (southern Basin non-irrigation LGAs) to A\$1082 (northern Basin non-irrigation LGAs) over the period of record (Fig. 3*a*).

Income disparity between the top and bottom five irrigation and non-irrigation LGAs in the northern and southern Basin showed the lowest difference was in southern Basin irrigation LGAs (grand mean A\$9250 person^{-1} year^{-1}), then northern Basin irrigation LGAs (A\$15,074 and, northern Basin non-irrigation LGAs (A\$15,579). Income disparity for these three groups showed inter-annual variation but was stable. Highest income disparity was for southern Basin non-irrigation LGAs (A\$23,671) which increased over the period of record (from A\$19,457 in 2011–12 to A\$28,444 in 2020–21) (Fig. 3*b*). This increased disparity in southern Basin non-irrigation LGAs may reflect a strong wages growth in large regional centres such as Queanbeyan, Orange and Bathurst.

The data on personal income and income disparity do not support the narrative that irrigation communities have experienced significant economic disadvantage since the implementation of the Basin Plan, as asserted by Sefton *et al.* (2020), who specified 12 towns experiencing 'acute social and economic conditions' (p. 46), yet provided no data in their report to support this claim. Of the 12 towns mentioned, 6 were in Basin LGAs in the upper 50% for mean personal income and 3 were in the upper 20%.

Indicator 5. Gross value of irrigated agricultural production

Targets. (a) Gross value of irrigated agricultural production (GVIAP) is stable or increasing and (b) the trend is equal to or greater than the national average.

Objective in the *Water Act*. The objective is to have regard to the consumptive and other economic uses of Basin water resources (S21(4)(c)(ii)).

Justification of indicator and target. Almost half the value of Australian irrigated agricultural production is from the Basin (cf. findings below), underpinning national food security and regional economic output. The indicator can be used to assess whether the irrigation sector has been adversely affected economically by the implementation of the Basin Plan.

Findings. Real GVIAP in the Basin (Australian Bureau of Statistics 2019) has remained stable between 2010–11 and 2019–20 (grand mean A\$6.83 billion year^{-1}; range: A\$5.9 billion–8.42 billion year^{-1}) (Fig. 3*c*) but has declined as a proportion of national GVIAP from 46% in 2010–11 to 39% in 2019–20 (long-term average: 47%). Values were lowest in 2010–11 and 2012–13, which coincided with the end of the Millennium Drought (September 2010) and highest in 2017–18 following a wetter than average year in 2016–17. During the Millennium Drought, irrigators in the Basin received only approximately one-third of their water allocations. A 67% decline in water use from 2000–01 to 2008–09 resulted in a 14% reduction in nominal GVIAP and a 20% reduction in price-adjusted gross value (Kirby *et al.* 2014). Many irrigators were able to adapt their production systems by substituting different crops and inputs and by improving irrigation efficiency. Accordingly, GVIAP on its own appears not to be particularly sensitive in the short term to reductions in irrigation water availability because of the economic adaptability of irrigators (cf. also findings for Indicator 6, below).

Indicator 6. Irrigation water use and production value

Target. GVIAP per unit of irrigation water used is steady or improving.

Objective in the *Water Act*. The objective is to achieve efficient and cost-effective water management (S3g).

Justification of indicator and target. The Commonwealth Government has funded irrigation-efficiency schemes to improve productivity and decrease irrigation water use,

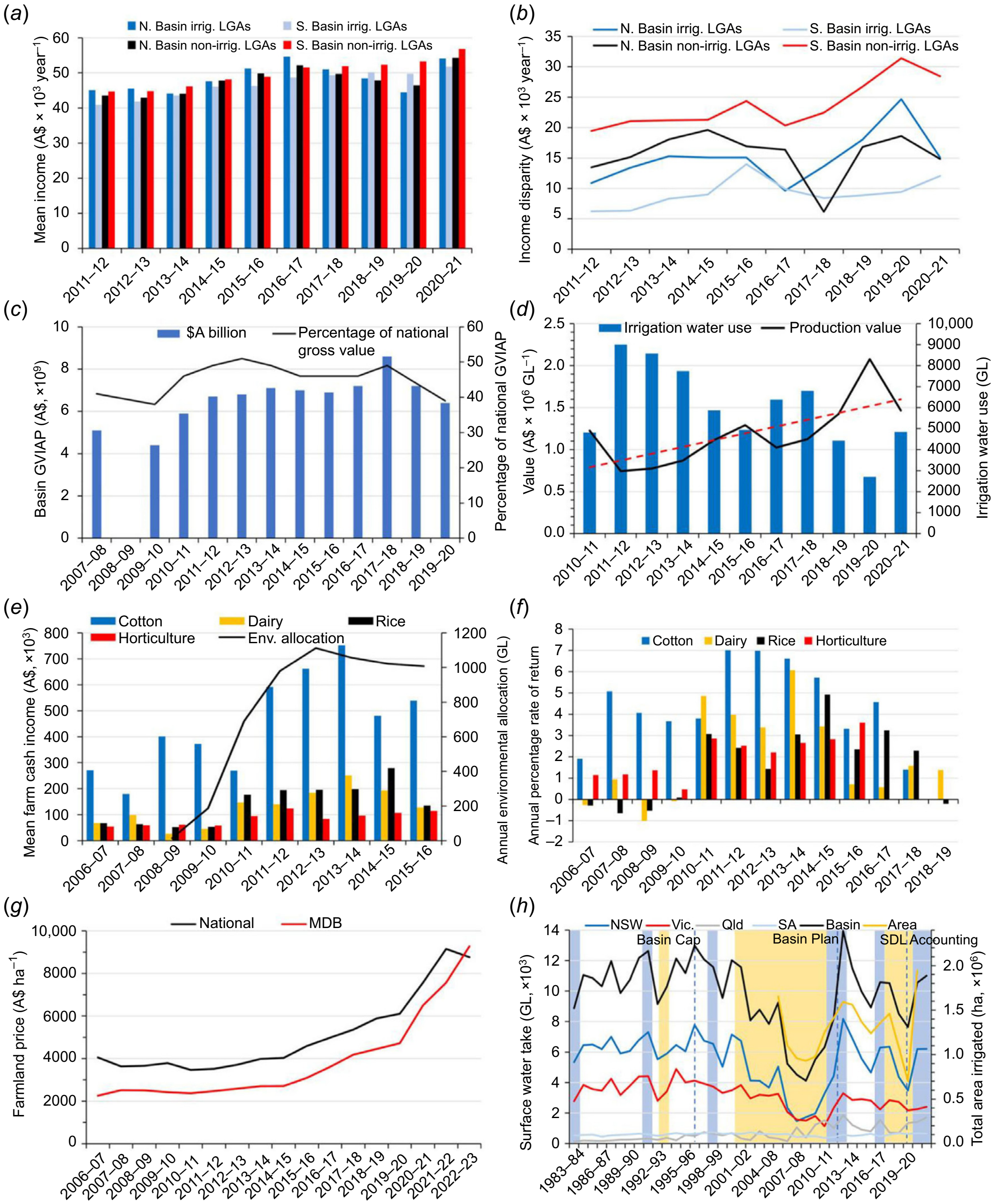

Fig. 3. Indicators, economic theme. (*a*) Mean personal community income in irrigation LGAs and non-irrigation LGAs in the northern and southern Basin. (*b*) Mean income disparity (range) in irrigation and non-irrigation LGAs in the northern and southern Basin. (*c*) Gross value of irrigated agricultural production (GVIAP; bars) and as a percentage of national GVIAP (line). (*d*) Production value of irrigation water (solid black line), with line of best fit (red dashed line) and irrigation water use. (*e*) Mean irrigation farm cash income (bars) and Commonwealth annual environmental water allocations. (*f*) Annual rate of return for irrigation farms. (*g*) Mean Basin farmland price compared with national mean. (*h*) Surface-water diversions by Basin State and total area irrigated, showing periods of drought (yellow) and flood (blue), and key events (vertical dashed lines).

providing a rationale for including an indicator of the economic value of irrigated agriculture and efficiency of water use. GVIAP per unit of irrigation water use is an indicator of the production efficiency of water use.

Findings. GVIAP per gigalitre of irrigation water use doubled over the period from 2010–11 to 2020–21, from A$0.75 million GL^{-1} to A$1.5 million GL^{-1} (calculated from line of best fit, Fig. 3*d*). Production value tended to be lower in wet years (2010–11 to 2012–13), during which time irrigation water use was relatively high and greater areas of crops and pastures were grown as a consequence, indicating relatively low water use efficiency (Marsden Jacob Associates 2020, fig. 2 therein). In dry years, and with lower irrigation water diversions (2014–16 and 2018–21), production value was high, indicating increased water-use efficiency. This pattern reflects changes in irrigation water availability and diversions in relation to rainfall, but also the high adaptability of irrigators during dry periods in switching crops, decreasing the area under production and substituting irrigation water sources (cf. findings for Indicator 5 above). Also, in the northern Basin, which accounts for an average GVIAP of 26% of the Basin total and where floodplain water harvesting is widespread, total on-farm storage capacity is ~3375 GL (Brown *et al*. 2022). These dams fill in very wet years, providing water for irrigation in subsequent drier years. But floodplain harvesting is not accounted for specifically in the ABS water use on Australian farm reports (Australian Bureau of Statistics 2022). Volumes for the category of water source listed as 'water taken from on-farm dams or tanks' are grossly underestimated.

It would be incorrect to infer that the increase in production value of irrigation water has been due mainly to improved irrigation efficiency. Since 2012–13, there were major increases in plantings of high-value almonds and cotton in the southern Basin (SunRISE Mapping and Research 2022; Kennedy and Mackintosh 2024), as well as improvements in production. For example, cotton yield in New South Wales increased from 10.5 to 13.8 tonnes (Mg) ha^{-1} between 2000–01 and 2018–19 (Marsden Jacob Associates 2020, p. 15). Such changes accord with the objective of the NWI, whereby adaptation could be achieved through water trading to shift water use to higher values and profitability. But the setting of this objective in the NWI did not account for the extent to which water availability would be limited by the Basin Plan and climate change. To limit competition for increasingly scarce irrigation water, the Almond Board of Australia urged the New South Wales and South Australian governments to follow the Victorian government and impose a moratorium on water licences for new plantings in the Lower Murray (Kennedy and Mackintosh 2024). The upward trend for this indicator cannot continue indefinitely. As demand for water outstrips supply and limits production, the area of permanent plantings of high-value crops will contract and the production value will decline accordingly.

Indicator 7. Cash income and rate of return of irrigation farms

Target. Cash income and rate of return of irrigation farms is increasing.

Objective in the *Water Act*. The objective is to optimise economic outcomes within the Basin (S20d).

Justification of indicator and target. Cash income and rate of return can be used to assess whether irrigators have been disadvantaged economically by the recovery of environmental water under the Basin Plan, as claimed in submissions to inquiries into the Basin Plan (Productivity Commission 2018, pp. 157–159; Senate Select Committee 2021, pp. 201–202).

Cash income is a more direct indicator than is GVIAP, which is influenced by changes in commodity prices. Data on cash income (Ashton 2020) cover only 4 years since commencement of the Basin Plan (2006–07 to 2015–16), but the time series corresponds with a period during which the majority of environmental water holdings were acquired, including by the Sustainable Rural Water Use and Infrastructure program (Murray–Darling Basin Authority 2023*b*, p. 55).

Trends in cash income do not necessarily reflect changes in profitability. The rate of return represents the net profit of irrigation farm investment. Data on rates of return for dairy and rice farms at Basin scale cover the period from 2006–07 to 2018–19 (to 2017–18 for cotton) (Goesch *et al*. 2020). Data for horticulture farms at Basin scale are available for the period from 2006–07 to 2015–16 (Ashton 2020).

