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Repairing Australia's inland river and groundwater systems: nine priority actions, benefits and the finance gap

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ABSTRACT

Inland river and groundwater systems in Australia, as elsewhere, have been heavily overexploited, modified and degraded and are subject to increasing pressures from anthropogenic activities and climate change. Here, we propose the following nine priority actions to repair these critical parts of our landscape not currently being implemented or not at a sufficient scale: (1) riparian revegetation, (2) incentivisation to retire riparian farmland, (3) water recovery to achieve sustainable levels of take in the Murray–Darling Basin, (4) restoration of riverine connectivity through constraints management, (5) removal or modification of fish barriers, (6) installation of cold-water pollution device on priority large dams, (7) installation of fish diversion screens on all irrigation pumps, (8) capping of open bores and conversion of open bore-drains remaining in the Great Artesian Basin and (9) restoration of groundwater extraction in the Murray–Darling Basin to a sustainable level of take. We estimate the scale and costs associated with each priority action and synthesise evidence demonstrating benefits. We discuss the importance of enabling and supporting regional communities, especially Indigenous nations, to implement these actions. To implement the priority actions outlined here at the scale indicated, our estimates suggest approximate annual investment from 2025 to 2054 of A$3.1 billion (2022 dollar values). Riparian revegetation across 14.4×10^6 ha could sequester 1.6×10^9 tonnes of CO_2, offsetting ~37% of Australia's net emissions over the next 30 years by using high-integrity carbon methods. Revenue generated through the carbon market could cover between 37 and 72% of the costs, reducing investment needed to between A$0.9 billion and A$2.0 billion (2022 dollar values).

Keywords: environmental flows, fish passage, flow constraints, groundwater, in-stream barriers, nature repair, restoration, riparian, water resources management.

Introduction

Inland waters globally are subject to mounting pressures from human population growth, agriculture, industry, urban development and anthropogenic climate change. Exploitation of water resources from surface and groundwater systems, with associated ecological and socioeconomic consequences, has led to water management consistently ranking as one of the world's foremost sustainability challenges (Bunsen *et al.* 2021), with reported planetary boundaries for sustainable use of both surface and groundwaters having now been exceeded (Richardson *et al.* 2023). At the same time, global freshwater biodiversity is declining at a rapid pace, outstripping that observed for terrestrial or marine species while also often being neglected by policy and broader conservation strategies (Reid *et al.* 2019). There is an undisputed and urgent need to repair our freshwater ecosystems.

In Australia, as elsewhere, exploitation of inland surface waters and the associated modification of freshwater systems, including disruptions to longitudinal and lateral connectivity through physical structures and clearing of vegetated riparian zones and catchments, has led to widespread degradation of river systems (Feio *et al.* 2021). Groundwater resources have also been increasingly developed in recent decades and face growing pressures from agriculture and mining, which are exacerbated by climate change (Barnett *et al.* 2020). Although a significant program of water reform has occurred in Australia since late last century (Crase et al. 2020), this is considered to have stalled in recent years in key areas such as groundwater management (Barnett et al. 2020) and, more broadly, beyond the Murray–Darling Basin.

In short, key actions needed to address current pressures and repair past damage are not currently being implemented, either at all or at a sufficient scale to facilitate nature repair. Further, Indigenous nations have been extensively dispossessed of their land and water resources since British occupation of Australia, demonstrated by the extremely low proportion, <0.2% in volume, of issued surface-water entitlements held by Indigenous owners (Hartwig et al. 2020). Throughout the 2021 National State of the Environment Report (Cresswell et al. 2021), Indigenous people identified ways in which control and ownership of water, for example cultural flows, are needed to improve their environmental, cultural and socio-economic outcomes. Indigenous people, and their knowledge of their respective Country, is an important source of information to identify the condition of inland river and groundwater systems and to inform the measures needed and opportunities for their repair (Moggridge and Thompson 2024). Repairing inland water ecosystems through Indigenous research methodologies offers ways to move beyond government policy rhetoric to contribute to improving water justice for Indigenous Australians (Moggridge et al. 2022).

Inland waterways cannot be restored without significant investment. Here, we propose and cost a suite of priority actions required to repair Australia's inland waters, including both river and groundwater systems. We consider 'inland river systems' to encompass all freshwater ecosystems beyond those coastal systems subject to tidal influences. While all efforts have been made to conduct this assessment at a national scale, data availability has constrained the assessment of some actions to particular priority regions, especially the Murray–Darling Basin and Great Artesian Basin. In some cases, this may reflect lower levels of degradation beyond these regions and a need for nature protection rather than repair. However, in others, these geographic gaps indicate the need for more comprehensive data regarding the condition of, and threats to, inland waters.

These actions address key threats of habitat degradation and water resource exploitation (Reid et al. 2019), and align with recommendations presented in The Emergency Recovery Plan for global freshwater biodiversity, including enhanced delivery of environmental flows, protection and restoration of critical habitats, improved management of the exploitation of freshwater ecosystem resources, and safeguarding and restoring river connectivity (Lynch et al. 2023). The actions presented here are not assumed to be comprehensive but are rather intended as an indicative estimate of what could be achieved at scale with concerted effort and investment. We seek to demonstrate the feasibility of embarking on a more ambitious national program of water reform and nature repair for our inland rivers. This will build on what we have already achieved and promote the resilience of our freshwater ecosystems and water resources into the future.

