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*Marine and Freshwater Research*

**Supplementary Material**

**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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**Supplementary material**

**Details of methods and data used for each indicator**

***Indigenous theme***

*Indicator 1. Indigenous water holdings*

We used the total standardised volume of surface water entitlements held by Indigenous organisations based on 2020 data from Hartwig *et al*. (2021), and 2009 and 2018 data from Hartwig *et al*. (2020). The 2009 and 2018 data only covers the NSW part of the Basin. Therefore, we excluded all other States from the data of Hartwig *et al*. (2021) to display the temporal change in the NSW Basin (Fig. 2.1). Data for the total annual non-environmental entitlement share is from DPE (2023).

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

Data on watering actions was from CEWO annual reports for 2012-13 (DSEWPaC 2013) and 2013-14 (DoE 2014), CEWO long-term intervention monitoring (LTIM) reports from 2014-15 to 2018-19 (Gawne *et al*. 2016; 2017; Hale *et al*. 2018; 2019; 2020; Appendix 1 therein). We compiled a database of Commonwealth environmental watering actions from the LTIM reports by converting tables in the .pdf files into Excel® spreadsheets. The LTIM reports contained data on the component of the flow regime, biotic elements and ecosystem functions targeted, the volume of water released, the dates of water release and cessation of flows and the expected environmental outcomes. After 2018-19, details of watering actions were published online on the CEWO website in a section on water use in catchments and the history of watering (e.g. DCCEEW 2022). The data is less detailed than previously (e.g. volumes but no dates) and we added what was useable to the database.

We calculated the volume of water released annually by the Commonwealth Environmental Water Office (CEWO) as flooding flows, identified by the flow component categories of 'overbank' and 'wetland' in the lists of annual Commonwealth environmental watering actions to wetlands in areas represented by Indigenous Organisations. Boundaries were based on the definition of Indigenous areas that include Native Title claim areas and 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; Figs. 1 & 2 therein). We used flooding flows only as these best represent aspects of the flow regime that correspond with the Indigenous concept of cultural flows and the cultural value of water (Moggridge and Thompson 2021; Weir 2009, pp. 119–128).

We included overbank and wetland flows for wetlands in the Border Rivers, Gwydir, Namoi, Macquarie, Barwon–Darling, Warrego, Lower Darling, mid-Lachlan, mid–Murray, Goulburn–Broken, Ovens, the Victorian Lower Murray and the South Australian Lower Murray between Morgan and Murray Bridge. We also included Indigenous Protected Areas (Werai and Toogimbie) and wetlands in which there has been a history of Indigenous engagement with environmental watering (Costanza-van den Belt *et al*. 2022; Table 1 therein), including Narran Lakes, Teringie and Sugar Shack wetlands and Gayini Nimmie–Caira. We then compared the volume of flooding flows for each of these wetlands with the total volume of environmental flows released by CEWO and calculated the percentage (Fig. 2.2).

***Economic theme***

*Indicators 3 and 4. Median personal income by Basin Local Government Area*

The indicators are: (3) median personal community income; and (4) the disparity between lowest and highest incomes. We included median income for all Local Government Areas (LGAs) that have most of their area within the Basin except where major population centres of LGAs were outside the Basin boundary. We overlayed a map of LGA boundaries (ABS 2023a) with a map of the irrigation districts in the Basin (MDBA 2021a) and divided the Basin LGAs into those containing irrigation districts and those without. We used data on median personal income for LGAs from 2011-12 to 2020-21 (ABS 2023b) and compared the overall mean for irrigation LGAs ($n$ = 37) with that for non-irrigation LGAs ($n$ = 73; excluding unincorporated areas and the ACT). We converted the nominal dollar income (as published by ABS) to real dollars (i.e. adjusting for increases in the Consumer Price Index (CPI) using 2011-12 as the reference year (RBA 2021). As a measure of change in income disparity between LGAs in irrigation districts and non-irrigation LGAs, we calculated annual difference between the means of the five lowest and the five highest LGAs in each of the two categories and expressed these as the range as a measure of income disparity within and between irrigation LGAs and non-irrigation LGAs (Fig. 2.3).