Findings. Mean annual cash income showed inter-annual variation, reflecting commodity prices and water availability. Over the 10-year period of assessment, cash income rose from A$101,625 to A$301,775, a three-fold increase (calculated from lines of best fit; Fig. 3*e*). Increase in cash income for rice farms was highest (from A$51,400 to A$231,800; a 4.5-fold increase), then dairy (from A$53,200 to A$202,900; a 3.8-fold increase), cotton (from A$248,400 to A$655,200; a 2.6-fold increase) and then horticulture (from A$53,500 to A$117,200; a 2.2-fold increase). During the same period, Commonwealth cumulative environmental water entitlements increased from less than 20 GL to 2432 GL and annual allocations from about 10 GL to 1682 GL (Fig. 3*e*). These figures indicate that when most water was recovered for the environment, irrigators were not adversely affected economically, despite fluctuations in commodity prices and water availability (Ashton 2020).

Between 2006–07 and 2015–16, the mean annual rate of return was highest for cotton farms at 4.5%, increasing from 1.9% in 2006–07 to 7% in 2011–12 after the breaking of the Millennium Drought (Fig. 3*f*), before declining to 1.4% in 2017–18 after the onset of drought in 2018. Horticulture farms (including almond orchards) were the next-most profitable, with a rate of return of 2.1%, recovering from 0.9% in 2006–07 during the Millennium Drought to 3.3% in 2015–16. Dairy farms had a mean of 2%, recovering from −0.3% in 2006–07 to 6.1% 2013–14, before falling back to 1.4% in 2018–19. Rice farms, hit hardest by the Millennium Drought, had a mean of 1.6%, recovering from −0.3% in 2006–07 to 4.9% in 2014–15, then declining to −0.2% in

2018–19 after the onset of drought that year. The period of greatest acquisition of environmental water coincided with a period of marked increases in profitability of irrigation farms.

Indicator 8. Farmland price

Target. Farmland price is improving.

Objective in the *Water Act*. The objective is to optimise economic outcomes within the Basin (S20d).

Justification of indicator and target. Farmland price (A$ ha^{-1}) is the average price paid for broadacre farmland (land used for large-scale crop production) (2006–07 to 2022–23), on the basis of data from Australian Bureau of Agricultural and Resource Economics and Sciences (2024). It is an indicator of the value of farmland as a capital asset.

Findings. The mean price per hectare (real dollar value) of broadacre farmland in the Basin increased from A$2259 in 2006–07 to A$9277 in 2022–23, a 4.1-fold rise, compared with a national increase from A$4055 to A$8769, a 2.2-fold rise. Prices rose exponentially from 2014–15 to 2022–23 (Fig. 3*g*). These figures represent a mean annual rate of increase of 25.7% for the Basin and 13.5% nationally. Farmland price growth over the 17 years was highest for the New South Wales Riverina (36.6% per year) and lowest for Queensland Darling Downs and Central Highlands (17.9% per year).

It is important to note that this indicator includes land used for dryland *and* irrigation cropping (Australian Bureau of Agricultural and Resource Economics and Sciences 2024), so a note of caution is required in interpreting the implications for irrigation enterprises. However, in regions dominated in extent by irrigated agriculture (including the New South Wales Riverina and the central north of Victoria), prices were well above the average for the Basin. The high rate of increase in the price of broadacre farmland indicates strong growth in the capital value of irrigation farms, with clear economic benefits for farmers. According to ABARES, there has been a decline in the rate of consolidation of farms, indicating fewer small farmers are exiting the industry. Fewer farms are being sold and at much higher prices than in 2010 (Chan 2024).

Indicator 9. Surface-water diversions

Target. The volume of surface water diversions for consumptive purposes is declining.

Objective in the *Water Act*. The objectives are to ensure the return to environmentally sustainable levels of extraction for water resources that are overallocated or overused (S3di), and to ensure the establishment and enforcement of environmentally sustainable limits on the quantities of surface water and ground water that may be taken from the Basin water resources (S20b).

Justification of indicator and target. The total surface-water diversions for consumptive purposes by each Basin State and Territory represent an expression of the magnitude of the economic benefit provided by Basin water resources. The ESLT is the level at which water can be taken from a water resource which, if exceeded, would compromise key environmental assets, ecosystem functions, the productive base or key environmental outcomes. The vast majority of surface-water diversions from the Basin are used for irrigation; hence, this indicator is included under the economic theme. So, to restore water to the environment, the volume of take for consumptive purposes must be reduced. The SDL caps the volume of Basin water that can be taken for consumptive use and must reflect the ESLT. We used data from annual water-take reports (e.g. Murray–Darling Basin Authority 2023*b*) for the period from 1983–84 to 2021–22. We note that the period covers three different water-accounting frameworks (Basin Cap from 1996–97 to 2018–19, transitional SDLs with no compliance for 2019–20 onwards and SDLs with compliance for WRPs accredited before 2020–21). The accounting methods differ for each. Because such a large proportion of surface-water diversions is used for irrigation, we examined the relationship between take and area irrigated, using area data from the Water Use on Australian Farms survey (e.g. Australian Bureau of Statistics 2022) between 2005–06 (when data at Basin scale were first published) and 2020–21, the most recent published survey.

Findings. Irrigation diversions accounted for 92.2% of surface-water take between 1999–2000 and 2011–12. Diversions follow rainfall and river inflows during wet and dry years (Fig. 3*h*; Murray–Darling Basin Authority 2023*b*). Between 1983–84 and 1999–2000, surface-water take was ~11,000 GL $year^{-1}$, before falling sharply during the Millennium Drought (2001–10) to 4000 GL $year^{-1}$ in 2008–09, with declines in all States except South Australia (with an annual entitlement of up to 1850 GL $year^{-1}$ under the Murray–Darling Basin Agreement, but less during dry years). Take recovered after the Millennium Drought broke, reaching a maximum of nearly 14,000 GL in 2012–13 at the commencement of the Basin Plan. Since then, in New South Wales, the largest consumptive water user (mean 55% of total volume, 1983–84 to 2021–22), Victoria (mean 32% of total volume) and Queensland (7% of total volume), take declined by between one-third and one-quarter from 2012–13 to 2021–22. Basin-wide, take declined from almost 14,000 GL $year^{-1}$ in 2012–13 to ~11,000 GL $year^{-1}$ in 2020–21. Yet, this reduction has not been reflected by increases in river flows (cf. findings for Indicator 11, below).

Increased irrigation water-use efficiency does not necessarily mean a reduction in water consumption, because increased efficiency tends to result in increased water use and total area irrigated (Adamson and Loch 2018; Wheeler *et al.* 2020). Increase in irrigated area is a major driver of increased water consumption (Puy *et al.* 2021). The area equipped for irrigation in Australia (i.e. the area that *could* be irrigated; AEI) increased between the calendar years 2000 and 2015, mostly in the Basin according to Mehta *et al.* (2024, table 2 and fig. 4 therein). These authors consider that AEI, rather than the area actually irrigated, allows for better assessment of broad temporal trends and minimises errors from attempting to integrate different agricultural census data. But, in reality, the actual area of the Basin irrigated each year shows considerable inter-annual variation and has not increased overall between the water years 2005–06 and 2020–21 (mean 1.3×10^6 ha; Fig. 3*h*).

Environmental theme

Indicator 10. Flooding of Ramsar wetlands

Target. Ramsar wetlands are flooded with managed environmental flows at frequencies and extents that meet their environmental water requirements.

Objective in the *Water Act*. To give effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources) (S3(b)) and the Basin Plan must promote the conservation of Ramsar wetlands (S21(3)b).

Justification of indicator and target. The Ramsar Convention obliges the Commonwealth Government to promote the wise use of all wetlands and maintain the ecological character of Ramsar sites. Maintenance of ecological character of those Ramsar wetlands located on floodplains depends on floods of a frequency, extent, depth and duration to meet the environmental water requirements of their constituent species and vegetation communities, for example, river red gum (*Eucalyptus camaldulensis*) forests and woodlands, black box (*E. largiflorens*) woodlands and lignum (*Duma florulenta*) shrublands (Chen *et al.* 2021; Kirsch *et al.* 2022). Floods may be generated by natural flows and releases of held environmental water by Commonwealth and State agencies.

Changes in the characteristics of flow and flood regimes of the major wetlands of the Basin are not regularly assessed by government agencies. Two-monthly data from 1988–2022 on the extent of flooding at the Basin scale are publicly available (Penton *et al.* 2023), but require specialist spatial-analysis tools to consolidate, visualise and assess the annual extent of flooding of natural wetlands. As a proxy measure, we used the maximum annual extent of open water and wet ground of Ramsar wetlands (1999–2000 to 2020–21), by using the Digital Earth Australia Wetlands Insight Tool (Geosciences Australia, see https://maps.dea.ga.gov.au, accessed 28 July 2024; Dunn *et al.* 2023). A limitation of this indicator is that Ramsar wetlands represent only a small proportion of the total area of natural wetlands that can be flooded with managed environmental flows.

Findings. Maximum extent of flooding and wet areas varied with wet and dry years, with highest values in 2010–11 when the Millennium Drought broke, and in 2016–17, a year with above-average rainfall in most of the southern Basin and the upper reaches of the Border Rivers, Gwydir and Namoi catchments (Stewardson and Guarino 2018, fig. 4 therein) (Fig. 4*a*). During the period after the Basin Plan commenced (2012–13 to 2020–21), maximum flood extent declined slightly, on the basis of lines of best fit to time series in Fig. 4*a*, at Riverland (14.8–12.1% of 30,615 ha), Barmah–Millewa Forest (24.2–23.5% of 66,535 ha) and Gunbower–Koondrook–Perricoota Forest (18.1–16.3% of 56,043 ha), and increased at Macquarie Marshes (10.2–21.9% of 19,850 ha), Gwydir Wetlands (8.4–13.9% of 823 ha) and Narran Lakes (9.3–20.2% of 8454 ha). Less than 17% of the total area (193,035 ha) of these six Ramsar sites was flooded in 6 of 9 years, representing 67% of the time for which data are available since commencement of the Basin Plan. At Macquarie Marshes, environmental watering of the Southern Nature Reserve has effectively ceased, with only one flood between 2016–17 and 2020–21, whereas the Northern Nature Reserve has received environmental water annually during this period (Schweizer *et al.* 2022).

Ramsar wetlands remain dependent on intermittent, unpredictable, high unregulated flows for the maintenance of their ecological character. Environmental watering had some buffering effect during dry years. The frequency of years during which the extent of flooding was particularly high or low (greater than the mean ± 0.5 standard deviations, s.d.) supports this finding (Fig. 4*b*). The proportion of years of low flood extent for the six wetlands prior to commencement of the Basin Plan was 0.47 (6.2 years in 13) compared with 0.26 (2.3 years in 9) after the commencement of the Basin Plan. The proportion of years of high flood was 0.26 (3.3 years in 13) prior to the Basin Plan and 0.15 (1.3 years in 9) after. The Basin was in drought for 8/13 years prior to the Basin Plan but only 2/9 years after (Fig. 4*a*).

Between 1999–2000 and 2020–21, an average of 17.9% of the total area of 193,085 ha of the six wetlands was flooded, or at least wetted, which is somewhat higher than the estimate of 10% (2000–01 to 2020–21) based on the area flooded to a depth of ≥0.5 m (Chen *et al.* 2021). The small extent flooded indicates that environmental water requirements of Ramsar wetlands are not being met, despite delivery of environmental flows to these wetlands in almost all years, except Narran Lakes, which was watered only in 2016–17. Only 21% of the volume of managed environmental flows released annually (2012–13 to 2020–21) (mean 1886 GL) was delivered as flood events (Chen *et al.* 2021).

Indicator 11. Vegetation condition of Ramsar wetlands

Target. Vegetation condition in Ramsar wetlands is maintained or improving.