Although beyond the scope of the current exercise, we recognise that to implement such a program would require significant design and governance considerations, including the role of different levels of government and the private sector. Importantly, repairing inland water ecosystems must involve substantial funding and support to Indigenous organisations to implement on-ground measures, particularly those of cultural significance. This would include procurement processes to contract Indigenous businesses and expansion of river ranger programs, as well as restitution of rights to own and manage water resources. Governance should be a key consideration in further design of the water reform program proposed here.

Approach

Here, we propose nine practical, priority actions for repairing the health of Australian inland waters (Table 1) that address key threats and align with recommended global actions for emergency recovery of freshwater systems in the Anthropocene (Lynch et al. 2023). Proposed actions have been selected to complement existing water reform and freshwater ecosystem management, with a focus on repairing key functions and services rather than attempting to return freshwater ecosystems to historical states. Actions solely involving substantial regulatory or governance changes, or those associated with high levels of uncertainty, have been excluded.

We estimated the scale and cost of proposed actions by using data from a range of available sources (Table 1). We determined an appropriate starting year, duration and sequence for each action within a 30-year timeframe (2025–55). We estimated both new capital expenditure requirements and operational investment needs (e.g. for maintenance, monitoring) over this period, with costs converted to Australian dollars for 2022 (2022 dollar values) on the basis of actual averaged inflation rates published by the Reserve Bank of Australia (2023). Annual costs over 30 years account for different start dates and tenures of actions. To account for the time value of money, we used a discount rate of 5% year^{-1} and an inflation rate of 2.5% year^{-1}, in line with the Australian Government's Intergenerational Report 2023, Department of Finance Factsheet 30 June 2023 and the Reserve Bank of Australia's longer-term projection of inflation (Australian Department of Finance 2023; Australian Government 2023; Reserve Bank of Australia 2023). Transaction costs, including legal costs associated with transfer of land tenure, regulatory compliance, information collection and opportunity costs associated with these activities etc., are assumed to be an average of 10% of upfront capital expenditure for each action.

This study was conducted as part of a broader exercise undertaken by the Wentworth Group of Concerned Scientists

Table 1. Scale and estimated costs of priority actions for repairing inland river and groundwater systems in Australia.

Action	Scale and extent	Cost estimations	Cost (total in bold)	Annual cost over 30 years (2022$)
Capital expenditure				
1. Riparian revegetation	Major rivers = 2,600,188 ha of riparian (100 m wide) buffers	Average cost per hectare (2022$) = $5909	A$15,364,916,272 (2022$)	**A$2,117,240,820**
	Minor rivers and streams = +10,621,957 ha of (50 m wide) buffers	Average cost per hectare (2022$) = $6411	A$68,097,440,671 (2022$)	
	Lakes = +1,205,792 ha of riparian (200 m wide) buffers	Average cost per hectare (2022$) = $5673	A$6,840,172,988 (2022$)	
			A$90,302,529,931 (2022$)	
2. Incentivise land holders to retire riparian farmland	As above	Opportunity costs for major rivers	A$3,362,823,419 (2022$)	**A$324,132,805**
		Opportunity costs for minor rivers	A$14,339,697,142 (2022$)	
		Opportunity costs for lakes	A$1,483,973,222 (2022$)	
			A$19,186,493,782 (2022$)	
3. Restore overallocated river systems of the Murray–Darling Basin to sustainable levels of take	Water recovery required to achieve science-based target = 726,000 ML $year^{-1}$	Cost per megalitre (2017$) = A$5100	A$3,702,600,000 (2022$)	**A$104,289,013**
			A$4,239,477,000 (2022$)	
4. Restore lateral connectivity between rivers and their floodplains and wetlands through constraints management	Five major projects	Total cost of five projects (2020$) = A$864,000,000 (Kahan *et al.* 2021)	A$664,000,000 (2020$)	**A$22,848,169**
		Subtract $200,000,000 committed by the Australian Government	**A$727,744,000 (2022$)**	
5. Restore longitudinal connectivity, fish passage, by removing or modifying high priority fish passages	Number of priority barriers = 2000	Mean cost per barrier for 95% of barriers (202$) = A$150,000	A$285,000,000 (2022$)	**A$107,818,575**
		Mean cost per barrier for 5% of barriers (2022$) = A$2,000,000	A$200,000,000 (2022$)	
			Subtract A$56.8 × 10^6 committed under Fish for the Future	
			A$428,200,000 (2022$)	
	Combined height of high-level large dams obstructing fish passage = 2790	Cost per metre (2016$) – A$1,000,000	A$2,790,000,000 (2016$)	
			A$3,255,930,000 (2022$)	
6. Install cold water pollution devices on priority large dams	Number of priority dams = 75	Cost per dam (2020$) = A$8,500,000	A$637,500,000 (2020$)	**A$20,447,932**
			A$698,700,000 (2022$)	
7. Install fish diversion screening on all licensed irrigation pumps	Number of irrigation pumps = 11,418	Cost per pump (2022$) = A$187,000	A$2,135,166,000 (2022$)	**A$61,331,094**
			Subtract A$39.5 × 10^6 committed under Fish for the Future	
			A$2,095,666,000 (2022$)	

(*Continued on next page*)

Table 1. (*Continued*).