*Indicator 5. Gross value of irrigated agricultural production*

Gross value of irrigated agricultural production (GVIAP) in the Basin is reported annually by the Australian Bureau of Statistics up to 2017-18, based on nominal (current) dollar values (ABS 2019), From 2018-19, GVIAP is published as part of the Water Account, Australia series, with 2019-20 as the latest release of data (ABS 2021a). Estimates of GVIAP were not included in the 2021-22 Water Account because the quality of survey responses was lower than required to produce the statistics (ABS 2023c). We reported real value from 2010-11 (the end of the Millennium Drought) to 2019-20, i.e. adjusting the figures by the CPI using 2010-11 as the reference year (RBA 2021), as well as the GVIAP for the Basin as a percentage of national GVIAP (Fig. 2.4).

*Indicator 6. Irrigation water use and production value*

We divided GVIAP, as detailed above, by the total volume of irrigation water use in the Basin (ABS 2021b) to derive GVIAP per gigalitre of irrigation water used (Fig. 2.5).

*Indicator 7. Cash income of irrigation farms*

Data on annual cash income for cotton, dairy, horticulture and rice farms (2006-07 to 2015-16) was from the ABARES survey of irrigation farms in the Murray–Darling Basin (Ashton 2020). Data on rate of return for cotton (2006-07 to 2017-18), dairy (2006-07 to 2018-19) and rice farms (2006-07 to 2018-19) was from the ABARES Murray–Darling water markets report (Goesch *et al*. 2020, Fig. therein). Data on rate of return for horticulture (2006-07 to 2015-16) is from (Ashton 2020). We compared change in cash income and rate of return of irrigation farms with the increase in volume of annual environmental water allocations to the Commonwealth Environmental Water Holder (CEWO 2024).

*Indicator 8. Farmland price*

Data on annual mean broadacre farmland price ($AU per hectare) for the period 2006-07 to 2022-23 was from ABARES (2024a). We used the mean price for those ABARES regions contained within, or partly within, the Murray–Darling Basin (ABARES 2024b; 121, New South Wales North West Slopes and Plains; 122, New South Wales Central West; 123, New South Wales Riverina; 221, Victorian Mallee; 222, Victorian Wimmera; 223, Victorian Central North; 321, Queensland Eastern Darling Downs; 322, Queensland Darling Downs and Central Highlands and 422, South Australian Murray Lands and Yorke Peninsula), compared with the national mean (Fig. 2.6).

*Indicator 9. Surface water take*

Data on annual metered and estimated surface water take for the period 2012-13 to 2021-22 was from the MDBA 2021-22 annual water take report 2021-22 (MDBA 2023a; Table 3.1 therein). The data represents the sum of surface water take for consumptive purposes from regulated rivers, watercourse (unregulated), from floodplain harvesting, under basic rights, by commercial plantations and by runoff dams (e.g. (MDBA 2023a; Table 3.2 therein). Data from 1999-00 to 2011-12 was from MDBA (2016; Table 2 and Appendix C therein) (Fig. 2.6).

***Environmental theme***

*Indicator 10. Ramsar wetlands – flooding*

Extent of flooding of Ramsar wetlands was determined using remote sensing data obtained from the Centre for Water and Landscape Dynamics, ANU (CWLD 2023). We used the Environmental Explorer function (https://www.wenfo.org/aex) to access data on the percentage extent of floods in Ramsar wetlands from 2000-2023. We selected five major wetlands that receive managed environmental flows: combined data for the adjacent Barmah Forest and Millewa Forest (the latter is part of the NSW Central Murray Forests Ramsar Site), Gunbower Forest, Riverland, Narran Lakes and Macquarie Marshes). Data was not available for Gwydir Wetlands. Areas of Ramsar wetlands are provided in the Ramsar Information Sheets (RISs) for each wetland. We plotted flood extent for each wetland, as well as the years in which drought or flood occurred (Fig. 2.8). We calculated change in flood extent between 2012 (the first year of implementation of the Basin Plan) and 2023, derived from the linear regression equation for the line of best fit.