Objective in the *Water Act*. The objective is to promote sustainable use of Basin water resources to protect and restore

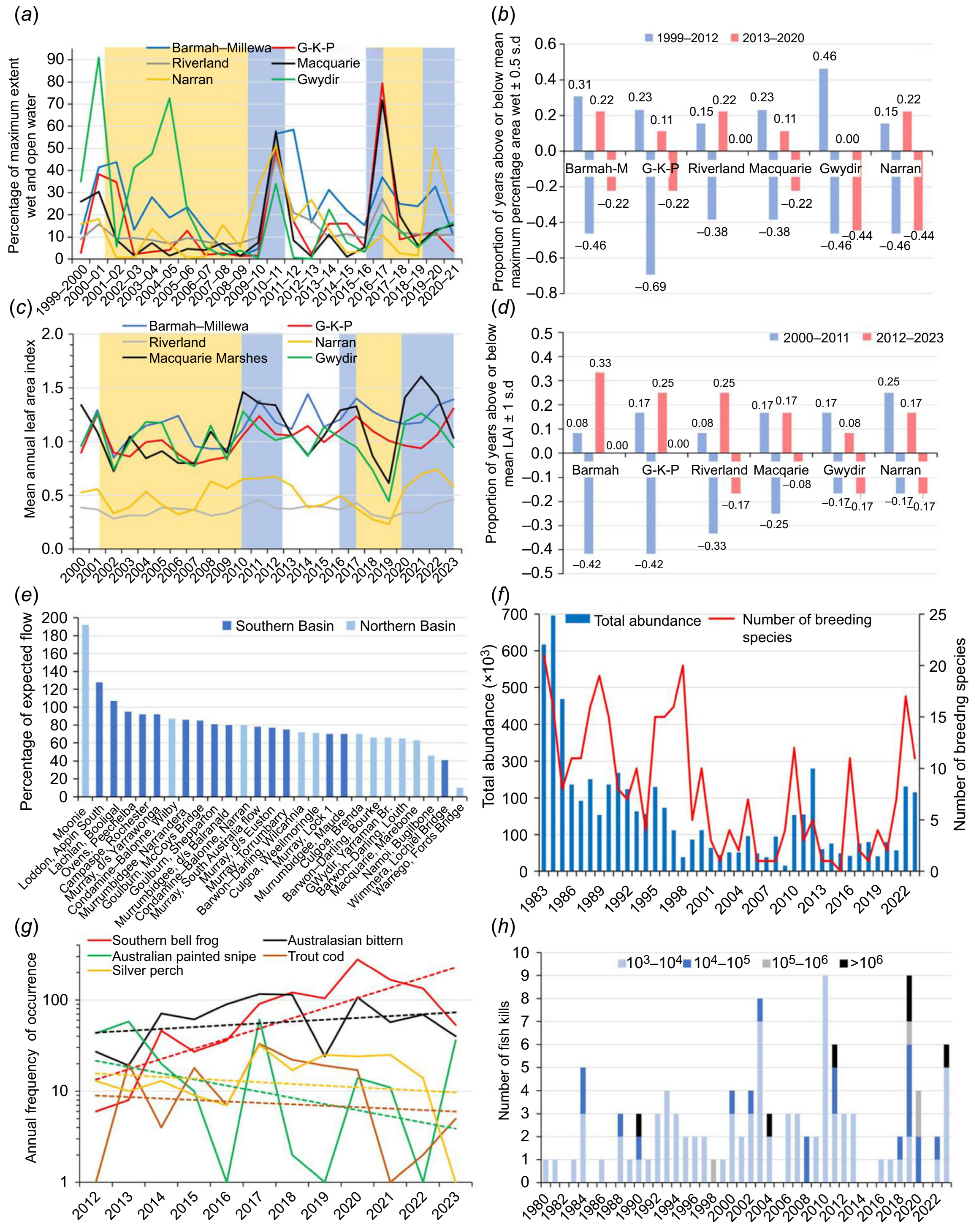

Fig. 4. Indicators, environmental theme. (*a*) Percentage of Ramsar wetland area flooded, showing periods of drought (yellow) and flood (blue); (*b*) Ramsar wetlands: frequency of years of large and small floods; (*c*) Ramsar wetlands: vegetation condition, based on mean annual leaf area index, showing periods of drought (yellow) and flood (blue); (*d*) Ramsar wetlands: frequency of years of good or poor vegetation condition; (*e*) river flows: observed *v*. expected; (*f*) abundance of waterbirds and number of breeding species; (*g*) frequency of occurrence of threatened species with lines of best fit; and (*h*) number of fish kills in the New South Wales Basin. G-K-P, Gunbower–Koondrook–Perricoota; d/s, downstream.

the ecosystems, natural habitats and species that are reliant on the Basin water resources and to conserve biodiversity (S21(2)(b)), as well as to give effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources) (S3(b)).

Justification of indicator and target. River red gum forest and woodland, coolibah (*Eucalyptus coolabah*) woodland, black box woodland and lignum shrubland are the wetland vegetation communities prioritised for managed environmental flows in the Basin-wide Environmental Watering Strategy (BWS), a statutory instrument of the Basin Plan (Murray–Darling Basin Authority 2019*b*). The BWS contains targets for maintenance of these communities in each catchment. Condition of river red gum forests and woodlands has been monitored (Cunningham *et al.* 2009) and reported in the Basin Plan Evaluation (Murray–Darling Basin Authority 2020*a*). Leaf area index (LAI) is a measure of crown extent (Asner *et al.* 2003). Floodplain trees shed their leaves to reduce transpiration and water uptake as a response to low water availability during drought (Gibson *et al.* 1994). Flooding recharges soil water and subterranean palaeochannels filled with coarse sediment (Colloff 2014, p. 9), leading to increased water uptake, leaf area (by epicormic growth) and transpiration, resulting in improved tree condition (Doody *et al.* 2015). We used mean annual LAI of vegetation, derived from remote sensing (Centre for Water and Landscape Dynamics 2020), in six Ramsar wetlands as an indicator of wetland woody-vegetation condition.

Findings. Mean annual LAI tends to be higher in wetlands with extensive forests of river red gum (Barmah–Millewa Forest, Gunbower–Koondrook–Perricoota Forest and Macquarie Marshes) or stands of water couch (*Paspalum distichum*) (Gwydir Wetlands) than in wetlands with more scattered lignum shrublands and open riparian woodland (Riverland and Narran Lakes). LAI at the six Ramsar sites showed no trend between calendar years 2000 and 2023 (Fig. 4*c*), other than improvements during wet years and declines during droughts. This pattern becomes more apparent when comparing frequency of years during which LAI was particularly high or low (greater than the mean ± 1 s.d.) (Fig. 4*d*). The mean proportion of low-LAI years for the six wetlands prior to implementation of the Basin Plan (2000–11) was 0.29, compared with 0.1 after (2012–23) and the proportion of high-LAI years was 0.15 before and 0.21 after. These figures might suggest that the Basin Plan is associated with improved vegetation condition at these wetlands, but the Basin was in drought for 9 of the 12 years prior to the Basin Plan and only 3 of 12 years after; so, no such inference can be drawn.

Indicator 12. River flows

Target. River flows at hydrological indicator sites increase as predicted under the Basin Plan.

Objective in the *Water Act*. The objective is to promote sustainable use of Basin water resources so as to protect and restore the ecosystems, natural habitats and species that are reliant on the Basin water resources and to conserve biodiversity (S21(2)(b)).

Justification of indicator and target. To restore and maintain healthy flow-dependent ecosystems, the volume, duration and frequency of flow events must accord with standards at the 124 'hydrological indicator sites' (HISs). Infrequent high flows are needed to inundate wetland ecosystems at higher elevations on the floodplains, for example, black box woodlands.

Findings. The Wentworth Group (2020) reported on observed *v*. expected flows under the Basin Plan at river gauges at 27 HISs across the Basin, with data adjusted for climatic variability, providing a basic indicator of whether sufficient water is available to maintain in-channel and wetland habitats and biota. An estimated 5591 GL was expected to flow across the South Australian border between 2012–13 and 2019–20, but the actual flows were 22% lower. Flows at 24 of the 27 sites were lower than expected, 13 received less than 75% of the expected flows and three received less than half (Fig. 4*e*). Year 2020 was the first year when the Wentworth Group analysis was undertaken, and it is likely to be ongoing. Modelled flow is based on past events and flows now are less than in the past, indicating a declining trend.

Indicator 13. Waterbirds

Target. Abundance of populations of waterbirds is increasing.

Objective in the *Water Act*. The objective is to give effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources) (S3(b)), and to protect, restore and provide for ecological values (S3(d)(ii)).

Justification of indicator and target. Waterbird populations are closely linked to the ecological condition of rivers and wetlands (Reid *et al.* 2013). Since calendar year 1983, the annual Eastern Australian Waterbird Survey has monitored abundance of waterbirds, numbers of species breeding and wetland area (Kingsford *et al.* 2020; Porter *et al.* 2020, 2024). Waterbird abundance and the number of breeding species are indicators of the availability of suitable habitat and resources within wetlands, which, in turn, are driven by rainfall, river inflows and flooding (Kingsford *et al.* 2017).

Findings. Annual waterbird abundance and number of breeding species in the Basin (1983–2023) have declined since the high values between 1983 and 1985 (Fig. 4*f*). Low values coincide with the Millennium Drought (2000–10) and the 2017–20 drought, with increases in 2010–11 after the

Millennium Drought broke and after wet years in 2016–17 and 2022–23.

Under current and predicted future climates, waterbird targets under the Basin Plan (increase in abundance by 20–25%, in frequency of breeding events by 50%, in breeding abundances by 30–40% and maintenance of species diversity; Murray–Darling Basin Authority 2019*a*, pp. 44, 45) are unlikely to be met (Bino *et al.* 2021). Abundance is predicted to continue to decline and remain below targets without improved policies and management for environmental watering to support waterbird populations.

Indicator 14. Threatened species

Target. Frequency of occurrence of selected flow-dependent threatened species is maintained or improving.

Objective in the *Water Act*. The objective is to give effect to relevant international agreements (to the extent to which those agreements are relevant to the use and management of the Basin water resources) (S3(b)), and to protect and restore ecosystems, natural habitats and species that are reliant on the Basin water resources and to conserve biodiversity (S21(2)(b)).

Justification of indicator and target. Monitoring of changes in distribution, abundance and occurrence of flow-dependent threatened species is required for their conservation, as detailed in mandated Species Recovery Plans (SRPs). But monitoring is fragmented and only a minority of flow-dependent threatened species have SRPs. Increases in occurrence and abundance provide evidence that environmental flows are meeting the water requirements of threatened species (Ryan *et al.* 2021); so, improved monitoring should be a priority for the Basin Plan.

We used data on annual frequency of occurrence (the number of times per year a species was recorded) from the Atlas of Living Australia (see https://www.ala.org.au/, accessed 8 February 2024) for five of the species selected by Ryan *et al.* (2021), updated for calendar years from 2019 to 2023, to assess the effectiveness of environmental flows for threatened species conservation (southern bell frog, *Litoria raniformis*; Australasian bittern, *Botaurus poiciloptilus*; Australian painted snipe, *Rostratula australis*; trout cod, *Maccullochella macquariensis*; and silver perch, *Bidyanus bidyanus*). These species are listed as Threatened under the *Environmental Protection and Biodiversity Conservation Act* 1999 (Cth) and one or more State and Territory conservation acts. They are distributed predominantly in the regulated catchments of the southern Basin, where almost 90% of environmental water was released between 2012–13 and 2018–19 (Chen *et al.* 2021). There are SRPs for southern bell frog and trout cod and draft plans for Australasian bittern and Australian painted snipe. Silver perch is Critically Endangered under the *Environmental Protection and Biodiversity Conservation Act* but has no SRP.