Action	Scale and extent	Cost estimations	Cost (total in bold)	Annual cost over 30 years (2022$)
8. Cap remaining open artesian bores and covert open bore-drains to pipe and trough systems in the Great Artesian Basin	Number of uncapped bores in GAB = 331	Cost per bore (2018$) = A$346,529	A$114,701,099 (2018$)	**A$4,493,072**
			A$128,924,035 (2022$)	
	Length of open bore-drains in GAB = 4560 km	Cost per kilometre (2018$) = A$8485	A$38,691,600 (2018$)	
			A$43,489,358 (2022$)	
			Subtract A$27.6 × 10^6 funding	
			A$144,813.394 (2022$)	
9. Restore groundwater extraction of the Murray–Darling Basin to sustainable levels of take	Water recovery required to achieve target = 3250 ML year^{-1}	Cost per megalitre (2018$) = A$1907	A$6,197,425 (2018$)	**A$216,129**
			A$6,965,906 (2022$)	
Subtotal			**A$121,086,520,012**	**A$2,762,817,606**
Transaction costs			**A$12,108,652,001**	**A$276,281,761**
Total capital expenditure			**A$133,195,172,014**	**A$3,039,099,367**
Operational costs (per year)				
1. Maintenance of riparian plantings	Extent of new riparian plantings along major rivers annually for 30 years = 86,673 ha	Average cost per hectare (2013$) = A$5	A$407,363 (2013$)	**A$26,811,594**
	A$501,056 (2022$)			
	Extent of new riparian plantings along minor rivers and streams annually for 30 years = 354,065 ha		A$1,664,107 (2013$)	
			A$2,046,851 (2022$)	
	Extent of new riparian plantings around lakes annually for 30 years = 40,193 ha		A$188,907 (2013$)	
			A$232,356 (2022$)	
			Total cost in year 1 = A$2,780,263 (2022$)	
2. Maintenance of fishways		1% of capital expenditure	**A$4,282,000 (2022$)**	**A$3,011,884**
3. Maintenance of cold water pollution devices		2% of capital expenditure	**A$12,750,000 (2022$)**	**A$8,968,128**
4. Maintenance of fish diversion screens		2% of capital expenditure	**A$47,110,572 (2022$)**	**A$33,136,754**
5. Maintenance of cap and bore system		2% of capital expenditure	**A$3,255,405 (2022$)**	**A$2,289,795**
Total operational expenditure			**A$70,178,240**	**A$74,218,155**
Total expenditure (2022$)			**A$133,265,350,254**	**A$3,113,317,522**

Total costs were converted to Australian dollars for the calendar year (e.g. 2022 dollar values are denoted as 2022$) on the basis of actual averaged inflation rates published by the Reserve Bank of Australia (2023). Actions have different start dates and tenures. To account for the time value of money, we used a discount rate of 5% year^{-1} and an inflation rate of 2.5% year^{-1}, in line with the Australian Government's Intergenerational Report 2023, Department of Finance Factsheet 30 June 2023 and the Reserve Bank of Australia's longer-term projection of inflation (Australian Department of Finance 2023; Australian Government 2023; Reserve Bank of Australia 2023). Totals in the Cost and Annual cost over 30 years columns are given in bold for each action. See the Supplementary material for full calculations. GAB, Great Artesian Basin.

to develop a Blueprint to Repair Australia's Landscapes (Wentworth Group of Concerned Scientists 2024). Since publication of this report, we have used updated data and refined the methodology for several actions, especially riparian revegetation, and revised estimated costs accordingly.

Priority actions

Action 1. Riparian revegetation

Revegetation of degraded and cleared riparian zones is widely recognised as a critical action for restoring river and catchment health, with significant benefits for biodiversity and people owing to the many essential ecological functions and ecosystem services provided (Mohan *et al.* 2022). Riparian vegetation conservation and restoration is also a priority for effective climate-change adaptation, for example, by shading and cooling aquatic ecosystems, providing corridors for wildlife movement, and acting as a buffer to both terrestrial and aquatic systems from a range of extreme events (Capon *et al.* 2013). It also contributes significant habitat to rivers and streams, for example, contribution of large wood or 'snags', supports important cultural values, for example, remnant sacred living trees, and regulates carbon inputs which are essential for the effective functioning of river systems.

To cost riparian revegetation requirements at a national scale, we generated a continental riparian buffer-zone layer by using Geoscience Australia watercourse data (Crossman and Li 2015) with an Australian Albers Geocentric Datum of Australia 2020 projection. We assumed a 100-m-wide buffer zone for watercourses classified as major rivers, 50 m for the additional zone of minor rivers, and 200 m for the additional zone of lakes, based on suggested widths provided in Hansen *et al.* (2010). In each case, only that area additional to the previously calculated buffer area was included to avoid double counting.

Following Mappin *et al.* (2022), we then used the Vegetation Assets, States and Transitions (VAST) dataset (Thackway and Lesslie 2006; Lesslie *et al.* 2010), to determine the area within these buffer zones assigned to a range of condition and land-use categories. The VAST framework provides a continental classification, at 1-km^2 resolution, of land types in relation to their degree of modification from a pre-European state on the basis of vegetation cover and land use. VAST Category 2, for example, encompasses modified areas with native vegetation communities that have been subject to minimal use or production from relatively natural environments, such as timber harvesting or grazing, whereas VAST Category 3 pertains to areas that have been transformed by land uses, for example, through significant tree thinning for pasture production, but still maintain native vegetation communities with the capacity to regenerate (Lesslie *et al.* 2010). Areas assigned to VAST Category 5 are those where native vegetation has been cleared and replaced with cultivated vegetation. VAST 0 (residual bare), 1 (residual) and 2 (modified) are considered to be in good ecological condition and thus not requiring significant revegetation efforts. We assume that VAST 3 (transformed), 4 (largely replaced and degraded) and 5 (replaced – managed) can be restored, whereas areas classified as VAST 6 (replaced with human-made structures) are considered to be unrestorable.

