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Review

Key steps to improve the assessment, evaluation and management of fish kills: lessons from the Murray–Darling River system, Australia

John D. Koehn [A,B]

[A]Applied Aquatic Ecology, Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, 123 Brown Street, Heidelberg, Vic. 3084, Australia. Email: john.koehn@delwp.vic.gov.au
[B]Institute for Land Water and Society, Charles Sturt University, PO Box 789, Albury, NSW 2640, Australia.

Abstract. Fish kills are very visible, with high levels of public scrutiny and major effects on populations. In 2018–19, extensive fish kills in the lower Darling River, south-eastern Australia, resulted in the deaths of millions of fish, including threatened and popular, iconic angling and important cultural species. This distressed local communities and the broader Australian society, who questioned the competence of fish and water management. Fish kills are increasing in frequency and severity, exacerbated by climate change. This paper reports on eight major fish-kill case studies across the Murray–Darling Basin that were examined to assess management adequacy. Field assessments and reporting have been poor, not documenting all species or numbers affected. Few values of fishes (cultural, conservation, recreational, social, ecological, economic) have been assessed and replacement or management costs not determined. There is a need to philosophically change our approach to take fish kills more seriously. More comprehensive approaches to assessment, evaluation and management are needed. Responsibilities for fish kills should be clarified and include water and habitat management agencies. Post-kill recovery plans that include the replacement of lost ecological assets should be published and enacted. This paper provides a fresh perspective on fish kills, with 15 key recommendations applicable to improve future management worldwide.

Keywords: Baakandji, cultural, economic and recreational values, fish deaths, Murray cod, Murray–Darling Basin, population restoration, social, water management.

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Introduction

Large rivers and their fishes are subject to a wide range of threats (Malmqvist and Rundle 2002) and are heavily affected by the cumulative and potentially synergistic effects of multiple stressors (Tockner *et al.* 2010). Fish kills can be dramatic events that give fish high visibility. This poses great sensitivities for public management authorities, often resulting in a reluctance for public reporting and requiring devotion to media public relations as well as to the fish kill itself. Whether caused by a single factor (e.g. poisons or temperature shock) or combinations of stressors (increased temperature, low flows and low dissolved oxygen), fish-kill occurrence is increasing worldwide (La and Cooke 2011). The loss of fish is the loss of a valuable public environmental asset and causes great community concern (Sinclair 2005; Australian Academy of Science 2019; Vertessy *et al.* 2019).

In late 2018 and early 2019, three major fish kills occurred in the lower Darling River in south-eastern Australia (Australian Academy of Science 2019; Vertessy *et al.* 2019) with numerous further, extensive kills occurring throughout 2020 (Ellis *et al.* 2021). With graphic images of large (≥20 kg) iconic Murray cod (*Maccullochella peelii*) and a 'sea' of floating dead bony herring (*Nematalosa erebi*), these events received widespread national and international media attention. These fish kills involved large numbers (estimated millions of individuals) of a range of species and were caused by high water temperatures and low dissolved oxygen levels as a consequence of prolonged drought, but exacerbated by water extraction and a rare storm event (Australian Academy of Science 2019; Vertessy *et al.* 2019). It was the dramatic and extensive fish kills of 2018–19 that prompted this special issue of *Marine and Freshwater Research* and this evaluation of fish-kill management.

The lower Darling River fish kills follow many other similar events in the southern Murray–Darling Basin (MDB) in the past 20 years (Koehn 2005; Sinclair 2005; King *et al.* 2012; Thiem *et al.* 2017), including impacts from wildfires (e.g. sediment; Lyon and O'Connor 2008; Legge *et al.* 2020). Fish kills appear to be occurring more regularly in the southern MDB, described as a crisis of water management (Jackson and Head 2020). Such events are expected to increase with climate change (Australian Academy of Science 2019; Vertessy *et al.* 2019). These fish kills occur within the historical context of a highly modified river system, stressed by a reduction of flows (Walker 2019) and a multitude of other threats (Koehn and Lintermans 2012). Most river reaches are in poor ecological condition (Davies *et al.* 2012) and native fish populations are estimated to be <10% of pre-European levels (Koehn and Lintermans 2012; Murray–Darling Basin Authority 2020). Fish kills will exacerbate the existing poor status of fish populations, limiting their recovery and jeopardising the recovery progress expected to be achieved by major water reforms, such as those proposed in the Basin Plan (Murray–Darling Basin Authority 2011).

The science of fish-kill investigations has been described as rudimentary, with a lack of recognition of multifactor stressors, acknowledgement of carry-over effects and a dearth of peer-reviewed case studies (La and Cooke 2011). Consequently, the true losses of such 'public' assets are invariably underestimated, because many values are not recognised and the associated costs are not adequately accounted for (Southwick and Loftus 2017). For example, Indigenous peoples across the world have long traditions of harvesting and valuing freshwater fishes, developing a profound understanding of these freshwater animals and their ecosystems, and have embedded them in their cultural identity (Noble *et al.* 2016). These cultural values and other important ecological, biodiversity, scientific, conservation and recreational aspects are rarely recognised in the investigation and evaluation of fish kills.

Fish kills can also cause significant economic losses, especially when involving recreationally and commercially valuable species that reduce tourism and recreation opportunities, limit fish as a food source for human consumption, incur clean-up and reputational costs and degrade ecosystem processes such as web dynamics and nutrient balances (Holmlund and Hammer 1999). In 2018–19, the Indigenous traditional owners, the local community and many sectors of Australian society were greatly distressed by the death of such large numbers of fish that included iconic and totemic species, leaving many questions regarding the health of the river and the adequacy of its management (Australian Academy of Science 2019; Beasley 2021; Colloff *et al.* 2021; Ellis *et al.* 2021). Human well-being is related to ecosystem health (Maund *et al.* 2020) and the community emotional trauma (social and cultural) incurred with the fish kills (Ellis *et al.* 2021) needs to be considered in order to properly evaluate and value all costs and losses of fish kills (see also Sinclair 2005).