Findings. Frequency of occurrence for all species between 2012 and 2023 was highly variable among years; however, on the basis of lines of best fit to time-series in Fig. 4*g*, increased markedly for southern bell frog (mean annual occurrence 11.6–164.9), increased slightly for Australasian bittern (55.2–75.3), stayed more-or-less the same for silver perch (12.9–16.8) and trout cod (13.7–9.1) and declined markedly for Australian painted snipe (33.8–7.2). The overall pattern is variable, with no clear benefits of environmental watering for flow-dependent threatened species. The distribution of species except Australasian bittern appears to have contracted since 1990 (Ryan *et al.* 2021, fig. 1 therein). Environmental watering has had some transient positive outcomes for some threatened species in some locations on some occasions, but monitoring and reporting is fragmented and inconsistent (Ryan *et al.* 2021). If the Basin Plan is to deliver on its environmental objectives, including Australia's international environmental treaty obligations, a comprehensive monitoring framework is required to support a more effective, targeted approach to managing environmental water requirements for threatened species.

Indicator 15. Fish kills

Target. The number of water quality-related fish kills is declining.

Objective in the *Water Act*. The objective is to protect, restore and provide for the ecological values and ecosystem services of the Murray–Darling Basin (taking into account, in particular, the impact that the taking of water has on watercourses, lakes, wetlands, ground water and water-dependent ecosystems that are part of the Basin water resources and on associated biodiversity) (S3(d)(ii)).

Justification of indicator and target. Freshwater fishes are sensitive to declines in water quality, particularly low dissolved oxygen concentration, which is often exacerbated by low flows (Australian Academy of Science 2019). Changes in frequency and magnitude of fish kills over time reflect changes in water quality, which may include de-oxygenation caused by blackwater events, cyanobacterial (blue–green algal) blooms or runoff from bushfire-affected areas (cf. Indicator 23 below). We used data from the New South Wales Department of Primary Industries fish kill database to estimate frequency and magnitude of fish kills (>1000 individuals killed).

Findings. Between calendar years 1980 and 2023, the mean annual number of fish kills in the New South Wales Basin increased from 1.5 to 3.6 (calculated from the line of best fit, Fig. 4*h*). During the period after the Basin Plan was implemented (2012–23), the annual number of events rose from 1.3 to 3.9, compared with an increase from 3 to 4.6 for the 12 years prior (2000–21). There have been six very large fish kills (>100,000 individuals) during the 2012–23 period, including the 2019–20 and 2023 kills at Menindee

Lakes in New South Wales (Australian Academy of Science 2019; Sheldon *et al.* 2022; NSW Chief Scientist 2023), compared with only 2 in the 12 years prior. Accordingly, there is no evidence that the Basin Plan settings are associated with a reduction in the number of fish kills. The number of very large events appears to be increasing.

Indicators 16 and 17. Salinity

Target. (16) Electrical conductivity of Murray River waters is below target levels and (17) mean annual discharge of 2×10^6 Mg of salt from the Murray Mouth is met.

Objective in the *Water Act*. Environmental outcomes can be enhanced by discharging 2×10^6 Mg of salt per year from the Murray–Darling Basin as a long-term average (S86AA(2)(d)).

Justification of indicator and target. Highly saline water inhibits animal health, the production of irrigated crops and pastures and flow-dependent ecosystems (Nielsen *et al.* 2003). Saline domestic water sources are a health risk for communities.

Ensuring that salinity is managed below target levels is important for agriculture, communities and ecosystems. Basin States monitor electrical conductivity at multiple sites (e.g. at selected river gauges; cf. Murray–Darling Basin Authority 2020*e*, table 16 therein). The Basin Plan salinity target is to have <800 EC at Morgan for at least 95% of the time, with 95% targets for four other sites as follows: on the Murray River at Lock 6 (580 EC), Murray Bridge (830 EC) and Milang (1000 EC) on the lower Darling at Burtundy (830 EC) (Murray–Darling Basin Authority 2015, 2020*e*, table 8 therein).

The annual target for salt discharged from the Murray Mouth is 2×10^6 Mg (on the basis of 3-year rolling averages), set by MDBA, on the basis of modelling of 1.95×10^6 Mg year^{-1} under the Basin Plan 2800 GL year^{-1} scenario for return of water to the environment (Murray–Darling Basin Authority 2012*b*, p. 31). Salt interception schemes diverted over 4×10^6 Mg (2009–10 to 2019–20; Murray–Darling Basin Authority 2020*e*). State and Territory governments report on salinity control, recorded by MDBA in registers of salinity credits and debits.

Findings. The salinity (EC) targets for Morgan, Murray Bridge and Lock 6 have been met and maintained since 2010 (Murray–Darling Basin Authority 2020*e*, p. 10). Salinity at Burtundy was above target for an average of 29% of the time and at Milang for 7% of the time between 2009 and 2020 (Fig. 5*a*).

The target for annual discharge of salt from the Murray Mouth shows that the target has not been achieved since 2011–12. The mean annual amount discharged since Basin Plan implementation in 2012–13 is only 0.8×10^6 Mg year^{-1} (Fig. 5*a*) and appears to be declining: from 1×10^6 Mg year^{-1} in 2012–13 to 0.6 year^{-1} between 2019 and 2022 (calculated from the line of best fit, Fig. 5*b*). The reason given for the failure to meet the target was because of 'relatively low inflows since the Basin Plan was introduced' and that 'the overall salt export objective should also be revisited in the context of the Basin's variable climate' (Murray–Darling Basin Authority 2017, p. 84). The MDBA has examined the appropriateness of the target and concluded that it was 'not effective' and should be 'improved ahead of the 2026 review of the Basin Plan' (Murray–Darling Basin Authority 2022*b*, p. 16). A factor not considered by MDBA regarding the salt export target is the failure to meet flow targets; actual flow at Lock 1, the nearest HIS to the Murray Mouth for which observed *v*. expected flows were assessed, was only 70% of the expected flow between 2012–13 and 2019–20 (cf. Indicator 12 above). Minimum flow required to keep the Murray Mouth open was estimated to be 730–1090 GL year^{-1} (Department for Environment and Water 2019, p. 29), yet average annual discharge over the Lower Lakes barrages since 2012–13 was 3925 GL year^{-1} (cf. Indicator 21 below), mainly owing to very high flows between 2021 and 2023, although flows were below or close to the upper bound of the minimum discharge volume (1090 GL year^{-1}; blue dashed line in Fig. 5*h*) in 2015–16 and 2017–20.

Indicator 18. Nutrient pollution

Target. Reduce nitrogen and phosphorus concentrations in river water towards Australian and New Zealand Environment and Conservation Council standards over time.

Objective in the *Water Act*. The Basin Plan must include a water-quality management plan (S21(1)), including objectives and targets (S25(1)(b)).

Justification of indicator and target. High nitrogen and phosphorus concentrations can trigger water-quality threats, including cyanobacterial blooms. State agencies monitor water quality at a range of sites, but information is publicly available only for those sites included in the River Murray Water Quality Monitoring program (Henderson *et al.* 2013), although data for Morgan were obtained from MDBA on request. Basin Plan targets for nutrient concentrations are listed in Schedule 11 of the Basin Plan, being based on standards for nutrients in waterbodies in south-eastern Australia (Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand 2000).

Findings. Weekly or monthly mean concentrations of Kjeldahl nitrogen (N) and total phosphorus (P), measured at locations representing the upper, central and lower Murray River (Kiewa River at Bandiana, Murray River at Swan Hill and Murray River at Morgan respectively) between 2000–01 and 2022–23, were above limits for the following proportions of time: Bandiana: N, 0.19; P, 0.34; Swan Hill: N, 0.2; P, 0.21;

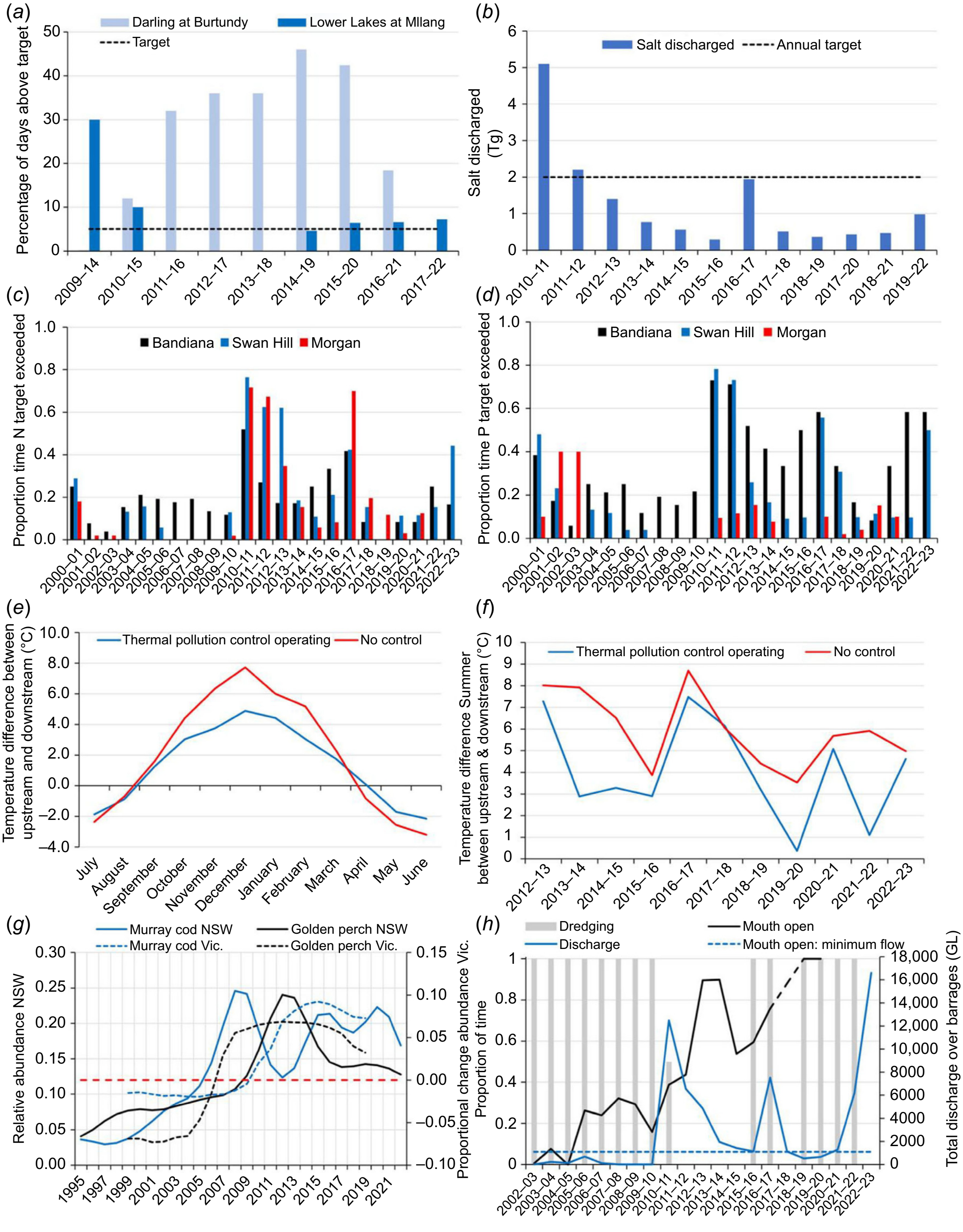

Fig. 5. Indicators, environmental theme. (*a*) Proportion of days salinity exceeds target values; (*b*) salt discharge through Murray Mouth; (*c*) proportion of days water-quality standards for total Kjeldahl nitrogen are exceeded; (*d*) proportion of days water-quality standards for total phosphorus are exceeded; (*e*) monthly difference in temperature upstream and downstream of dams with and without thermal pollution control operating; (*f*) difference in mean summer temperature upstream and downstream of dams with and without thermal pollution control; (*g*) fish populations, New South Wales and Victorian Basin, the red dashed line indicates no proportional change for Victoria; (*h*) proportion of time Murray Mouth is open and dredged. Tg, teragram (i.e. 1×10^6 tonnes).