*Indicator 11. Ramsar wetlands – vegetation condition*

Leaf area index (LAI) was used as an indicator of vegetation condition at Ramsar wetlands using remote sensing data obtained from the Centre for Water and Landscape Dynamics, Australian National University (CWLD 2023). We used the Environmental Explorer function (https://www.wenfo.org/aex) to access data on the LAI, at the same Ramsar wetlands as for Indicator 8, from 2000-2023. Because the LAI plots for the five wetlands are variable but show no apparent trend (Fig. 2.9a), to obtain an estimate of frequency of high and low LAI, indicating improvement or decline in vegetation condition, we compared the number of years during which LAI was more than one standard deviation greater or lesser than the long-term mean, both before the Basin Plan was implemented (2000-2011) and after (2012-2023) (Fig. 2.9b).

*Indicator 12. River flows*

The data represents the percentage difference between observed flows, measured at 27 hydrological indicator sites throughout the Basin, compared with expected flows at the same sites(gigalitres per year), modelled under the Basin Plan. The data covers the seven-year period 2012-13 to 2018-19 (Wentworth Group 2020, Table 2 therein) (Fig. 2.7).

*Indicator 13. Waterbirds*

The data for the Basin on abundance and number of breeding species is from the annual Eastern Australian Waterbird Survey (Kingsford *et al*. 2020; Porter *et al*. 2020) and its associated database (https://www.unsw.edu.au/research/ecosystem/our-research/rivers-and-wetlands/eastern-australian-waterbird-survey) (Fig. 2.10).

*Indicator 14. Threatened species*

We used data on the annual frequency of occurrence of five of the eight species selected by Ryan *et al*. (2021) 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*. We did not include Sloane's froglet *Crinia sloanei*, Murray hardyhead *Craterocephalus fluviatilis* or flathead galaxias *Galaxias rostratus* because these species have highly restricted ranges and there are very few records added annually to the relevant databases.

Annual frequency of occurrence (2012-2023) was derived from records from the Atlas of Living Australia (ALA 2024), which incorporates data from the Victorian Biodiversity Atlas (DELWP 2024) and the New South Wales BioNet Atlas (DPIE 2024a). We downloaded records for each species, removed those from outside the Basin and used the annual number of records for each species as a measure of frequency of occurrence. We corrected for sampling bias, i.e. where multiple records were made for the same sampling event (e.g. on the same day) at the same location and by the same observer, they were counted as a single record. To show a comparative range for each species on the graph, occurrence data was transformed using $\log_e(n + 1)$ (Fig. 2.11).

*Indicator 15. Fish kills*

We compiled data on fish kills between 1980 and 2023 within the NSW Basin using data obtained from the NSW Department of Primary Industries fish kill database, which covers the period 1929-2019. Data for the NSW Basin since 2019 was published online until March 2023 but is now restricted to the 2023-24 water year (DPIE 2024b). Basin-wide data on events between 1975 and 2019 was collated in the report of the Australian Academy of Science into the 2018–19 fish kills at Menindee but is incomplete (AAS 2019). We used four categories of magnitude, based on the estimated number of fishes killed: 1,000-10,000; 10,000-100,000; 100,000-1,000,000 and >1,000,000 (Fig. 2.12).

*Indicators 16 and 17. Salinity*

The indicators are: (16) electrical conductivity of River Murray waters and (17) mean annual discharge of salt from the Murray Mouth. Data are from MDBA reports on Basin salinity management targets (2010-11 to 2021-22) (e.g. MDBA 2022a). The data for Indicator 13a represents the percentage of days where electrical conductivity (EC) of river water was above the target electrical conductivity (EC) values (in $\mu S\ cm^{-1}$) for 95% of the time at five indicator sites (River Murray at Murray Bridge: 830 $\mu S\ cm^{-1}$; River Murray at Morgan: 800; River Murray at Lock 6: 580; Darling River at Burtundy: 830 and Lower Lakes at Milang: 1,000; between 2009-10 and 2021-22, based on five-year rolling averages) (Fig. 2.13a). Indicator 13b represents the discharge of salt over the Lower Lakes barrages to the Coorong and Murray mouth, which was reported annually up until 2018-19 (MDBA 2020a) but subsequently as three-year rolling averages (MDBA 2021b; 2022) (Fig. 2.13b).