Despite their very public nature and apparent increasing frequency and severity, relatively few peer-reviewed fish-kill studies have been published (La and Cooke 2011). Many government reports are not widely publicised, even though they can include many recommendations. For example, in the case of the lower Darling River, two assessments of the fish kills produced findings with 33 (Australian Academy of Science 2019) and 27 recommendations (Vertessy *et al.* 2019), whereas an inquiry into broader MDB water management contained 112 key findings and 44 recommendations (Walker 2019). Such long documents, although valuable assessments, are often narrowly focused (on particular events) and do not always provide succinct directions for fish kill or broader river management to stakeholders or the public.

This paper reviews eight notable (large or public) fish-kill case studies from the southern Murray–Darling River system over the past 20 years (including the 2018–19 lower Darling River kills) to produce recommendations for assessments, reporting and management. This study does not attempt to repeat the findings of previous reports, especially those relating to water management. Rather, it takes a holistic view of fish kills, identifying all values (including social and cultural) and reviewing the adequacy of assessments, reporting and responses. This paper provides a fresh perspective on evaluating fish-kill events and, although the focal area is the MDB, this approach is applicable to many locations and situations.

Methods and review

A range of aspects of the values of fishes, assessments and reporting, as well as evaluations of natural resource losses, were examined from eight non-urban fish kills that occurred in river channel habitats (not lakes or wetlands) in the southern MDB (Victoria and New South Wales (NSW); 2002–20; Fig. 1; Table 1). These were all considered typical examples of major kills events from this region and exemplified the three current (and likely future) major causes of fish kills in these habitats: (1) low flows and low dissolved oxygen levels; (2) blackwater; and (3) post-fire sediment. Many other substantial fish kills have occurred but have gone largely unnoticed or unreported (see also Lintermans and Cottingham 2011). For example, fish kills in the Goulburn River in 2010 and 2017 had no formal reports (Whitworth *et al.* 2011; Koster *et al.* 2012). In many widespread fish kills, such as 2010 and 2016, there were often multiple kills at other locations that were not comprehensively assessed (Whitworth *et al.* 2011; Watts *et al.* 2017). Similarly, many remote, minor kills in isolated waterholes in 2019 in the lower Darling River were not reported (I. Ellis, NSW Department of Primary Industries (DPI) Fisheries, pers. comm.). During drought conditions (2018–20), many fish kills also occurred in isolated refuge pools throughout the northern MDB (G. Butler, NSW DPI Fisheries, pers. comm.; G. Ringwood, MDBA, pers. comm.).

Background

Australia's MDB in south-eastern Australia (Fig. 1) is one of the world's most regulated river basins (Grill *et al.* 2019) and is under great stress. There is competition between water use for agriculture and environmental needs in what is described as Australia's 'food bowl' (Koehn 2015), with much concern about water overallocation, resulting in the demise of environmental and social values (Walker 2019; Gray 2020). The Darling River is the traditional land of the Baakandji people, who call the river the *Baaka* (Baakandji language). The Darling River flows over 2740 km through semi-arid landscapes before joining the Murray River near Wentworth (Fig. 1). Its highly variable flows are altered by regulation and water extraction, converting many reaches from flowing to non-flowing, with much greater cease-to-flow periods than would occur naturally (Mallen-Cooper and Zampatti 2020; Ellis *et al.* 2021). The highly regulated Murray River and connected tributaries have a more predictable flow regime, and flow east to west for 2530 km. The Darling River was once considered a national stronghold for Murray cod *M. peelii* (Harris and Gehrke 1997) but, following such major fish kills, this population can no longer be considered secure.

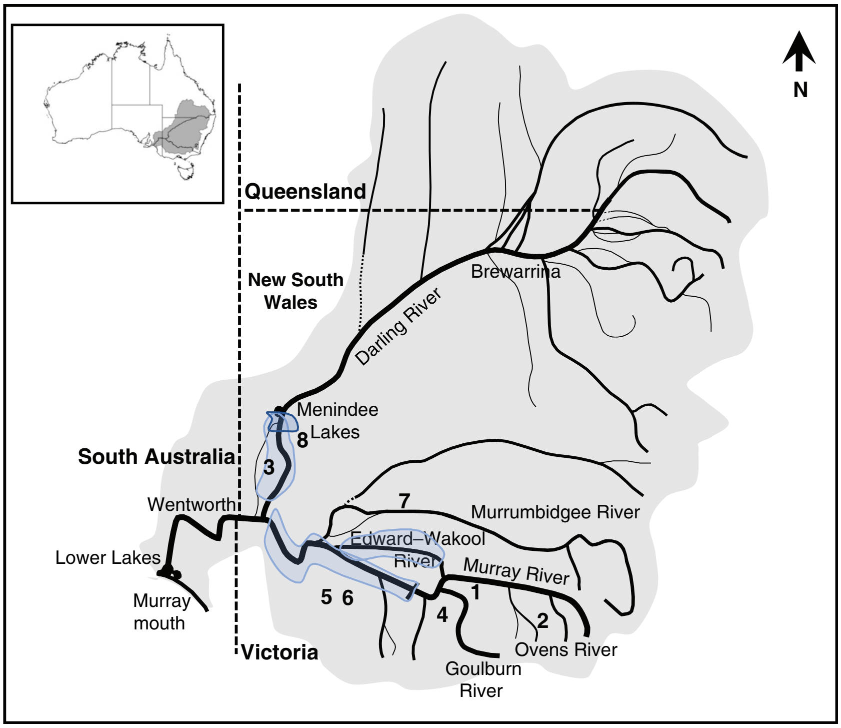

Fig. 1. Map indicating the locations of the fish-kill case studies in this paper within the southern connected Murray–Darling Basin (MDB; grey shading). 1, Broken Creek (2002); 2, Ovens River (2003); 3, Lower Darling River (2004); 4, Goulburn River (2004); 5, Murray River + Edward–Wakool rivers (2010–11); 6, Murray River + Edward–Wakool River system (2016–17); 7, Murrumbidgee River (2018–19); 8, Lower Darling River (2018–19). The dates of fish-kill events are given in parentheses. See Table 1 for additional site details.