Morgan: N, 0.16; P, 0.08 (Fig. 5c and d). Since 2012–13, the proportion of time that N targets were exceeded has improved at Bandiana (0.23–0.13; calculated from line of best fit), Swan Hill (0.3–0.16) and Morgan (0.29–0.8). Exceedance of P targets has barely changed at Bandiana (0.41–0.39), increased slightly at Swan Hill (0.19–0.24) and declined slightly at Morgan (0.08–0.05). Peak exceedances were associated with high unregulated flows during 2010–13, 2016–17 and 2021–23, but, overall, some reductions are evident in N and P concentrations in the Murray since implementation of the Basin Plan.

Indicator 19. Cold-water pollution

Target. Cold-water pollution is declining.

Objective in the *Water Act*. The Basin Plan must include a water-quality management plan (S21(1)), including objectives and targets (S25(1)(b)), so as to protect and restore the species that are reliant on the Basin water resources (S21(2)(b)).

Justification of indicator and target. Water released from the bottom of large dams is colder than water at the surface or the upstream rivers (Pittock and Hartmann 2011; Lugg and Copeland 2014). The release of cold water lowers the temperature of the river downstream, causing harmful ecological effects, including limiting spawning, survival and growth of fishes if water temperature is consistently below thermal preferences (Koehn et al. 2020). The water-quality target for temperature in the Murray–Darling Basin Plan (Schedule 11) is for the monthly median to be within the range of the 20th and 80th percentile of the natural monthly water temperature.

Installation of thermal-pollution control devices (TPCDs) at dams (Department of Primary Industries 2017) or use of other mitigation methods (Gray et al. 2019; Michie et al. 2020) has been undertaken in New South Wales in a program to restore natural water temperatures and mitigate ecological damage (Department of Primary Industries 2017, 2021). Despite the publication of an action statement on cold-water pollution in Victoria (Department of Sustainability and Environment 2003) and an assessment of the prevalence of the problem over two decades ago (Ryan et al. 2001), we found no evidence for the installation of TPCDs on dams in the Victorian Murray–Darling Basin. Accordingly, the data for this indicator are from the New South Wales Basin only.

Findings. Dams with operating strategies for cold-water pollution (Burrendong and Windamere) had a maximum mean monthly downstream water temperature 4.9°C lower than in upstream (2012–13 to 2022–23), compared with 8°C for dams without such strategies (Burrinjuck, Hume, Keepit and Wyangala) (Fig. 5e). Burrinjuck has a TPCD installed but an operating protocol is yet to be fully implemented. Temperatures downstream of the Hume Dam increased to a maximum of 4°C cooler between spring and summer, potentially disrupting spawning of fishes (Sherman et al. 2007). Keepit Dam, considered of low potential for cold-water pollution (Department of Primary Industries 2021), had a maximum difference of only 2.9°C cooler downstream (December), whereas maximum difference at Wyangala Dam was 11.2°C (January).

Mean temperature difference during summer (December–February) between 2012–13 and 2022–23 showed consistently smaller differences at dams with cold-water pollution strategies in operation (grand mean 4°C, range 1.1–7.5°C) than in those without such strategies (grand mean 6°C, range 3.5–8°C; Fig. 5f), although with considerable variation. High values were recorded in 2012–13 and 2016–17. The TPCD installed at Burrendong had been operational only since May 2014 (Gray et al. 2019). There was some indication of a slight decreasing trend over time for both types of dams, but the high inter-annual variation urges caution in making such an inference.

The indicator value is the temperature difference during the summer months, when fishes are spawning, for dams with and without operating TPCDs. If more dams are retrofitted, the gap would be expected to narrow. Our assessment was hindered by incomplete water temperature records at appropriate river gauges (Supplementary Table S1). An improved temperature-monitoring program has been implemented to address this deficit (Department of Primary Industries 2017, p. 12, appendix 1 therein).

Indicator 20. Fish populations

Target. Populations of fishes are maintained or improved.

Objective in the *Water Act*. The objective is to protect, restore and provide for the ecological values and ecosystem services of the Murray–Darling Basin (taking into account, in particular, the impact that the taking of water has on watercourses, lakes, wetlands, ground water and water-dependent ecosystems that are part of the Basin water resources, and on associated biodiversity) (S3(d)(ii)).

Justification of indicator and target. Populations of native fishes have been under threat from flow alteration associated with irrigation diversions, drought and climate change, poor water quality, barriers to movements, invasive species, habitat alteration, cold-water pollution and commercial and recreational fishing (Koehn et al. 2020). Populations have declined substantially since European settlement (Murray–Darling Basin Authority 2020f). The Native Fish Recovery Strategy includes the objective that threats to native fishes are identified and mitigated (Murray–Darling Basin Authority 2020f). The BWS contains several recommendations relating to river flows and connectivity for improving fish populations (Murray–Darling Basin Authority 2019b).

We used data on relative abundance of two large-bodied species, Murray cod and golden perch, from New South Wales Basin (calendar years 1995–2022) from the New South Wales

Department of Primary Industries Freshwater Ecosystem database (Crook *et al.* 2023) and the annual proportional change in abundance of the same species from the Victorian tributaries of the Murray River between 1999 and 2019 (Yen *et al.* 2021). The units used to express abundance are incompatible for these two datasets, but the overall trends can be compared.

Findings. New South Wales populations showed marked increases over the 28-year period of record, but with considerable variation among years (Fig. 5*g*). The commercial inland fishery for native finfish in New South Wales was progressively restricted during the 1990s (Reid *et al.* 1997) and ceased altogether in September 2001 (Department of Primary Industries 2024). Increases in populations are likely to reflect reduced harvesting pressure as well as extensive stocking with hatchery fishes (Crook *et al.* 2023). Regulation of recreational fishing, use of managed environmental flows, provision of fishways and habitat restoration may also have contributed to increased abundance. Peak abundance of Murray cod in 2008 during the Millennium Drought may be due to the selective advantage of this channel-dwelling species compared with the floodplain-spawning golden perch, which showed a peak in abundance 2 years after the drought broke. Subsequent fluctuations of Murray cod, and declines for golden perch, may be due in part to the six very large fish kills (>100,000 individuals) in the New South Wales Basin during the period 2012–23 (cf. Indicator 15 above).

The increases in populations of Murray cod and golden perch in the New South Wales Basin were generally similar to population trends in the Victorian Murray tributaries, although the increase in golden perch populations commenced earlier than for Murray cod (2007–08 *v.* 2010–11) (Fig. 5*g*). High spring discharge and a reduction in the number of low-discharge days relative to the long-term average probably influenced the increase in abundance of the two species (Yen *et al.* 2021).

Indicator 21. Murray Mouth

Target. The Murray Mouth is open >95% of the time without dredging.

Objective in the *Water Act*. Environmental outcomes can be enhanced by ensuring that the mouth of the Murray River is open without the need for dredging in at least 95% of years, with flows every year through the Murray Mouth barrages (S86AA(2)(c)).

Justification of indicator and target. The target for keeping the Murray Mouth open without dredging is mandated in the *Water Act* and the Basin Plan (Schedule 5, paragraph 2(c)).

Findings. The target was not met (Fig. 5*h*). The minimum annual flow required to keep the Murray Mouth open has been estimated by the MDBA to be 730–1090 GL year^{-1}. The 2020 Basin Plan evaluation concluded the following: 'it appears that under the drying climate the target for the Murray Mouth opening is unachievable' (Murray–Darling Basin Authority 2020*a*, p. 53).

Social theme

Indicators 22 and 23. Town water security

Target. Improved water security for regional towns with historically insecure water supply, whereby (22) there are fewer days of water restrictions and (23) the number of drinking-water quality incidents (e.g. boil water alerts) is declining.

Objective in the *Water Act*. The objective is to improve water security for all uses of Basin water resources (S3e).

Justification of indicator and target. Many communities have experienced reduced water security and water quality because of decreased flows and low volumes in public dams during recent droughts (Barbour *et al.* 2020). There are little in the way of publicly available data on town water security and quality Basin-wide, but number of days per year in which restrictions on domestic water use were in place has been available for LGAs in the New South Wales Basin, as were data on the annual number of water-quality incidents (boil water notices) by LGA (Department of Planning, Industry and Environment 2024).

Findings. The mean number of days with water restrictions for 10 LGAs that had water restrictions in place for some of the time between 2013–14 to 2019–20 increased sharply in 2018–19 (194 days) and 2020–21 (232 days) from a relatively stable period between 2013–14 and 2017–18 (mean 62 days) (Fig. 6*a*). The annual total number of water-quality incidents rose sharply from two in 2012–13 to 13 in 2022–23, with peaks in 2016–17 (9 incidents) and 2019–20 (15 incidents).

Indicator 24. Water-quality threats

Target. Water-quality threats are declining in frequency.

Objective in the *Water Act*. Include water-quality objectives and targets for Basin water resources (25(1)(b)). Critical human water needs are the highest-priority water use for communities who are dependent on Basin water resources (S86A(1)(a)).

Justification of indicator and target. This indicator overlaps with indicators from other themes. Cyanobacterial (blue–green algal) blooms, hypoxic blackwater events, high turbidity owing to high flows or debris from bushfires have detrimental cultural, environmental and social impacts. Low dissolved oxygen has been responsible for major fish deaths at Menindee Lakes, associated with cyanobacterial blooms (Australian Academy of Science 2019) and high degradable biomass (NSW Chief Scientist 2023). The ecological condition

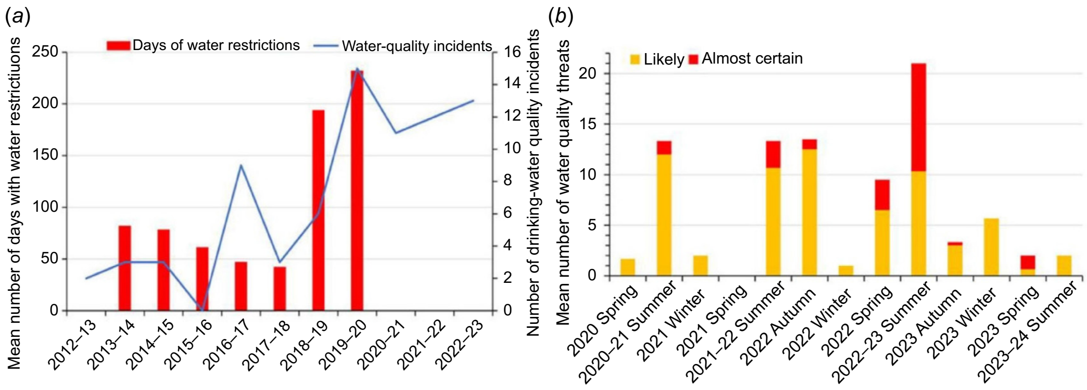

Fig. 6. Indicators, social theme. (*a*) Town water security, New South Wales Basin: number of days of water restrictions (bars) and number of drinking-water quality incidents (line); (*b*) number of water-quality threat events (blue–green algal blooms, low dissolved oxygen, hypoxic blackwater and high turbidity).

of rivers and wetlands is inherently connected with the health, livelihoods and wellbeing of local communities and Indigenous peoples (Bates *et al.* 2023). Poor water quality restricts use of water for irrigation, stock and domestic purposes, recreational use of waterways and tourism, and negatively affects personal, community and economic wellbeing. Water-quality threats are likely to intensify in frequency and severity under climate change (Baldwin 2021).

The data were derived from water-quality threat maps published several times per year by MDBA, commencing in October 2020 (e.g. Murray–Darling Basin Authority 2023*c*).

Findings. Some 464 water-quality threat events were identified between October 2020 and December 2023, of which 25% were due to cyanobacterial blooms, 15% to low dissolved oxygen, 9% to hypoxic blackwater and 2% to high turbidity. The mean number of threats per season showed highest numbers during summer and autumn, but no apparent trend over the relatively short period of record (Fig. 6*b*). The high number of threats in the summer of 2022–23 was due to increased risks of low dissolved oxygen and blackwater event following high flows and flooding during that year.