*Indicator 18. Nutrient pollution*

We used data on total Kjeldahl nitrogen (TKN) and total phosphorus (P) concentrations measured at three sites representing the upper, central and lower River Murray (Kiewa River at Bandiana, River Murray at Swan Hill and River Murray at Morgan, respectively), collected as part of the River Murray Water Quality Monitoring Program (MDBA 2021c). Weekly data (2000-01 to 2012-13) and monthly data (2013-14 to 2022-23) for the Kiewa River at Bandiana (site no. 402205) and weekly data for the River Murray at Swan Hill (site no. 409204) was downloaded from the Victorian Government Department of Environment, Land, Water and Planning (DELWP) water monitoring website (https://data.water.vic.gov.au/). Weekly data (2000-01 to 2021-22) for the River Murray at Morgan (site no A4260554) was supplied by the MDBA. We assessed whether nutrient concentrations were above or below water quality target values (defined as annual medians) as detailed in Schedule 11 of the Basin Plan (Commonwealth of Australia, 2012), using values for streams and rivers and names and abbreviations for Target Application Zones therein: Bandiana (A6 Kiewa, lowland): TKN 0.29 $mg\ L^{-1}$; P 0.03 $mg\ L^{-1}$; Swan Hill (cM1 Central Murray, lower): TKN 0.7 $mg\ L^{-1}$; P 0.08 $mg\ L^{-1}$; Morgan (1M Lower Murray): TKN 1 $mg\ L^{-1}$; P 0.1 $mg\ L^{-1}$. We then assessed the proportion of time these standards were exceeded at each site. Indicator 14a is for time exceeded for TKN concentration (Fig. 2.14a), Indicator 14b is for time exceeded for total P (Fig. 2.14b).

*Indicator 19. Cold water pollution*

To assess the effects of mitigation of cold water pollution we compared monthly means of water temperature (2012-13 to 2022-23), recorded as daily means, at the nearest river gauges upstream and downstream of major dams (>350 GL capacity) in the NSW Murray–Darling Basin (Table S1). Temperature data was sourced from river gauge data reported by BoM (2024). We calculated the mean monthly difference between upstream and downstream temperature (upstream minus downstream; a positive value indicating downstream is colder and a negative value it is warmer) at dams fitted with cold water pollution mitigation infrastructure and with operating protocols in place (Burrendong, Windamere) and those without (Hume, Keepit, Wyangala), including one with infrastructure but no operating protocol (Burrinjuck) (Fig. 2.15a). We then calculated the mean upstream-downstream difference for the summer months (December-February) for each water year from 2012-13 to 2022-23 (Fig. 2.15b).

*Indicator 20. Fish populations*

We used relative abundance data of Murray cod and golden perch, derived from the graphs published by Crook *et al.* (2023; Fig. 2 therein), which are based on data from the New South Wales Department of Primary Industries (NSW DPI) Fisheries Freshwater Ecosystem database for catchments in the NSW Murray–Darling Basin. We generated raw mean relative abundance data in Excel® format for each species for each year (1994-2022) by digitising each graph using GetData Graph Digitiser (version 2.26) software (cf. Informer Technologies Inc., https://getdata-graph-digitizer.software.informer.com/) (Fig. 2.16).

*Indicator 21. Murray Mouth*

Estimation of the number of days the Murray Mouth is open is based on the diurnal tide ratio (DTR): the ratio of tidal energy between Goolwa Barrage and Victor Harbor (DEW 2018). A ratio of 0.3 indicates the mouth is functionally open, allowing flow to the ocean and the flushing of salt, whereas a ration of 0.2 indicates the mouth is constricted by sand deposition from the ocean and requires dredging. We used the proportion of each year in which dredging was undertaken, from 2002-03 to 2018-19 (regardless of whether one or two dredgers were in operation), the proportion of time the mouth was open and discharge from the barrages, using data from DEW (2019, p. 38). We digitised each graph using GetData Graph Digitiser (version 2.26) software (cf. Indicator 16 above) (Fig. 2.17).