Table 1. Fish-kill case studies in the southern Murray–Darling Basin included in this paper

Numbers relate to case study location indicated in Fig. 1. ?, possible cause; 2BF, two-spined blackfish; AS, Australian smelt; BH, bony herring; C, carp; CG, carp gudgeons; DO, dissolved oxygen; DS, downstream; EW, Edward–Wakool River system; GP, golden perch; MC, Murray cod; MCr, Murray crayfish; SP, silver perch; TC, trout cod. For species names, see Table 2. References are as follows: 1, Koehn (2005); 2, Lyon and O'Connor (2008); 3, Koster *et al.* (2004); 4, Ellis and Meredith (2004); 5, King *et al.* (2012); 6, McCarthy *et al.* (2014); 7, Whitworth *et al.* (2011); 8, Thiem *et al.* (2017); 9, Watts *et al.* (2017); 10, Webb *et al.* (2019); 11, Vertessy *et al.* (2019); 12, Australian Academy of Science (2019); 13, Murray–Darling Basin Authority (2019); 14, I. Ellis, NSW DPI Fisheries, database and reports (see also Ellis *et al.* 2021)

Case study	Year	Location	Possible causes	Affected river reach (km)	Estimated total number of fish	Species formally recorded	References
1	2002	Broken Creek (DS Rice's weir)	Low DO: *Azolla* bloom	2	>179	MC	1
2	2003	Ovens River (DS Myrtleford)	Fire sediment	200	>178	MC, TC, GP, AS, CG, C, 2BF	2
3	2004	Lower Darling River (DS Menindee)	Low DO	160–200	3000	Mostly MC, ~50 GP	1
4	2004	Goulburn River (DS Nagambie weir)	Herbicides (?), low DO	15	91		3
5	2010–11	Murray River + EW (DS Barmah)	Blackwater	1800	>10 000[A]	BH, MC, GP, SP, MC, MCr	4,5
6	2016–17	Murray River + EW (DS Barmah)	Blackwater	2000	Hundreds of thousands[A]	BH, MC, GP, SP, MC, MCr	8,
7	2018–19	Murrumbidgee River (DS Balranald)	Reduced flows, drought	~5	Thousands[A]		9,10
8	2018–19	Lower Darling River (DS Menindee)	Reduced flows, drought	40 (Menindee) then ~600	>5 million[A]	BH (millions), MC (hundreds at Menindee; thousands downstream), GP and SP (thousands to tens of thousands)	11, 12, 13, 14

[A]I. Ellis, NSW DPI Fisheries, database and reports.

Fish kills

Tens of thousands of fish died along a 30-km stretch of the lower Darling River on 15 December 2018 (Fig. 1; Table 1, Case study 8), with a second, larger event (hundreds of thousands of fish) occurring on 6 January 2019. A third event followed on 28 January 2019, killing millions of fish, with a fourth event beginning 4 February 2019 (Australian Academy of Science 2019; Vertessy *et al.* 2019). Many subsequent fish kills also occurred along remote reaches of the river throughout 2019 (Ellis *et al.* 2021; NSW DPI Fisheries, unpubl. data). These fish kills were all considered as one fish-kill 'event'. The seven other fish kills examined in this study occurred at a range of sites from 2002 to 2018 (Fig. 1; Table 1, Case studies 1–7).

The values of fishes

Valuing natural environmental resources can be difficult (Helm 2015), extending beyond economics to ecosystem services (Holmlund and Hammer 1999) and shared and social values (Kenter *et al.* 2016). Seven categories of values applied to Atlantic (Baltic) salmon *Salmo salar* (Ignatius and Haapasaari 2018) are useful. These categories (with notes for Murray cod in parentheses) are: (1) civic worth, centrality of fair management (to include all stakeholders); (2) green worth, carrier of diverse ecological values (an iconic keystone, predatory species); (3) domestic worth, have traditional Baakandji cultural and recreational fishing values; (4) inspirational worth, emotional attachments and recreational importance (a highly sought after species); (5) worth of fame, symbolic (a large iconic Australian fish); (6) market worth, the economic value of recreational fishing and associated tourism; and (7) industrial worth, declining importance as a production resource (no longer really applicable because Murray cod commercial fisheries closed in the early 2000s).

Darling (*Baaka*) River fishes are of great importance to Indigenous people (the Baakandji, the people of the *Baaka*), providing a food resource for over 30 000 years (e.g. Dargin 1976; Humphries 2007), with cultural values and roles as totems and figures in traditional ancestral belief systems (Ginns 2012; Ellis *et al.* 2021). The cultural importance of fishes is heightened by the site of the traditional Aboriginal fish traps at Brewarrina (Fig. 1), over 1500 km upstream of the Murray River junction. This is one of the great Aboriginal meeting places of eastern Australia, shaping the spiritual, political, social, ceremonial and trade relationships between Aboriginal groups from across the greater landscape (Balme 1995). Fish kills cause community emotional trauma in both Indigenous and non-Indigenous communities (Sinclair 2005; Ellis *et al.* 2021). The loss of bony herring (*Nhaampa*), a totemic species for Baakandji families, and the rejection of recreational fishing as an activity by some non-traditional community members following the trauma of the fish kills are cultural and social losses that cannot be ignored.

Recreational fishing is a significant pursuit that 19% of Australians participate in annually (Henry and Lyle 2003). Fishing for iconic trophy fish, such as Murray cod, provides social and recreational opportunities for remote rural communities and substantial economic benefits through tourism and travel expenditure (Ernst and Young 2011). A range of economic analyses can financially value these aspects (e.g. Zhang and Li 2005; King 2015).