Compliance and enforcement theme

Indicators 25 and 26. Sustainable Diversion Limits

Target. Target for Indicator 25 is to ensure that SDLs for surface-water resource units are met and Indicator 26 to ensure that the adjusted cumulative balance for each resource unit is stable or increasing, i.e. trending away from the SDL.

Objective in the *Water Act*. The objective is to ensure the return to environmentally sustainable levels of extraction for water resources that are overallocated or overused (S3(d)(i).

Justification of indicator and target. The MDBA determines the SDL for each SDL resource unit (or catchment). SDLs are the long-term average volume of water that can be diverted from each SDL resource unit for consumptive use and represent the level of take that is considered economically, socially and environmentally acceptable (Murray–Darling Basin Authority 2011, pp. 2–3). This definition does not equate with the volume required to sustain healthy, flow-dependent ecosystems. This so-called 'triple-bottom-line' definition is not legislated in the *Water Act*, and is considered unlawful (Walker 2019, p. 53). SDLs are part of the legislative mechanism for reducing diversions in the Basin, so it is important to determine whether they are being complied with. We used the adjusted cumulative balance, expressed as a proportion of the long-term SDL, for each surface-water SDL resource unit for 2019–20, 2020–21 and 2021–22, to indicate whether take was increasing or decreasing and moving towards or away from the SDL. Accounting for New South Wales SDL resource units is subject to change on the basis of accreditation of methods used to estimate annual permitted and annual actual take. New South Wales water-resource plans for surface SDL resource units were accredited between March and June 2024, but those for Gwydir and Namoi remained outstanding at the time of writing (August 2024).

Findings. SDL compliance reports and registers of take for 2019–20, 2020–21 and 2021–22 indicate that water take has been below the SDL compliance trigger in all SDL resource units, except for Barwon–Darling, in all 3 years and Gwydir in 2021–22 (Fig. 7*a*). For the Barwon–Darling, exceedance is apparently due to 'modelling limitations and incomplete environmental water recovery' and in the Gwydir due to 'the result of the growth in take by floodplain harvesting' (Murray–Darling Basin Authority 2023*d*, pp. 5–7).

In the 2021–22 SDL compliance statement, the Inspector-General of Water Compliance stated the following: 'The situation in New South Wales is deeply concerning, particularly as there is an increasing number of areas on the interim SDL accounts pointing to an SDL excess beyond the SDL compliance threshold, specifically, the Barwon–Darling

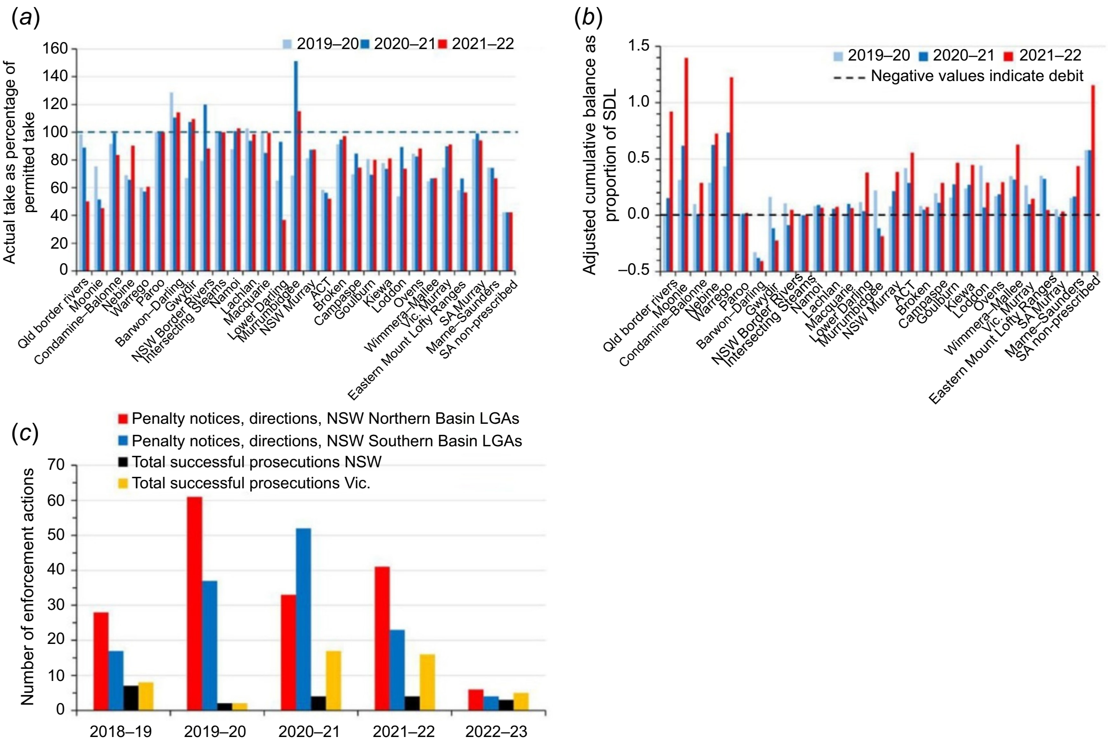

Fig. 7. Indicators, compliance theme. (*a*) SDL compliance; (*b*) adjusted cumulative SDL balance; (*c*) breaches of water laws: number of prosecutions, penalty notices, directions and enforceable undertakings issued.

watercourse by 40%, Gwydir surface water by 21% and the Murrumbidgee is trending toward the SDL compliance threshold at 18% SDL exceedance' (Inspector General of Water Compliance p. 12). On the basis of this concern, we consider that Indicator 25 has not been met.

Exceedance of the SDL compliance trigger does not provide an indication of trajectories of change in take relative to the SDL. We found that the adjusted cumulative balance of annual permitted take minus annual actual take was negative (i.e. in debit) in 2019–20 in one surface-water SDL resource unit (Barwon–Darling), in five units in 2020–21 (Barwon–Darling, Gwydir, New South Wales Border Rivers, Murrumbidgee and South Australian Murray) and in three units in 2021–22 (Barwon–Darling, Gwydir and Murrumbidgee) (Fig. 7*b*). The mean trajectory of change in adjusted cumulative balance over the 3-year period declined in eight surface-water SDL resource units (Barwon–Darling, Gwydir, New South Wales Border Rivers, Murrumbidgee, Loddon, Victorian Murray, Eastern Mount Lofty Ranges and South Australian Murray), was stable in three (change was within 10% of the mean; Intersecting Streams, Namoi and Broken) and increased in the remaining 18 units. The number of SDL resource units in which annual actual take was greater than 90% of annual permitted take doubled from 6 in 2019–20 to 12 in 2020–21 and 2021–22. We consider that Indicator 26 has not been met.

A shortcoming of the SDL accounting framework is that surface-water SDLs can be increased over time when estimates of baseline diversion limits (BDLs; the volume of water being used prior the Basin Plan) are updated and increased (Murray–Darling Basin Authority 2023*d*, p. 7). Evidence for justifying changes in BDLs has generally been poor, rarely adequately articulated and always involve increases. The BDL has been adjusted upward for the Murrumbidgee, with consequent increases in the SDL. Accordingly, the trend towards exceedance that we found is likely to be greater and more extensive had it not been for repeated increases in BDLs and SDLs.

Estimated take from floodplain harvesting for SDL resource units in the northern Basin is reported as identical, 448.2 GL year^{-1}, for 2020–21 and 2021–22 (Murray–Darling Basin Authority 2022*c*, p. 34; Murray–Darling Basin Authority 2023*d*, p. 37). This volume is likely to be a considerable underestimate of the actual volume harvested (Brown *et al.* 2022, p. 51). Accordingly, annual actual take relative to annual permitted take in these SDL resource units is likely to be significantly higher than in the SDL compliance reports and registers of take.

Indicator 27. Breaches of water laws

Target. Compliance with the *Water Act* and State law; number of enforcement actions is declining.

Objective in the *Water Act*. This indicator relates to Part 2, management of Basin water resources; Division 3A, offences and civil penalty provisions and, specifically, S73B, taking water when not permitted under State law. The Commonwealth and the Basin States and Territory agreed to the Murray–Darling Basin Compliance Compact in June 2018 to address compliance and integrity of Basin water management (Murray–Darling Basin Authority 2018). The Compact is intended to ensure that water users comply with State, Territory and Commonwealth laws.

Justification of indicator and target. In July 2017 the Australian Broadcasting Corporation aired a *Four Corners* report, 'Pumped', into theft by irrigators of taxpayer-funded water for the environment from the Barwon–Darling River. The report prompted an independent investigation into compliance in New South Wales (Matthews 2017*a*, 2017*b*), which led to the establishment in 2018 of the Natural Resources Access Regulator (NRAR), responsible for enforcement of water laws in that State. We used data from the NRAR Public Register on enforcement actions (successful prosecutions, penalty notices, directions and enforceable undertakings; New South Wales Natural Resources Access Regulator 2024) as well as data on successful prosecutions in Queensland, Victoria and South Australia (cf. Indicators 1 and 2 in the Supplementary material).

Findings. Legal structures, processes and administration of penalties operate quite differently in each jurisdiction and data cannot readily be sourced, aggregated and compared at whole-of-Basin scale (Seidl and Wheeler 2024). The number of enforcement actions in any jurisdiction will vary according to the degree to which enforcement is implemented. In Victoria, alleged compliance breaches increased since 2014–15 because of improved telemetry and metering to detect unlawful water extractions, whereas in New South Wales, alleged breaches tripled following establishment of the NRAR (Seidl and Wheeler 2024).

Despite the limitations of this indicator, some broad comparisons can be made regarding prosecutions. In the Queensland Basin, there was only one prosecution of an offence committed between 2018–19 and 2021–22 (Queensland Government 2024), and only two in South Australia between 2014–15 and 2022–23 (Department for Environment and Water 2024). In Victoria, there were 48 successful prosecutions between 2018–19 and 2022–23 (Department of Energy, Environment and Climate Action 2024) (Fig. 7*c*). The small number of successful prosecutions in the New South Wales Basin by NRAR between 2018–19 and 2022–23 indicates the low likelihood of detection and prosecution for serious breaches of the *Water Management Act* 2000 (NSW) (Fig. 7*c*). Some 17 convictions are listed on the Public Register (New South Wales Natural Resources Access Regulator 2024), plus 3 in the 2022–23 annual progress report (New South Wales Natural Resources Access Regulator 2023), from 40 prosecutions initiated between 2018–19 and 2022–23, with a conviction rate of 50%. In total, 303 penalty notices, directions and enforceable undertakings were issued over the period, with 56% within LGAs in the northern Basin and 44% in the southern Basin. Although these figures appear to indicate a reasonably even geographical distribution between north and south, the number of enforcement actions per irrigation farm is four times higher in the northern Basin; of an estimated 8390 irrigation farms in the Murray–Darling Basin, only 2001 (24%) are in the northern Basin (Australian Bureau of Statistics 2022). No apparent trend is detectable from what is only 5 years-worth of data. It would be incorrect to assume that the low number of enforcement actions indicates a downward trend over the previous 3–4 years. Rather, because 2022–23 was a particularly wet year, it is likely that there was less incentive for irrigators to break the law.

Successful prosecutions in the New South Wales Land and Environment Court tend to carry much higher fines and costs for common offences of unlawful taking of water and unlawful construction of water supply works (mean fine A$173,281, $n = 7$; mean costs A$162,127, $n = 5$) than in the New South Wales Local Court system (mean fine A$15,486, $n = 7$; mean costs A$8125, $n = 6$). Fines and costs in the Land and Environment Court typically remain lower than the value of the water taken unlawfully, lessening the incentive for compliance. Under the *Water Management Act* 2000 (NSW), the Minister for Water has the power to cancel the water licence of a person convicted of an offence. We could find no record of any such cancellation. By comparison, fines in Victorian Magistrates courts for unauthorised take of water under the *Water Act* 1989 (Vic.) are extremely lenient (mean A$1900, $n = 27$; costs A$ 2985, $n = 41$). In 58% of proven cases, no conviction was recorded. As for New South Wales, there is no apparent trend in 5 years-worth of data (Fig. 7*c*). Seidl and Wheeler (2024) found that the probability of detection and prosecution for water theft in New South Wales is very low, resulting in an average penalty value of stealing water well below existing water market prices, thus providing an incentive for non-compliance.