***Social theme***

*Indicators 22 and 23. Town water security*

The indicators are: (22) the number of days of water restrictions and (23) the number of drinking water quality incidents (e.g. boil water alerts). We used the number of days per year in which restrictions on domestic water use were in place for LGAs in the NSW Murray–Darling Basin (DPIE 2024). Between 2013-14 and 2019-20, 39 LGAs in the NSW Basin had water restrictions in place for some of the time and 17 did not. We ranked LGAs with restrictions according to average number of days over the period of record, from most to least and calculated the decile values of the range as a basis to select ten LGAs (Bourke, Carrathool, Central Darling, Dubbo, Gwydir, Lachlan, Liverpool Plains, Walgett, Warren and Yass Valley). We then calculated the mean number of days per year water restrictions were in place for these ten LGAs (Fig. 2.18).

*Indicator 24. Water quality threats*

Data for total number of threats in the Basin were compiled from threats of cyanobacterial (blue-green algal) blooms, low dissolved oxygen, hypoxic blackwater and high turbidity. We only included events considered likely and almost certain (excluding those deemed only possible: all bushfire contamination and elevated salinity threats) (Fig. 2.19). The data was derived from water quality threats maps published by MDBA, commencing in October 2020 (for example, MDBA, 2023b). The maps are produced approximately monthly between the warmer November-April period and less frequently during the cooler May-October period. The maps were obtained on request from the MDBA but are not archived by MDBA publicly. The Wayback Machine (https://archive.org/) can be used to locate what was publicly available at the time. We collated the data into seasonal numbers of likely and almost certain threats. Because the data were incomplete, we divided the total of likely and almost certain threats by the number of months-worth of data in each season to obtain a crude seasonal mean.

***Compliance and enforcement theme***

*Indicators 25 and 26. Sustainable Diversion Limits*

The indicators are: (25) compliance of Sustainable Diversion Limits (SDLs) for each surface water resource unit in the Basin and (26) the adjusted cumulative balance for each surface water resource unit. came into effect in July 2019. We used data from the annual registers of take of surface waters from the 27 SDL resource units for the years 2019-20, 2020-21 and 2012-22 (MDBA 2021d, 2023c) and 2019-20 and 2020-21). The registers report annual permitted take (APT), which is 'an annualised expression of the SDL volume' and is 'based on the management rules and assumptions about water user behaviour given the climate conditions in the 2021–22 water year. The annual permitted take (APT) should be less than or equal to the long-term average SDL.' (MDBA 2023c, p. 9). Subtracting the annual actual take (AAT) from the APT gives the annual balance. AAT is based on metered or estimated volumes measured by the Basin States and Territory. The annual balance, as a credit or debit, is then used to derive the cumulative balance over time, whereby credits and debits are added to those from previous years, with opening and closing balances for each water year. The cumulative balance is then adjusted to account for acquisition and use of held environmental water or its incomplete recovery in some resource units (MDBA 2023c, pp. 11–12). We used the adjusted cumulative balance (ACB) at the end of each of the three water years for each surface water SDL resource unit, expressed as a proportion of the long-term average SDL. Increases in the ACB over time indicate a reduction in take and the ACB is moving away from the SDL, while decreases indicate take is increasing and is moving towards the SDL (Fig. 2.20). Because change in ACB as a proportion of the SDL may be non-linear (e.g. with a decrease in 2020-21 relative to 2019-20 and then an increase in 2021-22), we calculated the mean trajectory of change from the line of best fit for the three years in order to assess which SDL resource units had increases in take and were moving towards the SDL.