Biodiversity is another important part of conservation and valuing nature that is affected through fish kills. Despite the loss of many individuals of species of international, national and state conservation importance (Table 2; most with published recovery plans), this value has received remarkably little attention. In addition to conservation listings for individual threatened species, 'The aquatic ecological community in the natural drainage system of the lowland catchment of the Darling River' was also listed threatened community in NSW in 2003 (see https://www.dpi.nsw.gov.au/fishing/threatened-species/what-current/endangered-ecological-communities/darling-river-eec, accessed 9 July 2021).

Fish are also a key component of riverine ecosystems. Fish kills can affect water quality, food availability, food webs and trophic structure (crustacean, molluscs and macro-invertebrates), competition and population processes (e.g. reduced predation pressure) and food sources for non-fish organisms (birds, terrestrial fauna; McGinness *et al.* 2020). Assessing the ecological values of species is difficult, but the removal of large numbers of fish predators (Murray cod and golden perch *Macquaria ambigua*) is likely to highly affect food chains.

Fish-kill assessments and reporting

Although fish kills are not uncommon in the MDB, with over 60 fish kills reported to the MDBA during the 2019–20 summer (G. Ringwood, MDBA, pers. comm.), obtaining details of the occurrence, location and frequency of the events, as well as accurate numbers of fish killed, has proven difficult. Unfortunately, the State of Victoria does not have a functional fish-kill database (L. Metzeling, Environmental Protection Authority, pers. comm.), nor is there a national reporting system. The NSW database is difficult to access and the numbers of fish killed are reported in categories (e.g. <100; $>100\,000$; but see some information in Vertessy *et al.* 2019). Hence, no overall assessment of the total losses, trends in the number, duration or extent of fish kills or the effects on fish populations in the MDB is possible.

The number of large-bodied (total length (TL) >200 mm) fish species killed was estimated from the 2018 lower Darling River, but not from sporadic kills that occurred in more remote waterholes during 2019. Given the size and importance of the 2018–19 kills, reporting in numerical categories rather than absolute counts was inadequate. Additional estimates for some species, derived from photographs, provided a useful way forward, but need further evaluation for their accuracy (I. Ellis, NSW DPI Fisheries, unpubl. data).

Ten native freshwater fishes, a crayfish (*Euastacus armatus*), a shrimp (*Paratya australiensis*), a freshwater prawn (*Macrobrachium* spp.) and the introduced common carp (*Cyprinus carpio*) were recorded in the fish-kill case studies (Tables 1, 2). The three invertebrates have not been fully considered in this paper but are included to highlight the need for their inclusion in future assessments. It is also noted that concern has been expressed towards other species, such as river mussels (*Alathyria jacksoni*) and river snails (*Notopala*

Table 2. Native fish (ten species and three macroinvertebrates) recorded in the fish-kill examples in this study, their maximum size, values and whether they were produced in hatcheries

See also Lintermans (2007) and Koehn *et al.* (2020*a*) for more details on species, including conservation listings. ?, uncertain; H, high; L, low; M, medium; N, no; NA, not applicable; Y, yes

Common name	Species name	Maximum length (mm)	Value						Hatchery production
			Cultural	Conservation	Recreational	Social	Ecological	Economic	
Murray cod	*Maccullochella peelii*	1400	H	H	H	H	H	H	Y
Trout cod	*Maccullochella macquariensis*	910	M	H	NA[A]	H	M	NA	Y
Golden perch	*Macquaria ambigua*	600	H	L	H	H	H	H	Y
Silver perch	*Bidyanus bidyanus*	450	H	H	M	M	M	M	Y
Bony herring	*Nematalosa erebi*	470	H	L	L	L	H	L	N
Freshwater catfish	*Tandanus tandanus*	500	H	M	M	M	M	M	N
Australian smelt	*Retropinna semoni*	100	L	L	L	L	M	L	N
Two-spined blackfish	*Gadopsis bispinosus*	350	?	L	L	L	M	L	N
Mountain galaxias	*Galaxias olidus*	140	L	L	L	L	M	L	N
Carp gudgeons	*Hypseleotris* spp.	70	L	L	L	L	M	L	N
Murray crayfish	*Euastacus armatus*	NA	H	M	H	H	M	M	N
Freshwater shrimp	*Paratya australiensis*	NA	L	L	L	H	M	NA	N
Freshwater prawn	*Macrobrachium* spp.	NA	L	L	L	H	M	NA	N

[A]Protected from take but caught incidentally.

sublineata sublineata) (Mallen-Cooper and Zampatti 2020). Some of these species were of high conservation value and cultural significance to Indigenous communities in the region, including those holding Native Title rights (Australian Academy of Science 2019). Assessments were made by the author of this paper for a range of potential values for each species (Table 2) based on knowledge of these species and information in sources such as Lintermans (2007), Koehn *et al.* (2020*a*) and the Murray–Darling Basin Authority (2020) and references therein.

Species with conservation status listings of critically endangered or endangered were considered of high conservation value, whereas vulnerable species were considered of medium conservation value. Six fish species were considered to have considerable cultural values (although all species are valued by Indigenous owners); four of these are threatened, five have social value, five have recreational fishing value, all are considered significant ecologically and five have economic value (through recreational fishing and tourism; Table 2). Four species are reared in hatcheries and stocked for either conservation or recreational fishing purposes (Table 2).