Underpinning the stark differences among jurisdictions in the enforcement of water laws is the mean annual number of successful prosecutions per capita (2018–19 and 2022–23), namely, 0.3 per thousand irrigation businesses in Queensland, 0.4 in South Australia, 2.8 in Victoria and 1.3 in New South Wales. In the report of the Murray–Darling Basin Royal Commission, Walker (2019, p. 67) observed that there is a 'high degree of inconsistency between Basin States in relation to matters including the range of offence and penalty provisions, and the use of administrative orders. Basin States may wish to give consideration to whether their respective offence and penalty provisions properly reflect community expectations.'

Targets, status and trends of indicators

We analysed trends for the 27 indicators. Technically, it could be argued that a fully comprehensive evaluation of the

Basin Plan would need to include estimates based on the counterfactual, i.e. what would have happened *without* the Basin Plan. For example, there may still be a decline in trend for some indicators, but those declines could have been worse without the Basin Plan. Every indicator we used is based on an objective in the *Water Act*, a target in the Basin Plan, or both. Accordingly, these objectives and targets represent predictions, either qualitative and aspirational or quantitative and empirically based, of what the water reform policies for the Basin could or would achieve. We argue that our analysis represents a test of those predictions.

Table 1 summarises the data available for each indicator and whether targets were met. Of the 27 indicators, 7 were met (26%), 10 were variable but showed no overall trend (37%) and 10 were not met (37%). Below we discuss the findings for the indicators from each of the five themes.

Indigenous theme

Both Indigenous targets were not met. Water holdings by Indigenous organisations are the most incomplete of the datasets. The small volume of Indigenous cultural water entitlements indicates continued disempowerment of Indigenous peoples for control over the management of water on Country, with knock-on effects for health and wellbeing. Water justice for Indigenous peoples is conspicuous by its absence from the *Water Act* and the Basin Plan. The Commonwealth government recently increased funding of the Aboriginal Water Entitlements Program from A$40 million to A$100 million, as 'part of a broader effort to strengthen the Water Amendment (Restoring Our Rivers) Bill 2023' and as 'a strong commitment to addressing historical water access challenges' (Department of Climate Change, Energy, Environment and Water 2024*b*). But even this increased sum is unlikely to substantially increase rights to water for Indigenous nations.

Economic theme

For the seven economic indicators, the following five targets were met: improvement in mean personal income, no increase in disparity in personal income in irrigation LGAs, steady GVIAP, improved value of production per gigalitre of irrigation water use and increased farmland price. These findings suggest, at the Basin scale, that irrigation communities are not necessarily experiencing severe economic hardship as a result of the implementation of the Basin Plan, as claimed by some (Vidot 2017; Sefton *et al*. 2020). But Schirmer and Mylek (2020) found that communities within the Basin had poorer social and economic conditions than did those outside the Basin for some indicators, including economy, employment and standard of living. The Southern Basin and inner regional areas had more positive aspects of community wellbeing than did more remote areas.

Surface-water take, primarily for economic purposes, has declined since 2012–13 by nearly 2500 GL, which appears to indicate that the Basin Plan is affecting take. Yet, GVIAP has remained steady and the production value of irrigation water has increased markedly, again indicating a lack of evidence for a significant economic downturn for the irrigated-agriculture sector, at least from the perspective of these indicators. Farmland price increased by a mean value of 26% per year between 2006–07 and 2022–23. Cash income and rate of return of irrigation farms, which represent direct indicators of the economic impact of the implementation of the Basin Plan, increased substantially when most environmental water was recovered, although rate of return subsequently declined during the drought of 2017–20.

Environmental theme

Of the 12 environmental indicators, only 2 were met, namely, nutrient pollution and improvements in populations of large-bodied fishes in New South Wales and Victoria. The following five indicator measurements showed no clear trend: flooding of Ramsar wetlands, wetland vegetation condition, occurrence of threatened species, salinity in the Murray River, and mitigation of cold-water pollution. The following five indicator measurements were not met: river flows, waterbird populations, fish kills, salt discharge from the Murray Mouth and the proportion of time the Murray Mouth is open without dredging.

For the indicators with no clear trend, several showed responses in relation to periods of drought and flood, particularly the 2001–10 Millennium Drought and the 2017–20 drought. With regard to Basin Plan policy measures, these responses are problematic when comparing periods pre- and post-Basin Plan commencement. From 2000–01 to 2011–12, the Basin was in drought for 75% of years, and in flood for 25% of years, compared with 25% of drought years and 42% of flood years between 2012–13 and 2022–23 (Fig. 7*a*). This disproportionate distribution of wet and dry years makes it difficult to draw inferences on the contribution managed environmental watering may have made to flow-dependent ecosystems compared with high unregulated river flows.

The gap between expected and observed flows and the low frequency and extent of flooding of wetlands with environmental water are causes for concern. These indicators point to shortfalls in the prediction of water availability and increasing water scarcity, but policy options to address these issues, such as improved water modelling and accounting, regulating interception activities, more effective use of environmental water and environmental triage and adaptation have not been implemented (Colloff and Pittock 2022). Irrigation communities adjusting to the effects of water reform and taxpayers need confidence that substantial public investment in water recovery has resulted in increased river flows. The possible reasons for the shortfall include the following: higher than expected conveyancing losses; illegal upstream diversions of environmental water; lower than

Table 1. Targets for the 27 indicators.

Number	Theme and target	Data can be used as reported publicly?	Data completeness (spatially and temporally)	Status	Trend
	Indigenous				
1	Proportion of water held by Indigenous organisations is improving	Additional analysis required	Available for NSW Basin; only 3 annual data points	Poor	Declining
2	Volume of water released to wetlands in areas of Indigenous organisations is increasing	Additional analysis required	Complete	Intermediate	No trend, variable
	Economic				
3	Personal income of Basin LGAs is steady or improving	Additional analysis required	Complete	Good	Improving
4	Disparity between LGAs with lowest and highest median income is steady or improving	Additional analysis required	Complete	Good	Steady overall for irrigation LGAS
5	GVIAP is steady or improving and the trend is equal to or greater than the national average	Yes	Most recent data are only for 2018–19	Good	Stable
6	Value of production per unit of irrigation water used is steady or improving	Yes	Most recent data are only for 2018–19	Good	Improving
7	Cash income and rate of return of irrigation farms is increasing	Yes	Most recent data are only for 2015–16	Good	Declines during drought then recovers
8	Farmland price is improving	Yes	Complete	Good	Improving
9	Surface water diversions are declining	Yes	Complete	Intermediate	No trend, variable
	Environmental				
10	Ramsar wetlands are flooded at an appropriate extent to meet their water requirements	Yes	Complete: based on remote sensing data	Poor, target not met	No trend, variable
11	Condition of vegetation in Ramsar wetlands is maintained or improving	Yes	Complete: based on remote sensing data	Poor, target not met	No trend, variable
12	River flows at Hydrological Indicator Sites match projections and predictions by MDBA	Additional analysis required	Complete	Poor, observed is below expected	Declining
13	Waterbird abundance of key species is steady or improving	Additional analysis required	Complete	Poor	Declining
14	Frequency of occurrence of selected threatened species is steady or improving	Additional analysis required	Data based on field surveys at only 9 sites Basin-wide	Intermediate	One species declining, two no change, two improving
15	Number of fish kills is falling	Additional analysis required	Only available for NSW Basin	Poor	Number of severe fish kills rising
16	EC in Murray River below target levels >95% of the time	Yes	Complete	Intermediate	Improving but EC not met at Burtundy
17	Discharge 2×10^6 Mg salt year^{-1} from Murray Mouth	Yes	Complete	Poor	Discharge target not met
18	Reduce nitrogen and phosphorus concentrations towards water quality standards	Additional analysis required	Only available for Murray River	Fair	Some improvement
19	Cold water pollution is declining (installation of TPCDs)	Additional analysis required	Complete	Intermediate	No trend; TPCD installation sporadic
20	Populations of large-bodied fishes are maintained or increasing	Yes	Only available for NSW and Victoria	Fair	Improving

(*Continued on next page*)

Table 1. (*Continued*).

Number	Theme and target	Data can be used as reported publicly?	Data completeness (spatially and temporally)	Status	Trend
21	Murray Mouth open >95% of time without dredging	Additional analysis required	Time Murray Mouth is open not reported regularly	Poor	Target unlikely ever to be met
	Social				
22	Town water security: days per year of water restrictions is declining	No – full dataset no longer publicly available	Complete for NSW Basin LGAs only	Poor	Number of days per year of water restrictions is increasing
23	Number of drinking water quality incidents is declining	No – full dataset no longer publicly available	Complete for NSW Basin only	Poor	Number of boil water notices is increasing
24	Water quality threat events to domestic, cultural and recreational water uses are declining in number	Data not publicly archived	Some reports missing	Intermediate	No trend, variable
	Compliance and enforcement				
25	SDL for each SWRU are met	Yes	Complete	SDL not met for 2 SWRUs	Trend toward increased exceedance of SDL compliance threshold
26	Adjusted cumulative SDL balance for each SWRU is stable or increasing	Yes	Complete	Target not met	Balance has declined in 8/29 resource units
27	Breaches of water laws: prosecutions and enforcement notices are declining in number	Additional analysis required	Data incomplete in NSW prior to establishment of Natural Resources Access Regulator	Intermediate	No trend, variable

Red indicates that data collection is inadequate, data are incomplete, status is poor, and trend is declining. Amber indicates that additional analysis is required, data are partly adequate, status is intermediate, with no trend. Green indicates that data can be used as reported, data are complete, status is good, and trend is improving. LGA, local government area; GVIAP, gross value of irrigated agricultural production; EC, electrical conductivity; TPCDs, thermal pollution control devices; SDL, sustainable diversion limit; SWRU, surface water resource unit.

expected yields from environmental water entitlements; reductions in return flows to rivers owing to increased irrigation efficiency; shortcomings in official water accounting and modelling; reductions in flows from exceedance of SDLs and inadequacies of SDL and BDL accounting (Wentworth Group 2020; Wheeler *et al.* 2020).

Social theme

The three indicators for the social theme were not met. Number of days of water restrictions and number of drinking-water quality incidents both increased. The third, numbers of water-quality threat events affecting domestic, cultural and recreational water use showed no clear trend, but the time series for this indicator was of relatively short duration.

Water quality and water security are major concerns for regional riverine communities in the Basin. For those that rely on river water for domestic supply, the prospect of poor water quality is heightened during periods of flood and drought. Basin States have been slow to upgrade domestic water infrastructure and many water treatment plants are aging and in need of replacement (Roberts and Vyver 2023). Remoteness is a major determinant of poor community wellbeing (Schirmer and Mylek 2020) and is linked to issues of poor water quality and security, especially for communities in the west of the Basin and particularly for Indigenous communities (Barbour *et al.* 2020). Lower Darling communities rely on the river for their domestic water; however, it has been frequently below minimum safety standards owing to low river flows and cyanobacterial blooms (Davies 2019). Bottled drinking water had to be trucked in because water-quality targets in the lower Darling were not met for turbidity, salinity, cyanobacteria, nitrogen and phosphorus concentrations (Department of Planning, Industry and Environment 2020). Yet, access to adequate, safe drinking water is a basic human right (United Nations 2021). Water for human consumption needs to meet highest standards for palatability, aesthetic qualities and safety from contaminants. The Basin contains multiple sources of contaminants from agricultural and pastoral land and urban areas. Monitoring, managing and public reporting of water quality are vital to protect water sources, human health and wellbeing (Wyrwoll *et al.* 2022; Beavis *et al.* 2023).