The ABARES National Land Use Mapping (NLUM) raster dataset, at 250 m, identifies secondary thematic land uses across agricultural and non-agricultural lands for 2015–16. Costs per hectare (ha) were estimated based on a hypothetical large-scale (1000 ha) revegetation project on an abandoned post-agricultural site, by using a density of 2000 native plants per hectare, including 30 species of groundcover, shrub and trees (Andres *et al.* 2024). We assumed that cleared riparian areas (VAST Category 5) would require active revegetation to be repaired to a good, albeit modified, ecological condition (VAST Category 2). For cleared riparian areas in cropping, forestry, mining and conservation land (NLUM Categories 1.1, 1.2, 1.3, 2.2, 3.1, 3.3, 3.4, 3.5, 4.1, 4.3, 4.4, 4.5, 5.1, 5.8, 6.3, 6.5), we assumed a mean cost for active revegetation of A\$5787 ha^{-1} (values were converted to 2022 Australian dollar values) for tube stock, labour and travel (costs supplied by S. Andres from Andres *et al.* 2024). On grazing land (NLUM Categories 2.1, 3.2, 4.2, 5.2), we assumed such active restoration would cost twice this amount, an average of A\$11,574 ha^{-1} (2022 dollar value), including costs of tube stock, labour, travel, fencing and provision of off-site watering points for livestock. For degraded areas (VAST 3), we assumed, on the basis of recent studies (e.g. Zivec *et al.* 2023), that passive revegetation would be sufficient to achieve a VAST Category 2, estimating costs to be half of those for active restoration for each land-use category. Riparian lands in residential, industrial or infrastructure areas were excluded. On the basis of the method used, the mean cost per hectare of repairing riparian buffer zones across Australia was A\$5909 for major rivers, A\$6411 for minor rivers and A\$5673 for lakes (2022 dollar values; Table 1).

While we recognise that streambank engineering works may also be required in some instances, costing these was beyond the scope of this assessment. However, we did consider ongoing operational costs associated with maintenance and monitoring, including replacing tube stock where initial plantings do not survive (Table 1). We assumed a cost of A\$4.7 ha^{-1} (2018 dollar value) to manage native vegetation plantings for weeds, pests, flooding, and fire on the basis of the annual marginal per-hectare cost spent by Australian Wildlife Conservancy (2016), Bush Heritage Australia (2016), the NSW and Queensland governments (as reported by Adams *et al.* 2011), and other State Governments, as reported by the Legislative Council of Tasmania (2012), for non-riparian native vegetation. We further assumed, as per Mappin *et al.* (2022), that revegetation actions would be understaken over a 30-year period, meaning that the area requiring management and monitoring will grow accordingly over this timeframe (refer to the Supplementary material for calculations).

We estimated the portion of costs that could be potentially financed through carbon markets, such as the Australian carbon credit scheme. We calculated carbon sequestration potential by using revised estimates of maximum potential biomass (MaxBio) across Australia (Roxburgh *et al.* 2019). MaxBio, a 250-m spatial raster dataset, represented the conservative maximum upper limit to above-ground biomass accumulation for any location attainable from native vegetation that has achieved a stable, mature state of growth. Areas designated within the protected-area estate, defined as '1.1 Nature Conservation' in the Australian Land Use and Management Classification Version 8 (2015–16) dataset (Australian Bureau of Agricultural and Resource Economics and Sciences 2024), were removed from our revenue calculations as these areas are currently not eligible with respect to delivering Australia Carbon Credit Units under the *Carbon Credits* (*Carbon Farming Initiative*) *Act* 2011.

The MaxBio layer was converted to vectors, then values were multiplied by area of each polygon in the riparian buffer zones. Values were summed to derive dry-matter tonnes of carbon for major rivers, minor rivers and lakes, by VAST and NLUM classes. Values were halved under the assumption that 50% of the dry biomass is elemental carbon, the same value applied in the 'Carbon Farming Initiative – Reforestation and Afforestation 2.0 Methodology Determination 2015' (Federal Register of Legislation 2015). We assumed that the passive restoration areas had 25% less potential carbon sequestration than the value identified by MaxBio, owing to the assumption that 25% native vegetation already exists in those areas, as per Mappin *et al.* (2022). Values of elemental carbon were multiplied by 3.67 to convert from tonnes of carbon (Mg C) to tonnes of carbon dioxide equivalent (Mg CO_2e). We divided this by 25 to get the per-year abatement over the 25-year post-restoration period.