Most field assessments of fish kills have been poor. None of the case study assessments examined recorded all species affected, precise numbers, fish sizes or comprehensive details of the spatial extent of the kill (Table 3). Mostly only large, popular fish species were counted, often not immediately or accurately, with belated observations underestimating numbers because carcases had sunk, been washed away, decomposed or been scavenged by birds, foxes (*Vulpes vulpes*) or feral pigs (descendants of the domestic pig, *Sus scrofa*). This lack of timely data understates the losses incurred. Incomplete assessment is likely due to a lack of priority, staffing, comprehensive searching, expertise and protocols. For example, only four large-bodied fish species were recorded for the lower Darling River fish kills, although general observations of the small-bodied Australian smelt (*Retropinna semoni*) were included. Six additional small-bodied (<200 mm TL) native species were considered likely to be present (NSW DPI Fisheries, unpubl. data), but their presence or deaths is uncertain. Australian smelt were noted 'gasping at the surface' (I. Ellis, NSW DPI Fisheries, pers. comm.) and, similarly, 'several thousand minnows and fingerlings' with no species identification were reported to have died in the Goulburn River in 2004 but were not recorded (Table 1; Environmental Protection Authority 2004; Koehn 2005). There is a continued lack of attention and data for small-bodied species despite increasing concern for their conservation (Lintermans *et al.* 2020). More immediate and complete surveys have occurred after fire rescue operations for some other small-bodied species (M. Lintermans, University of Canberra, pers. comm.; T. Raadik, Arthur Rylah Institute, pers. comm.), but many fish kills are not actually formally evaluated or reported on at all.

The overall lack of such quantification and the almost total lack of information on small-bodied and juvenile large-bodied fishes are concerning and indicative of the need for a revision of assessment procedures. The widespread and abundant introduced common carp were only included in some counts of large-bodied fish, and other non-native species, such as redfin (*Perca fluviatilis*), goldfish (*Carassius auratus*) and eastern gambusia (*Gambusia holbrooki*), may have been expected to be present. This highlights the importance of searching for, and recording, all species affected.

Table 3. Evaluation of the extent to which each fish-kill case study in this paper included criteria for assessment, values, costs, management and recovery pathways

Numbers next to case studies correspond to those in Table 1. References are as follows: 1, Koehn (2005); 2, Sinclair (2005); 3, Lyon and O'Connor (2008); 4, Koster *et al.* (2004); 5, Ellis and Meredith (2004); King *et al.* (2012); 7, McCarthy *et al.* (2014); 8, Whitworth *et al.* (2011); 9, Thiem *et al.* (2017); 10, Watts *et al.* (2017); 11, Webb *et al.* (2019); 12, Vertessy *et al.* (2019); 13, Australian Academy of Science (2019); 14, Murray–Darling Basin Authority (2019). EW, Edward–Wakool River system; MC, Murray cod; N, no, not undertaken; P, partially undertaken; DO&F, preventative actions in the form of early warning dissolved oxygen detector and the provision of flow diversions from the Murray river enacted; Re, rescue; S, stocking; TC, trout cod; Y, yes, undertaken

	Case studies							
	1. Broken Creek (2002)	2. Ovens River (2003)	4. Goulburn River (2004)	3. Lower Darling River (2004)	5. Murray River + EW (2010)	6. Murray River + EW (2016)	7. Murrumbidgee River (2018–19)	8. Lower Darling River (2018–19)
Assessment								
Formal report	P	N	P	N	N	P	N	Y
All species recorded	N	N	N	N	N	N	N	N
Precise fish numbers recorded[A]	N	N	N	N	N	N	N	N
Listed threatened species	Y	Y	Y	Y	Y	Y	Y	Y
Scientific data (e.g. age)	N	P	N	N	P	P	P	P
Impact on population	N	N	N	N	N	N	N	N
Values considered								
Cultural	N	N	N	N	N	N	N	Y
Ecological	N	N	N	N	N	N	N	N
Recreation	N	N	N	N	N	N	N	P
Social	N	N	N	N	N	N	N	P
Conservation	N	N	N	N	P	P	P	P
Costs								
Economic	N	N	N	N	N	N	N	N
Fishery	N	N	N	N	N	N	N	N
Replacement of fish	P	N	P	P	N	N	N	N
Management and clean-up	N	N	N	N	N	N	N	N
Management								
Community involvement	N	N	N	N	N	N	P	Y
Angler response	N	N	N	N	N	N	N	P
Conservation response	N	N	N	N	N	N	N	Y
Agency response	Y	Y	Y	Y	Y	Y	Y	Y
Recovery pathway								
Recovery plan or actions	N	N	N	N	N	N	N	Y
Additional conservation measures	P (DO&F)	P (S)	N	N	N	N	N	P (Re, S)
Revision of recovery plan	N	N	N	N	N	N	N	N
Fishery closure	N	N	N	N	N	N	N	N
Recovery assessments	Y	Y	Y	P	Y	Y	Y	Y
Fishery stocking	N	P (TC)	N	P (MC)	N	N	N	P (MC)
Impacts addressed	Y	NA	N	N	N	N	N	N
Recovery rates and options	P	N	P	P	N	N	N	N
References	1, 2	3	4, 2	2, 5	6, 7	8, 9, 10	11	12, 13, 14,

[A]I. Ellis, NSW DPI Fisheries, database and reports.

Except for the 2018–19 Darling River fish kills, cultural, ecological, recreational and social values have not been considered in assessments. Conservation values have only been partially considered in half the case studies and full economic costings have not been undertaken (economic costings for tourism, recreation, management actions or clean-up). The only estimates for some replacement costs (stocking of Murray cod only) and likely timelines for recovery were undertaken by Koehn (2005; see Table 3).

Management and resourcing

The multijurisdictional nature of the MDB means that management, with responsibilities for fish and water management, resides within different agencies (Koehn and Lintermans 2012). This is problematic for fish (see Koehn 2005). For example, NSW DPI Fisheries assumed the unpleasant responsibility of managing the dead fish, but these kills were exacerbated by the management of water resources (Australian Academy of Science 2019; Vertessy *et al.* 2019). Water and environment agencies (e.g. EPA, Water NSW, MDBA) had little public involvement in the immediate management or aftermath of the fish kills. There is a need to explicitly link water and fish management agencies to ensure a fair and clear delineation of responsibilities such that response approaches are adequately resourced and coordinated. There has generally been limited community involvement in fish kills, and surprisingly limited responses from angler and conservation organisations.