Compliance theme

None of the three indicators was met. SDLs for surface-water resource units and adjusted cumulative balance for surface-water resource fell short of targets. The indicator for breaches of water laws is a relatively short time-series and showed no apparent trend, but there is no indication that prosecutions for breaches of water laws are in decline.

Compliance relates to the responsibilities of government agencies, but also for individual water users, to adhere to the relevant water-management rules and laws of the Basin States and Territory. The Inspector-General of Water Compliance is responsible for enforcing compliance with the *Water Act*, the Basin Plan and water-resource plans and monitoring performance of obligations of the Commonwealth and Basin States and Territory. These responsibilities include review of SDL accounting and registers of take. The Inspector-General has expressed extreme concern about shortcomings in SDL compliance in New South Wales and made strong recommendations to the New South Wales Minister for Water to act to address the issues raised (Inspector General of Water Compliance 2023, pp. 13–14). In a comprehensive assessment of compliance in the Basin, these shortcomings were highlighted and recommendations made to reform national and state data and reporting, increase the probability of detection of breaches, reduce regulatory capture, reform legislation and penalties and improve regulator visibility to increase deterrence and successful prosecution (Seidl and Wheeler 2024).

Adequacy and public availability of data

Data collection and reporting for indicators across all themes were generally poor. Of the 27 indicators, only 14 satisfy the criterion for complete data collected and reported and for only 12 could the data be used as reported, i.e. without additional processing and analysis (Table 1). There are clear opportunities to improve data curation, public availability, monitoring, evaluation and reporting. We also identify important gaps in reporting that could be readily improved, such as Basin- and farm-scale measurement of water consumption as part of a comprehensive water audit, which was included in the *Water Amendment* (*Restoring Our Rivers*) *Act* 2023 (Cth).

Some data that have been freely available in the past are no longer made public. For example, CEWO had published details of their watering actions in annual outcomes reports from 2008–09 to 2013–14 (e.g. Commonwealth Environmental Water Office 2010; Department of Sustainability, Environment, Water, Population and Communities 2013; Department of Environment 2014) and in CEWO long-term intervention monitoring (LTIM) reports from 2014–15 to 2018–19 (e.g. Hale *et al.* 2020, appendix 1 therein). These publications contain valuable information on the component of the flow regime, biota and ecosystem functions targeted, water volume and dates of each watering action, these being essential data for estimating where, when, how and why environmental water was used. From 2013 to 2014, environmental watering actions were published on the MDBA website under the annual Basin Plan implementation reports, Matter 9.3, environmental water-use reports. Some actions in the Matter 9.3 reports differ in their details from the same actions in the LTIM reports. From 2019 to 2020, details of watering actions were published on the CEWO website under a section on the history of watering in each catchment (e.g. Department of Climate Change, Energy, Environment and Water 2022), but volumes, locations, dates and objectives were not always included. Some events did not involve CEWH water, for example, the spring 2021 watering of Hattah Lakes (Department of Climate Change, Energy, Environment and Water 2023*c*), comprising 30.3 GL from the Victorian Environmental Water Holder and 15.9 GL from The Living Murray program (Victorian Environmental Water Holder 2023*a*, p. 15). Regarding these partial (and sometimes contradictory) data, the Department of Climate Change Energy Environment and Water (2023*b*) stated as follows:

> The data sources and methodology are documented internally. The data sources include State registers that have accounts of annual water allocations; and water entitlements of all water holders, including the Commonwealth [p. 53].

The Inspector-General of Water Compliance (2022), in an assessment of environmental watering, concluded the following:

> The inherent complexity in the system, together with inconsistencies in how information is collated and presented, can act as a barrier to reaching the community. It also makes it difficult for the majority of individuals to navigate. This is likely leading to a trust deficit from some stakeholders [p. 4].

We note that complete data on environmental watering actions are publicly accessible and easy to find on the relevant agency websites for Victoria (Victorian Environmental Water Holder 2023*b*), New South Wales (Department of Planning and Environment 2023) and South Australia (Department for Environment and Water 2021).

In the case of the fish-kill data from New South Wales, the data from the last water year is publicly available, although access to earlier data requires completion of a licence agreement with New South Wales Department of Primary Industries. Data that are not publicly available, but should be, include drinking-water quality data held by New South Wales Department of Health (Wyrwoll *et al.* 2022). Access is restricted to New South Wales local water utility-performance monitoring database (Department of Planning, Industry and Environment 2024), despite the requirement for public performance monitoring and benchmarking under the National Water Initiative. What is now the New South Wales

Department of Climate Change, Energy, the Environment and Water monitors and reports the performance of local water utilities in the annual New South Wales water-supply and sewerage-performance monitoring reports, but at the time of writing, these reports were available online only for 2013–14, 2014–15 and 2015–16, whereas the data we used on the number of days of water restrictions and the number of drinking-water quality incidents were no longer publicly available as of April 2024.

Recommendations for improvements in data availability

The following list summarises some simple improvements that could be made to monitoring, reporting and public availability of data to create a more reliable State of the Basin report and help build trust with stakeholders.

Indigenous: socio-economic, health and cultural indicators for Indigenous communities in each water-resource plan area.

Environmental: (1) an archive of threats to water quality (e.g. bushfire runoff, hypoxic blackwater, low dissolved oxygen, turbidity and cyanobacterial blooms); (2) a central register of fishway and thermal pollution control construction and operation; (3) centralised data on environmental water quality; (4) a centralised database on occurrence and magnitude of fish kills; (5) improved availability of annual flood maps; (6) reinstatement of full details of Commonwealth environmental watering actions on the CEWO website, including joint actions with States.

Economic: availability of data on median income within the Basin at catchment scale. In addition, so as to assess socio-economic impacts of water recovery, information on water recovery at postcode scale, along with access to farm financial data would be valuable.

Social: centralised data on town water security and supply and domestic water-quality testing at Basin scale.

Compliance: a centralised register of breaches of water laws (including issuing of penalty notices, directions and enforceable undertakings) as well as an attempt to achieve consistent definitions and descriptions of breaches and penalties across the States.

These improvements could be achieved at a relatively little cost (compared with the price of already implemented water reforms) by improved co-ordination between Commonwealth and Basin State and Territory agencies and the mutual recognition and agency to co-ordinate monitoring and reporting activities more effectively and transparently.

Concluding remarks

This assessment is not comprehensive or complete, but it indicates poor Indigenous, environmental and social outcomes since the Basin Plan commenced in 2012–13 and beforehand. Despite A$13 billion committed to water reforms, trends of most indicators (74%) show no improvement or are worsening. Of those indicator targets that were met, five of seven were from the economic theme. Our results support the finding that 'irrigators came out of each subsequent stage of the reform process better placed than the environment' (Marshall and Alexandra 2016, p. 689).

The Basin Plan is now not due to be delivered in full until December 2027, but after more than three decades of water reform, the objectives of the underpinning policy and legislative frameworks, namely, the National Water Initiative (2004), the *Water Act* (2007) and the Murray–Darling Basin Plan (2012), are still not being translated into effective actions and benefits. Major changes will be required to governance and policy implementation, namely, what works and what does not work, for the revised version of the Basin Plan (which is due for review in 2026) if the status and trends of indicators and their associated targets are to improve.

The outcome indicators and targets presented here are broader and more ambitious than the output focus of the 2020 Basin Plan evaluation. It is important to know not just what data are lacking, but what data can best inform an adaptive management approach into the future. To expand existing monitoring and reporting into a fit-for-purpose framework for future strategic adaptive management, the intended outcomes need to be integrated with the objectives of the *Water Act*. A first step in this process would be to establish an independent assessment process to determine whether the objectives of the *Water Act* and Basin Plan are being achieved, which can then inform the 2026 review of the Basin Plan (Department of Climate Change, Energy, Environment and Water 2023*a*).

Analysis of the successes and failures of Basin water reforms requires establishing clear criteria for the effectiveness, efficiency and equity of policies, backed by high-quality data. These criteria were defined and applied using six key factors to identify policy success in a comparison of water-recovery mechanisms in the Basin (Wheeler 2024). We suggest that such an approach could be readily applied as a key part of the Basin Plan review.

Under pressures from unregulated water diversions (particularly floodplain harvesting in the Northern Basin), land-use change and global warming, Basin water reforms must be underpinned by rigorous monitoring and reporting if they are to stand any chance of delivering on intended outcomes. Historically, numerous drivers of change have negatively affected Basin wetlands and rivers to the extent that they now represent modified ecosystems (Colloff *et al.* 2015). Historical drivers such as high saline water tables, acid sulfate soils and high nutrient and sediment loads, together with additional threats and risks to water resources under climate change (Pittock *et al.* 2023) are likely to impede ecological recovery anticipated from the allocation of environmental flows. Although the effects of some drivers may be slight compared with the effects of prolonged and severe low flows, there are likely to be cumulative effects that limit the achievement of environmental objectives in the future.

This prospect underpins an issue that has not been adequately addressed in the Basin Plan process, namely, the determination of baseline ecological conditions for maintenance and restoration of flow-dependent ecosystems. Choosing an appropriate baseline is fundamental to assessment of changes that require a management intervention and for determining the difference between natural variation and regime shift (Pritchard 2022), together with the appropriate indicators. The intent of the Ramsar Convention is to describe ecological character prior to listing, along with natural variability and known past and current trends (Ramsar Convention 2012; Gell *et al*. 2016; Finlayson *et al*. 2022). However, Australian governments have interpreted ecological character as dating from the time of listing (Department of the Environment, Water, Heritage and the Arts 2009, p. 5; Gell *et al*. 2016), ignoring the fact that wetlands were already degraded by decades of river regulation and irrigation diversions. By relying only on environmental flows as a management tool, the best that can be hoped for is the maintenance of wetlands in their modified, degraded state as they were at the time of listing.

A more ambitious target for restoration of wetland ecosystem functions and biodiversity that goes beyond 'just add water' would include addressing the impacts of those drivers of ecological change other than alterations in flow regimes. Such an approach is consistent with Australia's obligations under the Kunming–Montreal global biodiversity framework (GBF) target of 30% of inland waters restored and 30% in protected areas by 2030 ('30 by 30'; United Nations Environment Programme 2022; Scientific and Technical Review Panel of the Ramsar Convention 2023). The opportunity exists in the upcoming review of the Basin Plan to address this issue and align wetland targets and policies with the GBF targets and Australia's National Biodiversity Strategy and Action Plan to meet commitments under the Convention on Biological Diversity and the Ramsar Convention on Wetlands.

Supplementary material

Supplementary material is available online.

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Data availability. Data supporting each indicator is publicly available at the Australian National University Data Commons under the title: 'Colloff *et al.* (2024) Data supporting the state of the Murray–Darling Basin report' (see https://dx.doi.org/10.25911/v2te-n739).

Conflicts of interest. Jamie Pittock, Fran Sheldon, Richard Kingsford and Brad Moggridge are members of the Wentworth Group of Concerned Scientists, Water Group. Matt Colloff, Quentin Grafton and John Williams are former members. The authors have no other conflicts of interest to declare.

Declaration of funding. The authors received no specific funding for this research.

Acknowledgements. We are grateful to staff from the Murray–Darling Basin Authority and the Office of the Commonwealth Environmental Water Holder for constructive discussions about State of the Basin monitoring and reporting and for reviewing a draft of this paper. We thank Dr Katherine Cheshire, Port Stephens Fisheries Institute, New South Wales Department of Primary Industries, for providing access to the DPI database on fish kills. Mike Ridley, Murray–Darling Basin Authority, kindly supplied water-quality threat maps for the Basin. Keith Chalmers, Victorian Environmental Water Holder, provided valuable advice on environmental watering actions and accounting. Dale Ashton, Australian Bureau of Agricultural and Resource Economics and Sciences, generously assisted with queries about the ABARES survey of irrigation farms. Finally, we thank Dr Michael Vardon, Fenner School of Environment and Society, Australian National University, for discussions and advice on environmental accounting methodology.

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