*Indicator 27. Breaches of water laws*

Data on court cases for breaches of water laws is held in databases of case law (e.g. NSW Caselaw 2023; AUSTLI 2024). However, some of these databases cannot be searched for specific offences (NSW caselaw is an exception). Data on enforcement actions is held by various State government agencies (e.g. NSW Ombudsman 2017) but typically cannot be dis-aggregated by offences committed within the Murray–Darling Basin. The exception is the Public Register of the New South Wales Natural Resources Access Regulator (NRAR 2024), which reports breaches by LGA for penalty notices, directions issued, enforcible undertakings entered into and prosecutions for offences under the *Water Management Act* 2000 (NSW), from the establishment of the NRAR in 2018. We downloaded the Public Register and sorted records by LGA, from 2018-19 to 2022-23, according to whether they were located in the northern or southern Basin. We also used data in the Public Register on successful prosecutions, cross-checked against annual NRAR progress reports (e.g. NRAR 2023) (Fig. 2.21).

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Table S1. Indicator 18, cold water pollution. Details of dams in the New South Wales Murray–Darling Basin with and without thermal pollution control devices (TPCDs) fitted and operating protocols implemented. Dams highlighted in grey have insufficient upstream and downstream water temperature data available to conduct an assessment. Dams with names in bold were included in the analysis. Cold water pollution risk is from DPI (2021)

| Storage | Capacity (GL) | CWP risk | Operating protocol? | Type of CWP mitigation infrastructure | Downstream river gauge | Upstream river gauge | Temperature data available U/S & D/S? | Notes |
|---|---|---|---|---|---|---|---|---|
| Blowering | 1,628 | High | N/A | None | Tumut River at Oddys Bridge 410073 | N/A | No | No appropriate upstream gauge. Not included in analysis |
| **Burrendong** | 1,188 | High | Yes | Cold-water curtain, operating since May 2014 | Macquarie River D/S Burrendong Dam 421040 | Cudgegong River at Yamble Bridge 421019 | Yes | Assumed yes to operating protocols as cold-water curtain specifically installed to address CWP (cf. Gray *et al.* 2019)s |
| **Burrinjuck** | 1,028 | High | No | Bi-level outlet and gate | Murrumbidgee River D/S Burrinjuck Dam 410008 | Yass River U/S Burrinjuck Dam (Riverview) 410176 | Yes | Operating protocol yet to be developed & implemented by WaterNSW. Used in analysis |
| Copeton | 1,364 | High | N/A | None | N/A | Gwydir River at Bundarra 418008 | No | No appropriate downstream gauge. Not included in analysis |
| **Hume** | 3,005 | High | N/A | None | Murray River D/S Hume Dam (Heywoods) 409016 | River Murray at Jingellic 401201 | Yes | U/S data from 2014 only for Mitta Mitta River at Tallandoon 401204. Data for River Murray at Jingellic 401201 used instead |
| Jindabyne | 690 | Medium | Yes | Variable level offtake, installed 2006 | Snowy River D/S Mowamba River Junction 222021 | N/A | No | Operating conditions incorporated into Snowy Water Licence in 2010. No appropriate upstream gauge. Not included in analysis |
| **Keepit** | 426 | High | No | Multi-level outlet | Namoi river at D/S Keepit Dam 419007 | Namoi River at Manilla Railway Bridge 419022 | Partly | Operating protocol yet to be developed and implemented by Water NSW. D/S temperature data available only from 2015 |
| Split Rock | 397 | Low | Yes | Multi-level outlet | Manilla River D/S Split Rock Dam 419043 | N/A | No | Missing temperature data for 2015-2018 and 2020-2021. No appropriate upstream gauge. Not included in analysis |
| Talbingo | 921 | Low | N/A | None | N/A | N/A | No | Releases enter Blowering reservoir, so no CWP mitigation of a natural downstream river channel. Also, no appropriate gauges. Not included in analysis |
| **Windamere** | 368 | Low | Yes | Multi-level outlet, destratification | Cudgegong River D/S Windamere Dam 421079 | Cudgegong River U/S Rylstone 421184 | Yes | Data gap for nearest upstream gauge 2015-2017: Cudgegong River at Moonbucca 42110040. Cudgegong River U/S Rylstone 421184 used instead |
| **Wyangala** | 1,217 | High | N/A | None | Lachlan River D/S Wyangala Dam 412067 | Lachlan River at Reids Flat 412027 | Yes | |