There have been some short-term management actions, including the use of flow aerators and fish rescues (lower Darling River), to prevent further deaths. The rescue of larger Murray cod to the Narrandera hatchery by NSW DPI Fisheries and the subsequent 2021 release of fingerlings produced from these fish not only may have contributed to the population recovery (quantum unknown), but was also an important goodwill gesture to the Baakandji traditional owners (Ellis *et al.* 2021). Such rescues are not always possible, and had not happened in most earlier fish kills. The rescue, housing and release of smaller native fishes has occurred for many other species to avoid post-fire sediment, providing an additional recovery mechanism for these species (Legge *et al.* 2020; M. Lintermans, University of Canberra, pers. comm.; T. Raadik, Arthur Rylah Institute, pers. comm.).

Although early warning water quality monitoring and the use of flushing flows have alleviated low oxygen levels in Broken Creek (since 2003), other longer-term options are few. The lack of consideration of all stressors and their effects on populations over the longer term means that such issues have not been addressed. The formulation of local post-kill recovery plans, additional conservation measures and the revision of threatened species recovery plans are rare. No fishery closures have been enacted and minor stocking has occurred for two fish kills, but their effect has not been assessed to date. There has been consideration of some of the stressors arising from water extraction for the Darling River 2018–19 fish kills (Australian Academy of Science 2019; Vertessy *et al.* 2019), but there have been no analyses of data to determine cause-and-effect relationships with such stressors (Table 3). There is a lack of quantification of population losses and an absence of appropriate pre-fish-kill population data to compare recovery against. There have been no efforts to estimate the effects of either individual or repeated fish kills on MDB populations or conservation values overall, population trajectories over the longer term, including with costed of actions for replacement, and timelines to recovery (but see Koehn 2005).

Discussion

Fish-kill assessments and reporting

From a broad perspective, fish-kill field assessments have been poor, with even basic ecological information missing and most sociocultural values ignored. Few fish kills have full investigations with well-documented public reporting or recovery plans. Economic evaluations of losses have not been undertaken. Actions to recover fish populations from such events have been limited, with inadequate evaluation of the scope or costs of most basic possible actions (e.g. how many fish stocked for how long to replace the population lost; implementation of other recovery actions, such as provision of flows).

Many MDB fish kills are not actually formally evaluated or reported on at all. This lack of fish-kill reporting is surprising, but is consistent with the general lack of publications globally (La and Cooke 2011). Most MDB information comes from post-fish-kill surveys (e.g. Stocks *et al.* 2021), usually conducted much later, or other routine monitoring (e.g. Koster *et al.* 2004, 2012). Although some of these may indicate rates of recovery, they rarely quantify the losses that occurred (Lyon and O'Connor 2008; King *et al.* 2012) and do not consider recovery potential or timelines. There has recently been some attention to the collection of other important ecological data, such as age structure (Thiem *et al.* 2020). Impacts (including from subsequent fish kills) need to be assessed so that recovery actions can be enacted and measured. There is a need for the development of more stringent protocols for fish-kill assessments, evaluation and management.

Despite all MDB kills affecting listed threatened species, there has been surprisingly little consideration of conservation values (by agencies or the public) or additional actioning of recovery plans, as recommended by Vertessy *et al.* (2019) for Murray cod (National Murray Cod Recovery Team 2010). The impacts of kills on either local or wider populations (percentage populations lost; wider implications to future recruitment and effects on metapopulations) have received little attention. There is a need for the acknowledgement and assessment of carry-over effects that may exist long after the fish kill occurs (La and Cooke 2011). There is also a need for the assessment of the cumulative effects of such multiple kills, because:

> …the continued loss of many adults and generations seriously reduces reproductive capacity and will eventually drive the species to a point where it cannot recover naturally [Rowland 2020].

Impacts of dead fish on water quality, general ecology and the ecology and health of other species that rely on fish also need to be considered (McGinness *et al.* 2020). These issues should all be addressed through the development and implementation of post-kill plans that aim to recover the populations and values lost.

On a positive note, some aspects of river management did change because of the disastrous Darling River fish kills of 2018–19. It is only with the occurrence these fish kills that some cultural and social values have been mentioned (Australian Academy of Science 2019; Vertessy *et al.* 2019; Ellis *et al.* 2021; but see Sinclair 2005) and, although detail was lacking, this provides an impetus to improve future fish-kill assessments. However, although there was some involvement of the Indigenous people and regional communities, there has not been true evaluation of these social values. With the minor exception of Koehn (2005), who provided some estimate of replacement costs for re-establishment of lost fishes through restocking (see below), there have been no estimates of the economic losses from these fish kills. There is a need to explicitly assess and value losses, including measuring recreational use losses (English *et al.* 2018).

In the case of international fish kills, such as those from oil spills, money from the entity responsible for the fish kills is allocated to restoration projects that will benefit the very same users who were affected by the fish kills (https://response.restoration.noaa.gov/about/media/how-do-we-measure-what-we-lose-when-oil-spill-harms-nature.html, accessed 21 June 2021) or can be used for claims for restitution (Southwick and Loftus 2017). It is worth noting that no such claims have been made in Australia for riverine fish kills such as those described in this paper. At the very least, replacement costs for the species lost should be estimated. Koehn (2005) used a population model to estimate the replacement cost of 3200 Murray cod from fish-kill Case studies 1–3 in Table 1 through stocking alone (no other costs) to be ~A$A7.4 million in 2020 monetary terms. No economic costing has yet been undertaken for staffing, clean-up, media, replacement of populations or other management actions for the Darling River fish kills. This leaves the fish greatly undervalued in the public and political eye.

Additional technologies, such as photography, satellite images, the use of drones and video footage, should be trialled for use in fish-kill assessments, particularly in remote areas. Such options may be applicable to only some species and would need further evaluation of their accuracy, but they may provide a useful way forward to improve assessments (I. Ellis, NSW DPI Fisheries, unpubl. data). Assistance from communities and stakeholders should also be incorporated.