It is assumed that a strong 'safeguard mechanism' will create sufficient demand for carbon credits over time. We modelled the following two carbon-price scenarios annually from 2025 to 2054: Scenario (1), an estimate based on extrapolating the current spot price of carbon increasing by a fixed percentage, and Scenario (2), an estimate based on extrapolating the Clean Energy Regulator's cost containment measures, which reflect current policy regarding the maximum compliance costs faced by facilities under the safeguard mechanism (Clean Energy Regulator 2024). Both scenarios are reasonably aligned with BloombergNEF's cover of the period (BloombergNEF 2024). The scenarios are conservative compared with the interim values of emissions reductions used by the Australian Energy Market Operator from 2025 to 2050 (see appendix A.11 in Australian Energy Market Commission 2024). It is assumed that the Australian carbon credit units (ACCUs) available on the market are high-integrity, following the Federal Government's commitment to implement the recommendations of the Independent Review of ACCUs (Chubb *et al.* 2022) and of the Climate Change Authority's review of the ACCU scheme (Climate Change Authority 2023).

- For Scenario 1: at the time of writing, the spot price for Australian carbon credit units on the secondary market was A\$38.50 Mg^{-1} CO_2e (CORE Markets 2024). We estimated income from carbon markets over 30 years by extrapolating from the current market conditions, assuming a carbon price of A\$38.50 Mg^{-1} CO_2e, increasing at a rate of 2% $year^{-1}$ plus 2.5% interest.
- For Scenario 2: safeguard facilities that exceed their baseline may apply to the Clean Energy Regulator to purchase the required number of carbon credits at a fixed price (Clean Energy Regulator 2024). The price of these credits was set at A\$75 Mg^{-1} CO_2e in 2023–24, indexed in future financial years by the consumer price index (CPI) plus an additional 2% $year^{-1}$. We extrapolated from these values to provide an estimate of income over 30 years (assuming 2.5% CPI for our assessment).

Indigenous organisations could play a key role in implementing this action, with significant social and environmental benefits to be gained by restoring Country and generating jobs through Indigenous businesses and ranger organisations. Services required may include construction of off-river livestock watering points, fencing, erosion control, plant propagation and planting.

Action 2. Incentivise landholders to retire riparian farmland

To further support riparian revegetation and riverbank health, we estimated the cost of incentivising landholders to voluntarily retire farmland from active production, with the exception of low-intensity grazing, from within the privately owned portion of the national riparian buffer. We calculated farm-cash income for broadacre industries within the riparian buffer zones identified in Action 1, paid out over 30 years (Australian Bureau of Agricultural and Resource Economics and Sciences 2022), to estimate the expected cost of forgoing cropping, forestry or grazing production on these lands (Table 1). Average annual farm-cash income estimates were derived from an Australia-wide, 1-km^2 resolution spatial layer for the 5-year period from 2016 to 2020 (assumed in 2022 Australian dollars; Australian Bureau of Agricultural and Resource Economics and Sciences 2022). We propose that such an action might initially be delivered via voluntary uptake but recognise that, should this be lower than required, may require increased incentives or mandatory measures. Voluntarily retired riparian farmland may, in many cases, be transferred to Indigenous custodianship for restoration.

Action 3. Restore overallocated river systems of the Murray–Darling Basin to sustainable levels of take

Multiple river systems across Australia, including six in the Murray–Darling Basin (MDB), remain at a high risk of water overallocation (National Water Commission 2014). With climate change already threatening water security in such areas (Prosser *et al*. 2021), returning these river systems to sustainable levels of take is a high priority to support the maintenance of critical ecological functions (e.g. safe drinking-water provision) and reduce risks to irrigated agriculture from salinity.

The best publicly available estimate for sustainable extraction levels in the MDB requires recovery of between 3,856,000 and 6,983,000 ML (Murray–Darling Basin Authority 2010). Given current water recovery targets presented in the Basin Plan of 3,200,000 ML (Hart 2016), a further 726,000 ML is still required to achieve the minimum target estimated under high uncertainty for sustainable environmental outcomes of 3,856,000 ML. We did not cost the volume of water that governments have committed to recovering to achieve the 3,200,000-ML target. On the basis of the average cost of water recovery by using infrastructure upgrades of A$5100 ML^{-1} (2017 dollar values) and purchase of entitlements (A$2200 ML^{-1} (2018 dollar values) (Wentworth Group of Concerned Scientists 2017), we assumed a cost of A$5100 ML^{-1} (2017 dollar values) (Table 1). Data are not available to extend this assessment beyond the MDB.

We further identified that the *Water Act* 2007 provides limited opportunity for the delivery of cultural water (also termed Cultural Flows), aiming to re-establish events that specifically deliver cultural benefits. For instance, the *Water Act* 2007 (s50 4A. a and b), through recent amendments, requests the Murray–Darling Basin Authority (MDBA) to report on matters relevant to Indigenous people in relation to the management of Basin water resources and recognise and protect the interests of and support opportunities for Indigenous people. The federal Department of Climate Change, Environment, Energy and Water (DCCEEW) Secretary also has to report annually on engagement and the above-mentioned MDBA reports (*Water Act* 2027, S85F 1). Further, through policy and commitments, DCCEEW provides funding for cultural flow plans to be developed, an Aboriginal Water Entitlements Program and the ongoing participation of Indigenous people through a designated body Committee on Aboriginal Water Interest (CAWI). We propose there is an opportunity to ensure that any future recovery and delivery of water is genuinely designed and implemented for cultural benefit by Indigenous people, for the protection of water. There are too few examples of this taking place in contemporary water management frameworks.