Management and resourcing

There is a need for a more dedicated and holistic approach to now be taken to fish kills, fish, water and waterway management. This must occur through both short- and long-term responses supported by increased management and resourcing. The reality is that rivers such as the Darling, and, indeed, the MDB as a whole, cover vast areas (MDB $>1 \times 10^6$ km^2); consequently, the resources needed to prevent, manage and recover populations from fish kills must be commensurate for this task. Responsibility for the protection of fish populations must include water and other agencies that manage fish habitats, because many fish kills have at least been exacerbated by water extraction issues. An interdisciplinary approach to the prevention, evaluation and restoration of populations following fish kills should be established with dedicated capacity and options for interjurisdictional cooperation. Fish-kill task forces should be established for high-risk areas that include community and Indigenous representatives, fish scientists and water, land and conservation managers to manage risk, coordinate assessment and responses and manage recovery efforts. Partnerships between key research institutions and water management agencies should be strengthened to enable a better understanding of the multiple impacts on fish populations and provide consequent improvements to fish kill and fish population management. The integration of social and Indigenous cultural values into water planning can provide additional stakeholder ‘ownership’ and may allow for cultural flows to be used to help protect culturally valuable assets, such as fish and other aquatic life (Moggridge *et al.* 2019).

Although attention to preventative and short-term measures may be important (water quality monitoring, aerators, fish rescues, some stocking), these measures need to be evaluated for their effectiveness (Archdeacon *et al.* 2020). Following the Darling River fish kills, some actions are already underway (e.g. mapping of refuges; limited stocking of fingerlings), but there is concern that some issues may remain insurmountable or unaddressed (e.g. Gray 2020; Chen *et al.* 2021). There may no longer be enough water remaining in the Darling River due to overallocation and a drying climate to avoid such catastrophic conditions being repeated (Australian Academy of Science 2019; Rowland 2020). The water management stressors raised for the Darling River (Australian Academy of Science 2019; Vertessy *et al.* 2019; Walker 2019; Mallen-Cooper and Zampatti 2020; Beasley 2021) must be taken seriously and addressed, in addition to the many other options for both restoring native fish populations and increasing their resilience to climatic variability (Koehn and Lintermans 2012; Koehn *et al.* 2020*b*; Murray–Darling Basin Authority 2020). Such approaches must be adapted to accommodate climate change predictions (Pittock and Finlayson 2011).

Given that water extraction was clearly recognised as a factor contributing to the stressors and reduced resilience of the river system in 2018–19 and other events (Koehn 2005; Australian Academy of Science 2019; Vertessy *et al.* 2019), improved water management is critical to the prevention of future fish kills and the recovery of the fish populations (Archdeacon *et al.* 2020). A full evaluation of the changes to river discharge and exact extraction rates (pumping and harvesting of overbank flows) are needed because the data presented to date have been recognised as underestimates (Australian Academy of Science 2019; Vertessy *et al.* 2019; Walker 2019). The many recommendations for water reform made in previous reports (Australian Academy of Science 2019; Vertessy *et al.* 2019; Walker 2019) need to be addressed, along with reduced flows predicted under climate change (Leblanc *et al.* 2012), water allocations and theft (Gray 2020), floodplain harvesting (capture of overbank flows) and the delivery of environmental flows of appropriate magnitude and frequency to facilitate restoration (Chen *et al.* 2021). Recent analysis of flows during drought periods has highlighted profound changes to historical flow rates (Mallen-Cooper and Zampatti 2020), and this impact needs to be fully quantified so that future risks can be assessed.

There are also many other recommendations for beneficial water management actions, including those to reduce the likelihood of blackwater events (Kerr *et al.* 2013; Whitworth and Baldwin 2016) and to build resilience in fish populations (Koehn *et al.* 2020*b*; Murray–Darling Basin Authority 2020).

Environmental water allocations and their delivery will be key not only for preventing fish kills, but also to promote population recovery (population maintenance, spawning, increased survival, recruitment, movements, recolonisation). Example hydrographs to achieve benefits have now been developed for Murray cod and golden perch (Sharpe and Stuart 2018; Stuart *et al.* 2019; Koehn *et al.* 2020*a*; Stuart and Sharpe 2021) and should be developed and implemented for other species. Given the poor state of MDB fishes, in addition to short-term actions there also must be a longer-term focus towards building resilience in populations and their general recovery, not just following fish-kill events (Koehn and Lintermans 2012; Murray–Darling Basin Authority 2020). Many other management actions, such as fishways that help in dispersal, recolonisation and recovery, preventing loss of larvae over weirs, can reduce existing stressors (Baumgartner *et al.* 2020; Koehn *et al.* 2020*b*).

Formal multispecies recovery plans (not just fishes, but also other aquatic species affected) should be developed following each major kill event. An improvement in the adequacy of assessments will allow for their success to be measured, providing adequate resourcing and implementation occurs. Timelines and pathways to recovery will differ among species (King *et al.* 2012) and with different management options, the costs and benefits of which can be predicted using population models (Koehn 2005; Koehn and Todd 2012). Murray cod may recruit at the reach scale, whereas more mobile species, such as silver perch and golden perch, may recolonise from the Murray River and other locations (e.g. from the mid-upper Darling River; Thiem *et al.* 2021).

To summarise, a fish-kill response strategy must encompass the inclusion of community (social, recreational, economic) and Indigenous cultural values; this then allows for assistance from these stakeholders to be included in the documentation of those values and losses. Assistance with early warning notification to agencies, assessment (photographs, drones, videos), fish rescues, scientific collections and monitoring could be considered. Dedicated fish-kill response teams should be established that that include agency and community members with tasks, responsibilities, processes and training established, and community members rewarded for their involvement. This strategy provides an opportunity to strengthen the roles of traditional owners, recreational fishers, conservation groups and the community. These are already recognised as key inputs to collaborative native fish management and recovery (Murray–Darling Basin Authority 2019, 2020) and could help increase confidence in water management (Jackson and Head 2020). Species rescue and recovery facilities should be established to capture, house and, where practical, breed fish and then release them back into the wild. This is especially important for small-bodied threatened species (Koehn *et al.* 2020*b*; Lintermans *et al.* 2020).

Many different sectors of Australian society and the Menindee community were distressed at such large numbers of fish dying and were concerned about the implications for the health of the river and the adequacy of its management (Australian Academy of Science 2019). They were also frustrated that their many previous concerns and warnings had been ignored (Rowland 2020). Sadly, such events were predicted by the NSW Fisheries Scientific Committee (FSC) in 2003 when discussing the listing of the aquatic ecological community (S. Rowland, past FSC member, pers. comm.). More broadly, some feelings have turned to anger, with suggestions of water fraud, maladministration and questioning of the integrity of science, management and public policy (Gray 2020; Beasley 2021; Colloff *et al.* 2021). This erosion of trust is not helpful for other restoration programs underway (Murray–Darling Basin Authority 2011, 2020). Unfortunately, most recommendations previously made to improve management of drought (including lessons from the Millennium Drought; Lintermans and Cottingham 2011) and fish kills, especially in relation to Murray cod, have never been implemented (see Koehn 2005; National Murray Cod Recovery Team 2010). It appears that once the media attention subsides and the drought conditions break, the last major fish-kill tragedy and the smaller events are forgotten until the next crisis. Given the increasing extent and frequency of fish kills, this approach must change.

Key recommendations

Given the increasing occurrence and magnitude of fish kills, there is a need for a philosophical change in our approach to their management, with a need to take this issue much more seriously. The principal of restoring the lost biological social and cultural assets following fish kills should be established. Key improvements can be made to: the assessment and evaluation of losses; the inclusion of community, cultural and recreational values; agency responsibilities; and reporting and actions to facilitate recovery. The following key recommendations can improve future management in the MDB and provide guidance for other regions.

Fish-kill assessments and reporting

1. Fish-kill losses must be rigorously assessed, including: estimating their spatial extent; species composition (all species; large, small, non-native) and abundance; size and age structure; and causes (data on all stressors, both at the site and elsewhere in the river system). Analyses of these data should be undertaken to determine cause-and-effect relationships.
2. Assessments must include losses to all values: ecological, scientific, cultural, social, recreational and economic. All economic costs should be calculated, including management and clean-up, losses to tourism expenditure and replacement of the biological assets (the fish population).
3. Fish-kill evaluation and management protocols should be established to outline detailed investigations and scientifically rigorous assessments of all losses. Additional technologies, such as photographs, satellite images, the use of drones and video footage, should be incorporated to assessments to estimate fish losses more precisely.
4. Assessment of the cumulative and overall impacts of fish kills on fish populations (both at local and larger spatial scales; short and long term) should be undertaken using databases, spatial mapping, population modelling and other information.
5. Dedicated fish-kill response teams should be established that include coordinators, data collectors, ecological scientific expertise, local knowledge, water delivery and flow specialists and fish carcass and otolith collections.
6. A publicly accessible fish-kill website with a database to track fish kills should be established to improve

accountability, public communication and trust. Reporting of fish kills and losses should be made publicly available in clear, simple and accurate language.

Management and resourcing

Short-term responses

7. Short-term options, such as aerators, rescues and stocking, should be critically evaluated for their short- and longer-term benefits or disbenefits.
8. High-risk fish-kill zones (e.g. the lower Darling River) should be identified for priority management and fish-kill risk reduction strategies should be established. Continuous water quality monitoring should be undertaken for key parameters at key sites, with early warning devices to provided alerts so emergency plans can be actioned.
9. Recreational fisheries should be closed immediately following fish kills to protect remaining populations and to prevent the harvesting of remaining fishes, which would delay population recovery (Koehn 2005). Closures should be reassessed following a fish-kill investigation, publication and enactment of a recovery plan. Other priority fish protection measures may also be needed (e.g. protection of refuge populations).

Long-term responses

10. Fish and water management agencies should have both fair and clearly delineated responsibilities for preventing, managing and recovering from fish kills. Resourcing should be reviewed to be commensurate with the increased importance of fish kills.
11. Fish population recovery plans should be developed, funded and implemented for all high-risk and affected reaches, noting that recovery options will differ among species, depending on their life history requirements. These should address key stressors and predict recovery trajectories and timelines.
12. Species rescue and recovery teams and facilities for housing and breeding recovered fish should be established (especially for small-bodied, threatened species).
13. Community involvement should be increased (e.g. to include Indigenous, angler conservation and local organisations). Assistance with assessment should be enhanced with tasks, responsibilities, processes and training established.
14. Isolated refuge water holes must be afforded to special risk prevention and protection measures to maintain adequate water levels and quality, habitats and remaining fish populations during drought sequences, because these provide the spawning stock vital to population recovery.
15. Other actions need to be undertaken to recover abundances and build resilience into fish populations and riverine ecosystems. For example, ecosystem connectivity should be enhanced through the provision of fish passage and flow movement cues, because this will reduce population accumulations downstream of barriers and allow potential for escape and recolonisation.

Conclusion

The Darling River fish kills in 2018–19 created anger, despair and dismay among broad sections of the Australian community, and resulted in serious questions being asked regarding the harvest, extraction and management of water in the Darling River and the MDB more broadly. Questions regarding the responsible management of cultural and social assets, in this case native fishes and river health, will increasingly be directed to the water industry and management agencies. Given the predicted increasing frequency and severity of fish kills under climate change, there is a need for greater dedication to this area of resource management. It is hoped that these recommendations can help with preparedness to avoid such future disasters, manage them much better if they do occur and more realistically account for and recover the losses. The likely continuation of fish kills will only further jeopardise the recovery of native fishes that is expected through programs such as the Basin Plan and the Native Fish Recovery Strategy (Murray–Darling Basin Authority 2011, 2020). This necessitates a renewed approach that ensures assessments quantify the losses to all values of fishes, and then restore these losses through funded recovery plans.

Conflicts of interest

The author declares that he has no conflicts of interest.

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