Action 4. Restore lateral connectivity between rivers and their floodplains and wetlands through constraints management

Numerous physical and operational constraints currently impede environmental water delivery within river systems, reducing connectivity both longitudinally along rivers and laterally between rivers and their floodplains and wetlands. By limiting the flow of water, these constraints reduce the extent and quality of ecological responses to flows and inundation of low-lying floodplains and wetlands, resulting, for example, in smaller native fish populations and degraded health of river red gum forests and woodlands (New South Wales Department of Planning and Environment 2023).

Removing constraints to environmental flow delivery can involve a range of options, including the removal or modification of physical infrastructure such as bridges, roads and flood works, or purchases of voluntary easements on private land. State government business cases for constraint management in five priority areas of the MDB (Hume to Yarrawonga, Yarrawonga to Wakool Junction, the Goulburn, the Murrumbidgee and Menindee Lakes (Lower Darling) and the Lower Murray in South Australia) were assessed by Kahan *et al*. (2021). We have assumed the total cost of these projects, minus A$200 × 10^6 already committed to constraints management by the Australian Government (Murdoch, 2020), as our estimate for this action (Table 1).

Wetlands, including billabongs and horseshoe lagoons, have significant cultural benefits for Indigenous people. Early accounts of Indigenous utilisation of wetland resources, and historic storylines, paint a rich narrative of connection between healthy communities and rivers (Moggridge and Thompson 2024). For instance, many species of small-bodied fish with little or no commercial or recreational benefit (in a contemporary sense) are of extreme significance to Indigenous communities (Humphries 2007). Nature repair actions need to extend beyond commercially and recreationally important species because a broad range of species traditionally had cultural significance. Thus, Indigenous groups must be adequately resourced to design and implement wetland recovery programs that seek to rehabilitate all aspects of wetland fauna and flora.

Action 5. Restore longitudinal connectivity, fish passage, by removing or modifying high-priority fish barriers

Freshwater fish and other fauna are threatened globally by habitat fragmentation and reduced flow connectivity (Harris *et al.* 2017). In Australia, fish passage and flow connectivity are limited by thousands of structures within channels and on floodplains, many of which are either legally non-compliant or unauthorised (Steinfeld and Kingsford 2013; Harris *et al.* 2017). Removal or remediation of these barriers can generate many benefits for freshwater fish and other biota, as well as generating co-benefits for recreational and commercial fisheries, tourism and First Nations (Makombe 2003). Furthermore, many of these structures were constructed either directly on, or required the destruction of, traditional fish traps, which were used by Indigenous people as a source of food and social cohesion. Significant numbers of fish traps were destroyed in the process of constructing dams and weirs.

Although national estimates of fish migration barriers do not exist, multiple regional studies inform an understanding of the extent of this problem. Baumgartner *et al.* (2014) estimated that there are more than 10,000 barriers in the New South Wales (NSW) portion of the MDB alone. We extrapolated from this estimate, recognising the high density of watercourses and modifications in this area, to assume at least 40,000 fish passage barriers exist nationally, with 5% of these likely to be a high priority for removal or modification on the basis of proportions identified in existing regional prioritisations (New South Wales Department of Primary Industries 2006; Lawson *et al.* 2010; Moore and McCann 2018). Costs vary significantly from removal of obsolete road crossings to construction of new bridges or culverts (Gordos *et al.* 2007), with costs for fishway installation on large barriers ranging from A$250,000 to A$1 × 10^6 (2017 dollar values) per vertical metre (O'Connor *et al.* 2017). However, it should be noted that inflationary pressures over recent years are likely to have disproportionately increased costs since these estimates were published.

We assumed a mean cost of A$150,000 (2022 dollar values) for remediation of 95% of high-priority fish barriers and a mean cost of A$2 × 10^6 (2022 dollar values) for the remining 5% of barriers, including 42 high-priority structures identified in the MDB in NSW (New South Wales Department of Primary Industries 2012). To estimate a national cost of this action, we then subtracted A$56.8 × 10^6 already committed by the Australian Government for the Fish for the Future: Reconnecting the Northern Basin (New South Wales Department of Climate Change, Energy, the Environment and Water 2024). However, we note that progress against this initiative has been significantly hampered owing to significant cost increases in a post-covid world. Although the works program was designed and approved several years ago, not a single fishway has been completed under this program yet.

For high-level dams with a vertical height of >10 m, we estimated costs for advanced fishways. We estimated that 2790 vertical metres of dam require fishways, given that the total height of large dams in Australia is 17,438 m (Australian National Committee on Large Dams 2022) and an assumption that 16% of Australia's total catchment area is obstructed by large dams on the basis of the NSW average (Harris *et al.* 2017). We then assumed a cost of A$1 × 10^6 (2016 dollar values) per vertical metre for installation of advanced fishways (Australian Fisheries Management Forum 2016). Although existing fishways are present on ~3% of dams (Harris *et al.* 2017), we assumed that the majority of these require replacement or significant upgrades (New South Wales Department of Primary Industries 2012). We assumed operational costs for maintenance and monitoring to be 1% year^{-1} of the total upfront capital cost (Table 1). In some instances, it may be worthwhile to review the functional relevance of these structures in a contemporary water management system. Many nations, internationally, are looking to remove large structures and these are leading to significant positive river health outcomes (Woodward *et al.* 2008).

Finally, we strongly recommend that in areas where traditional fish traps have been destroyed or built over, Indigenous groups are appropriately resourced to rehabilitate these sites. There is a significant amount of Indigenous ecological knowledge, which is required to effectively rehabilitate these sites in a culturally appropriate manner. This would require programs to re-establish local community connections, to educate regional communities on the importance of these structures and to re-establish historical narratives and storylines for future generations.

Action 6. Install cold-water pollution devices on priority large dams

Water released from dams can be colder than natural flows by up to 13°C in summer (Australian Fisheries Management Forum 2016), with this cold-water pollution (CWP) often extending significant distances downstream, up to 2,000,000 river kilometres annually, with deleterious consequences for the reproduction, development, growth, movement and survival of freshwater fauna (Lugg and Copeland 2014; Michie *et al* 2020). To address this problem, dams can be retrofitted with multi-level offtakes, or techniques to mix thermally stratified water bodies can be applied (Chaaya and Miller 2022). CWP mitigation can also offer further downstream benefits with respect to improved water quality and reduced transport of cyanobacteria (Chaaya and Miller 2022).

Of 93 dams studied in NSW in 2024, nine were associated with severe CWP, defined in relation to structures with deep intake of ≥10 m and large discharge (≥1000 ML day^{-1}) (Preece 2004). We therefore assumed that ~15% of Australia's large dams will be high priorities for CWP devices. Costs for CWP solutions vary among dams but can range from <A$1 × 10^6 to A$170 × 10^6 (2000 dollar values; Sherman 2000 in Chaaya and Miller 2022). Projects proposed under the Northern Basin Toolkit program to address CWP comprised installation of a multi-level offtake at Pindari Dam for an estimated cost of ~A$14 × 10^6 (2020 dollar values) and one at Glen Lyon Dam for A$3 × 10^6 (2020 dollar values; Capon *et al.* 2020). On the basis of these figures, we assumed a mean cost per dam of A$8.5 × 10^6 for initial capital works and labour. Operational costs were assumed to be 2% year^{-1} of the total upfront capital cost (Table 1).

Action 7. Install fish diversion screening on all licensed irrigation pumps

Native fish populations in many parts of Australia are further threatened by irrigation pumps, which can remove hundreds to thousands of fish from watercourses daily, equating to millions of fish each year (Boys *et al.* 2021). Following extraction, these fish have limited, if any, opportunities to return to the main river channel (Baumgartner *et al.* 2009). Essentially, these fish become 'lost' from the main river system. Installation of 'fish-friendly' pump diversion screens can significantly (>90%) reduce fish injury and mortality, while simultaneously generating co-benefits for irrigators by reducing debris levels entrained by pumps and subsequent reductions in their operational costs (Boys *et al*. 2021; Rayner *et al*. 2023).

Rayner *et al*. (2023) estimated that there are ~4500 licensed irrigation pumps (>200 mm) in NSW requiring diversion screens. Average annual water sources from rivers, creeks or lakes for irrigation in NSW was 843,987 ML (Australian Bureau of Statistics 2021) between 2017 and 2020, which equates to ~187 ML per pump (assuming there are 4500 pumps). Australia's average annual water soured from rivers, creeks or lakes in the same period is 2,141,578 ML (Australian Bureau of Statistics 2021). On the basis of the NSW ratio, we have assumed that ~11,418 pumps therefore require diversion screens nationally. The main benefit of a national screening program is to ensure that more fish, which are spawned in main channel environments, actually stay in the rivers.

On the basis of figures provided by Fish Screens Australia (see https://fishscreens.org.au/faqs/), we have assumed a cost of A$1000 (2022 dollar values) per megalitre of pump or channel capacity. Assuming this to be 187 ML per pump, a cost of A$187,000 per pump is estimated. Our national costs also exclude A$39.5 × 10^6 (2022 dollar values) already committed under existing pump screening programs (Rayner *et al*. 2023). Operational costs for monitoring and maintenance are assumed to be 2% $year^{-1}$ of the total upfront capital cost (Table 1).

Action 8. Cap remaining open artesian bores and convert open bore-drains to pipe and trough systems in the Great Artesian Basin

Groundwater accounts for ~30% of all water use in Australia (Barnett *et al*. 2020; Walker *et al*. 2021). Groundwater is extremely significant to Indigenous people in a dry landscape such as Australia; there is extensive knowledge and values connecting to groundwater-dependant sites (Moggridge 2020). Exploitation of groundwater has resulted in declines in aquifer pressure as well as loss and degradation of groundwater-dependent ecosystems (GDEs; Fensham and Laffineur 2022). Capping free-flowing bores and converting inefficient, high-evaporation bore drains into pipe and trough systems is an effective way of repairing groundwater systems (Barnett *et al*. 2020) and GDEs (Fensham and Laffineur 2022), with co-benefits for farmers including improved grazing management (Pegler *et al*. 2002).

To cost this action, we assumed that effective groundwater management in the Great Artesian Basin, the largest and deepest aquifer in the world, requires all bores to be capped to ensure a reliable supply of water and to protect GDEs. We estimated that at least 331 uncapped bores remain in the GAB, given that recent bore rehabilitation projects have addressed 100 of the 431 open bores reported in 2019 (Great Artesian Basin Coordinating Committee 2019). Costs for bore capping range from A$14,131 to A$1.4 × 10^6 per bore (2018 dollar values), with an assumed average cost of A$346,529 per bore (2018 dollar values) (Centre for International Economics and Resource and Policy Management 2003; Hassall and Associates Pty Ltd 2003). We also estimated that 4560 km of open bore-drain remain in the GAB, given 576 km of 5136 km of open bore drains reported in 2019 have already been converted to pipe and trough systems (Great Artesian Basin Coordinating Committee 2019). Costs of conversion are estimated at A$8485 km^{-1} (2018 dollar values) (Centre for International Economics and Resource and Policy Management 2003; Hassall and Associates Pty Ltd 2003). Current Australian Government funding commitments of A$27.6 × 10^6 were subtracted to generate total cost estimates (Table 1). Operational costs, for monitoring, maintenance and to address bore failure, were assumed to be 2% $year^{-1}$ of the total upfront capital cost.

Action 9. Restore groundwater extraction of the Murray–Darling Basin to sustainable levels of take

This action concerns returning groundwater extraction to sustainable levels in the MDB by strategic purchases of water licenses from willing sellers. In recognition of the need to protect groundwaters in the face of climate change and growing demand, the 2012 Basin Plan established sustainable levels of take for groundwater systems in the MDB. In the Upper Condamine alluvium, 3.25 GL still needs to be recovered, in addition to 32.5 GL recovered by June 2023, to achieve this target of 38.45 GL (Murray–Darling Basin Authority 2023). The cost of these acquisitions is assumed to be A$1906.90 ML^{-1} (2018 dollar values) on the basis of those associated with the purchase of 35,697.40 ML of groundwater entitlements purchased through open tender in the Upper Condamine Alluvium for A$68,070,646 (2018 dollar values; Department of Climate Change, Energy, the Environment and Water 2023).

Discussion

To implement the priority actions we have outlined here at the scale indicated, our estimates suggest an approximate annual investment from 2025 to 2054 of A$3.1 × 10^9, including a total of ~A$2763 × 10^6 in capital costs and A$276 × 10^6 in transaction costs over the 30-year period, as well as A$74 × 10^6 in annual operational expenditure (2022 dollar values; Table 1; refer to the Supplementary material for calculations). On the basis of 2022–23 figures published by the Australian Bureau of Statistics, this equates to ~0.13% of GDP (refer to the Supplementary material for calculations). The investment requirement over 30 years aggregates to upfront funding of A$93 × 10^9 (2022 dollar values). If funded on an annualised future basis, the total investment required would be considerably greater – between A$4.5 × 10^9 and A$8.7 × 10^9 $year^{-1}$, with an average of A$6.2 × 10^9 $year^{-1}$.

Revegetating riparian areas across 14.4×10^6 ha on the basis of the actions identified could sequester 1.6×10^9 Mg of CO_2, offsetting ~37% of Australia's net emissions over the next 30 years by using high-integrity carbon methods, contributing to mitigation needed to meet obligations under the Paris Climate Agreement as well as agreed biodiversity targets under the Kunming–Montreal Global Biodiversity Framework. At an average price of A$35 to A$75 Mg^{-1} of CO_2e, rising at 2% $year^{-1}$ plus inflation from 2024, restoring riparian buffer zones on private land could generate A$$1.1 \times 10^9$ to A$$2.2 \times 10^9$ $year^{-1}$ in carbon market revenue within 30 years, leaving a finance gap of between A$$0.9 \times 10^9$ and A$$2.0 \times 10^9$ for inland water actions identified (2022 dollar values).

Expenditure of the scale proposed here would bring significant co-benefits to regional communities, in particular, to Indigenous nations who should be funded and supported to undertake a substantial portion of the on-ground repair works as one contribution towards improving water justice. Some actions may also be funded, at least partially, by private sector contributions. For example, installation of fish diversion screens on irrigation pumps could be a condition of their licensing. Emerging opportunities in nature financing, such as Australia's Nature Repair Market, will also likely present opportunities to direct private funds into rehabilitation of inland waters. It is also important to recognise the significant costs savings likely to be wrought by ensuring continued protection of inland waters that remain in relatively good ecological, especially beyond the Murray–Darling Basin.

We acknowledge that, even with sufficient funding provisions, implementing a continental-scale program of actions as proposed here would require significant efforts towards its design and governance, especially with regards to the necessary coordination across multiple levels of government, Indigenous nations, regional communities and private organisations. Determining the additional priorities and costs entailed should be a focus of further development of the proposed package of works in addition to more nuanced regional downscaling. In doing so, there is much to be gleaned from the wide range of natural resources management programs that have been designed and implemented in Australia over recent decades at both regional and national scales, for example, Landcare, Caring for Country, Regional Land Partnerships, etc. However, regardless of these inevitable complexities, we hope the exercise presented here demonstrates that repairing inland waters is eminently affordable for Australia with the potential to deliver substantial socio-economic and environmental benefits for all Australians well into the future.

Supplementary material

Supplementary material is available online.

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Conflicts of interest. S. J. Capon, C. Steinfeld, J. Pittock, B. Moggridge, F. Sheldon, M. Ward and D. Medaris are either members of the Wentworth Group of Concerned Scientists or were engaged by this group to undertake work contributing to the development of this paper. All of the authors are actively engaged with relevant research and restoration practice and regularly provide advice to a range of government and private organisations regarding conservation needs of Australian inland waters. The authors have no further conflicts of interest to declare.

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